Assessing alternative discharge distributions at the Pannerdensche Kop and IJsselkop to address climate change impacts on the Dutch Rhine system by 2100

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Figure 1: Pannerdensche Kop at low flow conditions, the Netherlands (Voskens, 2022)

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Preface

This is the final version of my thesis for my master's degree in Civil Engineering and Management at the Water Engineering and Management (WEM) department of the University of Twente. About one year ago, we began this journey with the idea to investigate the discharge distribution in the Dutch Rhine. This was followed by an one-pager, a literature review, and a proposal. Last October, I began working on this thesis and I have really enjoyed discovering the complexity of the Dutch Rhine system and modelling it for both current and future scenarios.

The research was done in collaboration with the engineering and architecture consultancy Sweco. I would like to thank the organisation for the opportunity to carry out this master thesis. Working on the thesis at the office at Sweco allowed me to meet inspiring people working in the field of water. I would like to give a special thanks to my daily supervisor Lieke van Haastregt. Lieke van Haastregt, you were very helpful during the complete process. The weeks always started well as we discussed the process, the results, and the planning. You also encouraged me to expand my horizon by for example working from different offices and by inviting me to professional activities such as the symposium for water and weather management, symposium Rivers2Morrow, and also to social activities such as the Christmas Drink and the curl clinic with the team.

Next to this, I would like to thank my supervisor Niels Welsch from the University of Twente for his support, feedback, and enthusiasm. The biweekly meetings really helped me move forward in the research, even if they ended with more questions than we started with. Thank you for being always available by both mail and (at the coffee machine) in the Horst for questions. Besides, I want to thank Jord Warmink for chairing the graduation committee. The meetings with the committee were full of ideas for improvement on my thesis. All the support kept me motivated and helped me to reach the finish line.

Finally, I would like to thank Ties, my family, my friends, and my housemates for supporting me. They were always there for me, whether it was proof reading one of these pages but especially for offering a listening ear.

I hope you enjoy reading my report.

Lianne Schoonderwoerd

Enschede, March 2025

Summary

The Dutch Rhine branches are among the most heavily engineered river systems in the world. Groynes, weirs, control structures, and flood channels are built to manage the flow and thereby support river functions such as conveyance, water supply, habitat, and transportation. In addition, the river system is affected by climate change. This is evident trough a change in the hydrograph. Extreme discharge events will be more extreme and occur more often. It is therefore questioned how the discharge, both low and high flows, should be distributed over the three distributaries Waal, Nederrijn-Lek and IJssel.

This study concluded on performance indicators to include in the evaluation of the river functions. The conveyance capacity is quantified on the water level rise along the length of the river branch from the current design discharge to future design discharge. The fresh water supply of the river has been quantified on the low flows, the low flow durations, and the return periods. The contribution of the river to habitat has been investigated based on both the water depth dynamics in the floodplain, and the area of the floodplain. Lastly, the transportation of the river has been evaluated based on the number of days per year that the minimum water depths are exceeded.

Thereafter, this study evaluated the impacts of climate change using the 1D hydrodynamical model SOBEK and a Multi Criteria Analysis. The results have shown that based on the KNMI climate scenarios, the river functionalities will depreciate except from habitat. Moreover, the scenarios showing a trend toward a drier future climate exhibit a larger negative impact on the river functions than the scenarios showing a trend toward a wetter future climate. Overall, the river functions are most vulnerable to a drier future climate in combination with high emissions.

The design discharge at Lobith is expected to increase from 16,000 m^3/s to 18,000 m^3/s in the year 2100. The current discharge distribution holds 2/3 towards the Waal, 2/9 toward the Nederrijn-Lek and 1/9 towards the IJssel. Based on literature and expert judgement, two alternative discharge distributions have been proposed where for both the Nederrijn-Lek is spared. The Nederrijn-Lek has relative narrow floodplains, is surrounded by ribbon development, and an increase in water levels along the Nederrijn-Lek will pose the larger flood risks than the Waal and IJssel. One scenario entails allocating 80% of the extra discharge to the Waal and 20% to the IJssel (80-20). The second scenario include a distribution of 60% to the Waal and 40% to the IJssel (60-40).

The model results showed that in the context of a drier future climate and high emissions an alteration in the discharge distribution is advantageous. Also, the distribution 60-40 is optimal as this is better for the conveyance, habitat, and transport.

A modification to the discharge distribution ratio from the current to 60-40 will result in an increase of discharge toward the Waal and IJssel. For this, three types of river widening measures have been proposed along the IJssel to account for the additional discharge. Including a dike relocation, the excavation of the floodplains and the lowering of the main channel have been investigated.

Additionally, the model results showed that a dike relocation and excavation of the floodplain do have a favourable impact on the river functions in the drier climate scenario based on high emissions. Contrary, excavating the main channel will have negative effects on the functions: habitat and transportation.

In conclusion, it is important to further investigate the technical feasibility of altering the discharge distribution for the additional 2,000 m^3/s design discharge and investigate the impacts outside of the scope of this study. Lastly, it is advised to critically reserve space for the river and investigate whether smaller interventions can yield the same effect on the river functions as either of two large scale river widening interventions.

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1 Introduction

Worldwide, the climate is changing, and this is also evident in the Netherlands through rising temperatures, increased frequency of droughts and intensifying precipitation events. These changes have profound implications for river discharge variability (van der Linde, 2022; WRIJ, 2024). Over the last century, human activities in industry, energy supply, transport, agriculture, and constructions have accelerated climate change, the warming of the atmosphere, ocean, and land through emissions of greenhouse gases. The warming of the earth also leads to an increasing rate of sea level rise (Core Writing Team & Hoesung, 2023). Furthermore, the extreme river flow events and sea level rise hazards increase the flood risks in increasing urbanised low lying and coastal zones (Core Writing Team & Hoesung, 2023). In addition to climate change, human interventions contribute to changes in the river system.

This thesis studies the discharge distribution of the river Rhine. The river Rhine is one of the major waterways in Europe and flows from Switzerland via Austria, Germany, France, and the Netherlands to the open sea. The Dutch branches of the river Rhine are among the most heavily engineered rivers in the world (Chowdhury et al., 2023). Over centuries, man-made interventions in the river system have managed the flow over the river branches in ways that supported various river functions. Examples of modifications are the construction of hydraulic structures such as groynes and weirs to manage the flow of the river and to facilitate navigation. In addition, rivers are also very important for safely discharging water, supplying fresh water, and providing habitats. Furthermore, embankments have been built to protect the hinterland from flooding and the Pannerdensch Kanaal was dug to prevent the avulsion of the IJssel. These human interventions have altered the hydrograph (Mosselman, 2022).

First, rivers serve as crucial transportation links between oceans and inland areas. The advantages of opting for waterborne transportation of freight include the substantial capacity of vessels, the cost-effectiveness, and the relatively small environmental impact in comparison to other transportation modes (Kriedel, 2022; Vinke et al., 2022). For comparison, one ship has the capacity to replace 200 freight trucks on the road. In addition to this, rivers are also used for the transportation of people by ferries and cruise ships. However, extreme weather events can disrupt transportation, leading to economic repercussions (Ademmer et al., 2023).

Second, the ability of a river to transport water, especially during high flows, from upstream areas to downstream areas is called the conveyance capacity (Gensen et al., 2020). A typical cross-section of the geometry of the Dutch Rhine branches consists of a main channel which is regularly dredged for navigation and floodplains on both sides of the main channel. The water will always be discharged via the main channel and in case of high flows also via the floodplains.

Next, a river supplies fresh water to downstream areas. Applications of fresh water supply from rivers include counteracting saltwater intrusion from the ocean, drinking water purposes, cooling water for industry alongside the river, and water level management in polders and canals. Additionally, freshwater supply contributes to the chemical and ecological quality of water bodies.

Fourth, rivers are essential for biodiversity, as river systems can provide habitats for diverse ecosystems. Each segment of the Dutch Rhine possesses distinct characteristics. In the east, the river meanders and flows through sandy areas and high sandy banks, while the Betuwe region is characterized by bowl clay areas with less meandering and higher elevations (BIJ12, 2023). Strategies such as expanding floodplain areas, improving water quality, enhancing fish migration opportunities, and increasing habitat variability can enhance the environmental value of these areas.

Concluding, climate change and human intervention have and will alter the hydrograph of the river and (in)directly affect the functioning of the river. It is important to study the agreed discharge distribution of the Rhine as there will be more extreme discharges in the future. The distribution will influence long-term decisions on spatial planning, freshwater supply, and flood protection in the river system. Additionally, the magnitude of climate change varies considerably between the climate scenarios made by the Royal Netherlands Meteorological Institute (KNMI) (Bessembinder et al., 2024). To make informed climate policy choices and to reserve space for the river, it is essential to consider the potential consequences of climate change for each of the river functions.

1.1 Theoretical background

The theoretical background of this thesis covers how climate change scenarios were defined and how they were translated into time-discharge series for the river Rhine. These time discharge series representing a climate are used as input in the model. Also, this chapter includes information on bifurcating river systems. Last, the chapter provides examples of river widening measures implemented in the fourth research question. Information on the study area is presented in chapter 2.

1.1.1 Climate change scenarios

The term climate refers to the long-term (30 years or more) averages and standard deviations of weather conditions. The Intergovernmental Panel on Climate Change (IPCC) has identified several key climate variables to describe the weather (Core Writing Team & Hoesung, 2023). These are temperature, precipitation, wind, atmospheric pressure, radiation, cloud cover, sea level, ice and snow cover, ocean salinity and currents, and the concentration of greenhouse gases (GHGs).

1.1.1.1 Global Climate Models

The IPCC prepares assessment reports about the current knowledge on climate change (IPCC, 2024). Also, they publish pathways to investigate climate change. Each pathway described one of the many viable scenarios, from low to high emissions. The scenarios are often used to investigate the causes, impacts and possible response strategies to climate change (T. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment, 2007).

It is important to recognize that a climate scenario is not a forecast of the weather conditions but rather it is a plausible and consistent representation of how climate might look in the future (T. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment, 2007).

1.1.1.2 Regional Climate Model

The global climate models are translated to regional climate models using several models and evaluation strategies to increase the detail and accuracy of climate projections on small scales. Latest, in 2023, the Dutch Royal Meteorological Institute (KNMI) translated the IPCC climate scenarios into regional climate scenarios for the Netherlands for several emission scenarios and time horizons. ‘H’ stands for high emission scenario, the ‘M’ stands for medium emission scenario and the ‘L’ stands for low emission scenario. The highest emission scenario has been viewed to be most relevant for management purposes (Viergutz et al., 2024).

The KNMI made two categories per emission scenario. The KNMI generated input data from 33 climate models (CMIP6), and they showed a lot of variation in the magnitude of increasing winter precipitation and decreasing amount of summer precipitation. One scenario is relevant for water safety (‘’wet’’ denoted with an ***n***) and one scenario relevant for water availability (‘’dry’’ denoted with a ***d***). In short, the KNMI translated the IPCC scenarios into 6 regional climate scenarios ***Hn, Hd, Mn, Md, Ln, Ld.***

Figure 2 shows the effects of the climate scenarios. The main expectations of the KNMI scenarios are that there will be an acceleration in the rate of sea level rise, an increase in both mean and extreme temperatures, an increase in sunshine, an increase in the frequency of droughts, an increase in the frequency of wet winters, an increase in the frequency of extreme summer showers, an increase in the intensity of strong winds during heavy showers and little change in wind speed and direction. However, the magnitude of these changes varies considerably between the six KNMI scenarios for 2100 (Bessembinder et al., 2024).

Figure 2: Four scenarios for climate change in the Netherlands. The number of small blocks represents the extent of climate change around 2100 compared to 1991-2020 (Bessembinder et al., 2024)

1.1.1.3 River discharge projections

The Knowledge Institute Deltares in turn translated the KNMI scenarios into river discharge scenarios using the hydrological model wflow_sbm for the rivers Rhine and Meuse and they analysed the effects of climate change on the river discharges (Buitink et al., 2023). Additionally, they published discharge series for each climate scenario for further research. Each of these discharge series consists of eight ensembles. One ensemble is a series of daily discharge with a length of 30 years. These ensembles can be used to investigate the effect of slightly different, but equally plausible initial conditions on the system response to identical radiative forcing, see Figure 3. One ensemble member resembles a coherent picture of the discharge values. The future can be one of the strings, but not a combination of strings.

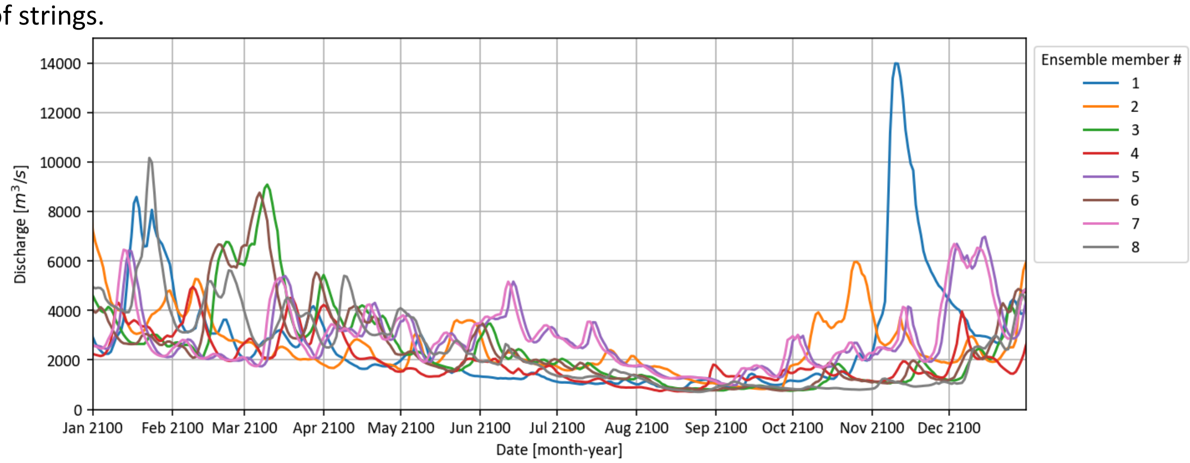

Figure 3: Example of the discharge ensembles at Lobith for the scenario 2100Hn

The expected long-term annual average discharge at Lobith does not show a substantial change from the current annual average discharge except in the scenarios ***Mn*** and ***Hn***. The annual discharge decreases in these scenarios by approximately 5%. Furthermore, the 7-day minimum discharge will decrease in all scenarios with 10% in the low emission scenarios to 30% in the high emission scenarios in 2100. The expected maximum discharges will increase in 4 out of 6 scenarios. The maximum discharges could increase between 5% in the ***Md*** scenario to 25% in the ***Hn*** scenario (Buitink et al., 2023). Lastly, according to the hydrological models used by Deltares, there will be a reduction of snow melt driver discharge peaks reducing late summer discharges. In conclusion, climate change affects hydrographs of rivers.

1.1.2 (Bifurcating) river systems

Figure 4 shows a typical cross-section of a branch of a Dutch river and the typical differences in the water levels in the summer and winter. As a result of climate change, the water levels in the main channel will decrease and the periods of low flow are also expected to be longer and occur more often. The maximum flows and water levels will increase; therefore, more room is needed to discharge water via the main channel and floodplains.

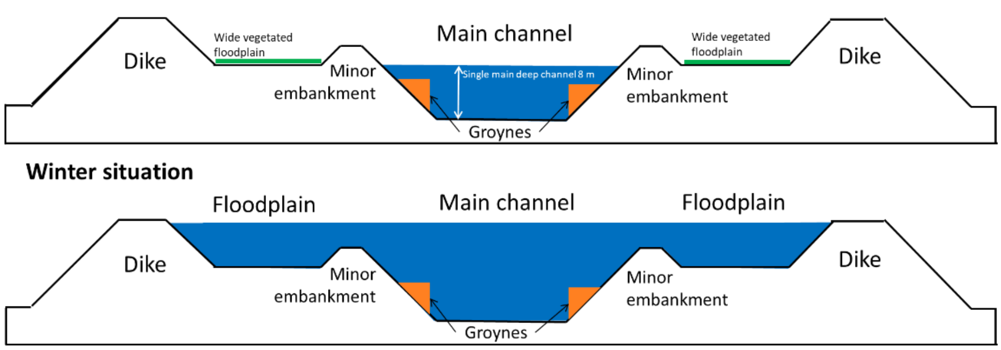

Figure 4: Typical cross-section of the Rhine distributaries in the summer and winter situation

A river can diverge into two or more branches, creating complex networks of interconnected branches. As the flow is distributed over the downstream branches, interactions occur between water levels, impacts of interventions and discharge distribution (Gensen et al., 2020). The water and sediment partitioning can be stable or unstable. A stable river bifurcate is a bifurcate in which both branches remain open and where no significant change of flow and sediment partitioning occurs. Figure 5 shows the bifurcation point Pannerdensche Kop, which is unstable (Blom et al., 2024). The area of the branch on the left (Waal) is about twice as large as the area of the branch on the right (Pannerdensch Kanaal) near the bifurcation point Pannerdensche Kop and is therefore also receiving more discharge.

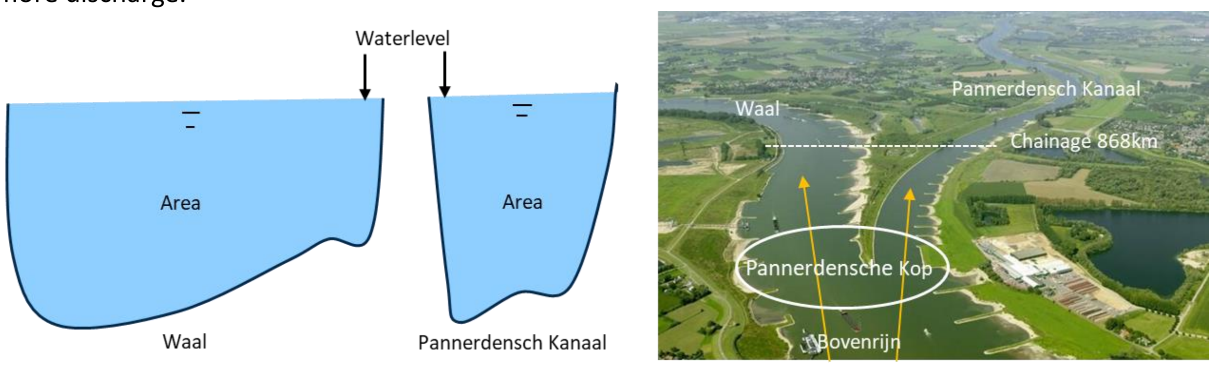

Figure 5: Example of a river bifurcation. (Left) Schematisation of the cross section of the downstream branches of the Pannerdensche Kop (Adapted from (Chowdhury et al., 2021)). (Right) The bifurcation points Pannerdensche Kop. The orange arrows indicate the direction of flow and sediment. Source: (De Scheepvaartkrant, 2021)

1.1.2.1 Flow distribution

At a bifurcation point, the total discharge is distributed over the branches. The ratio in which the water is distributed is determined by the cross-sectional area of the branches and the roughness and slopes of the downstream branches. Moreover, the cross-sectional areas of the downstream branches fluctuate with the water level. This creates a feedback mechanism in the discharge distribution and the water levels around the bifurcation (Gensen et al., 2020). In general, water flows faster towards the smoother and steeper branch. The discharge distribution is thus not constant, but the discharge distribution varies with the discharge.

However, there is a large uncertainty in the discharge distribution in bifurcations (Gensen et al., 2020). In a single river branch, a lower roughness will result in lower water levels. In the case of a single river branch, a lower bottom roughness will result in lower water levels. However, in the case of a bifurcating river in which one of the downstream branches has a lower roughness, the reduction in water levels is less pronounced. The smoother branch will in turn receive more discharge as a greater amount of water flows towards this branch instead. This illustrates that a change in local roughness has a different effect on the downstream levels in single-branching rivers than in bifurcating rivers.

1.1.2.2 Sediment distribution

Besides water, rivers transport sediment. Sediment transport includes both the transport of bed load and suspended sediment load. To determine the amount of sediment transport, it is important to know the shape, density, fall velocity, chemical composition, and pore content of the sediment, next to flow characteristics. Accelerating flow tends to pick up sediment whereas decelerating flow tends to accumulate sediments. Erosion and deposition of sediment change the channel width, bed level and or slope over time. The bed of Dutch rivers mostly consists of sand and gravel. Sand has a lower roughness than gravel and flow velocities are general higher for a lower roughness.

Section 1.1.1 described that climate change causes more extreme flows in the river Rhine. Peak flows cause changes in bifurcation locations, slope, and width of natural rivers by for example deepening the main channel and depositing sediment in the wide sections. However, in engineered river systems primarily the bed level and bed surface change. Groynes regulate the flow and provide a fairway of sufficient depth and width (Chowdhury et al., 2023).

In conclusion, flow (distribution), sediment (transport) and bathymetry for an infinite feedback loop in a bifurcating river system.

1.1.3 River widening measures

Rivers used to have much space until dikes were built to protect the adjacent cities. The need to create space for rivers has become more important due to the increasing magnitude of discharges. Figure 6 provides an overview of possible interventions in a river system to provide more room for the river. This not only benefits the conveyance capacity of a river, it also promotes the development of natural habitats and recreational areas (Rijkswaterstaat, 2025).

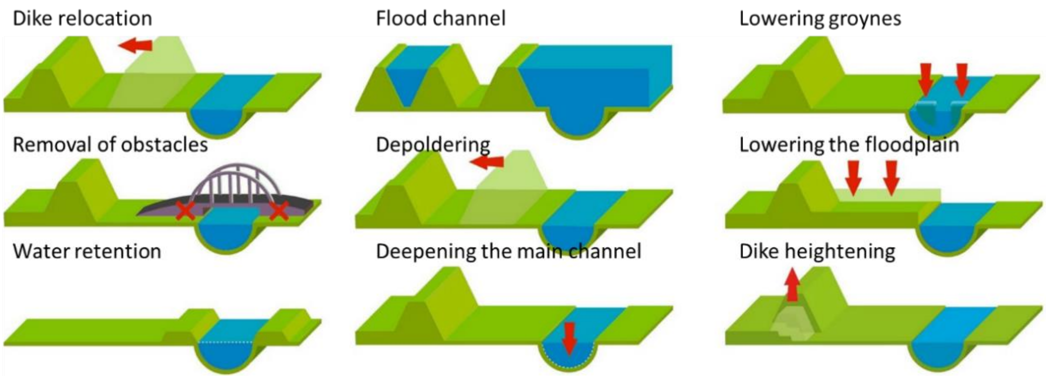

Figure 6: Examples of river widening measures. The figure is adapted from Rijkswaterstaat (2025)

1.2 Research gap

Many studies into the discharge distribution at the Dutch Rhine bifurcations are constrained by short planning horizons and are quickly outdated concerning the impacts of climate change on river discharge. Additionally, existing literature predominantly focuses on one (river) function and often overlooks the interactions between the hydrological, ecological and socio-economic aspects of a river (Silva et al., 1999; Brandsma, 2016).

The planning horizon of most projects in river management range to 2050. While some projects like the Dutch program Integral River Management have an outlook for 2100, they often do not contain the most recent climate scenarios. For example, the program Integral River Management was published just before the KNMI'23 scenarios were translated to the time discharge series by Deltares and thus used the KNMI'14 scenarios.

Furthermore, current research on alternative discharge distributions often does not look at the multi-functional requirements of river systems in the context of future climate change. Current research is mainly focused on cost-effectiveness (van den Top & ENW, 2021). Previous studies in supporting river management policies did for example only consider heightening the dikes as a measure to increase the conveyance capacity, instead of also looking at widening the river. River widening is more expensive than dike heightening, however it also can have positive effects on other river functions besides flood safety in contrast with dike heightening.

To conclude, the impact of varying climate scenarios on river functions remains uncertain due to the inherent unpredictability of future conditions. While there is general agreement that climate change will lead to more extreme hydrological events such as higher peak discharges and longer periods of low flow, it is unclear if the current discharge distribution is the benefits all functions for future conditions and whether there is a more optimal one viable at the bifurcations Pannerdensche Kop and IJsselkop.

1.3 Research aim and research questions

The aim of this research is "*to explore the desired discharge distribution of the Dutch Rhine at the bifurcations Pannerdensche Kop and IJsselkop at Lobith in 2100 for the KNMI climate scenarios and how they contribute to the performance of river functions"*. For this, four research questions are formulated:

RQ1: Which performance indicators can be used to assess the performance of river functions along the Dutch Rhine branches under time-varying flow conditions?

RQ2: In what ways will climate change affect the conveyance, water supply, habitat, and transportation in the Dutch Rhine system by the year 2100?

RQ3: What are alternative discharge distributions and how do these affect the conveyance, water supply, habitat, and transportation in the Dutch Rhine system by the year 2100?

- RQ3.1: Based on the results of RQ2 and literature, what are possible alternative discharge distributions for the increasing design discharge on the Rhine branches?

RQ4: River widening measures can be used to account for the additional discharge on a river branch resulting from the proposed alternative discharge distributions. How do these affect the conveyance, water supply, habitat, and transportation in the Dutch Rhine system by the year 2100?

1.4 Research scope

The study focuses on the discharge distribution in the Dutch Rhine branches under the impact of climate change, with consideration given to the alterations in both upstream and downstream boundary conditions. However, the meteorological climate change parameters (such as the changes in temperature, precipitation, and evaporation) are not incorporated in the study.

The spatial scope of the research encompasses the Dutch Rhine branches from Lobith to Krimpen aan de Lek, Hardinxveld and Ketelbrug. Thus, the rivers included in this study are the Bovenrijn, Pannerdensch Kanaal, Waal, IJssel and Nederrijn-Lek. The scope encompasses both the main channel and the floodplains. Additionally, the study excludes morphological development.

The temporal scope of the research is 2100. Considering a larger time horizon would increase the uncertainty. With the KNMI'23 scenarios, the scenario for 2100 is derived from the climate model CMPI6. However, the scenarios for 2150 are extrapolated from the 2100 scenario. The uncertainty in the discharge ensembles is thus larger.

The research will add to existing research by examining several river functions as opposed to focusing on a single function. This study will focus on the river functions conveyance, water supply, habitat, and transportation. Other functions such as recreation, cultural significance, the generation of hydropower, and spatial planning are not within the scope of this research.

1.5 Thesis outline

Chapter 2 elaborates on the study area of the project. Chapter 3 outlines the methodology of the study including the data and models used in the study. The results of the study are presented in Chapter 0. Chapter 5 provides a discussion of the study. Chapter 6 presents the conclusions to the research questions and gives recommendations for future studies.

2 Study area

The study area covers the Dutch rhine distributaries. Figure 7 presents a map of the study area. The upstream boundary is the Rhine at the German city Dornick. The average discharge of the Rhine is approximately 2,200 m^3/s (Gensen et al., 2020). The upper Rhine enters the Netherlands at Lobith and then bifurcates at the Pannerdensche Kop to the Waal and the Pannerdensch Kanaal. The downstream boundary of the Waal is Hardinxveld. Moreover, the Pannerdensch Kanaal continues in the Nederrijn-Lek, and after a few kilometres, the IJssel bifurcates from the Nederrijn-Lek. The downstream boundary of the Nederrijn-Lek is near Krimpen aan de Lek. The Ketelbrug marks the downstream boundary of the IJssel and connects the IJssel to the IJsselmeer.

Furthermore, there are several hydraulic structures present in the study area. The discharge distribution at extreme flows is influenced by the hydraulic static structures Hondsbroeksche Pleij and Pannerden. The water level in the Nederrijn-Lek is controlled by three weirs. They are located near Driel, Amerongen and Hagestein. Last, the flood channels Reevediep and Veessen-Wapenveld were constructed to lower the water level in the IJssel.

This chapter first gives more detailed information on the river branches focussed on in this study. This is followed by information about the agreements on the discharge distribution around the bifurcation points and the hydraulic static controls which influence the discharge distribution. Thereafter, the behaviour of the downstream boundaries under climate change is explained. Last, the chapter explains the morphological development of the Rhine branches.

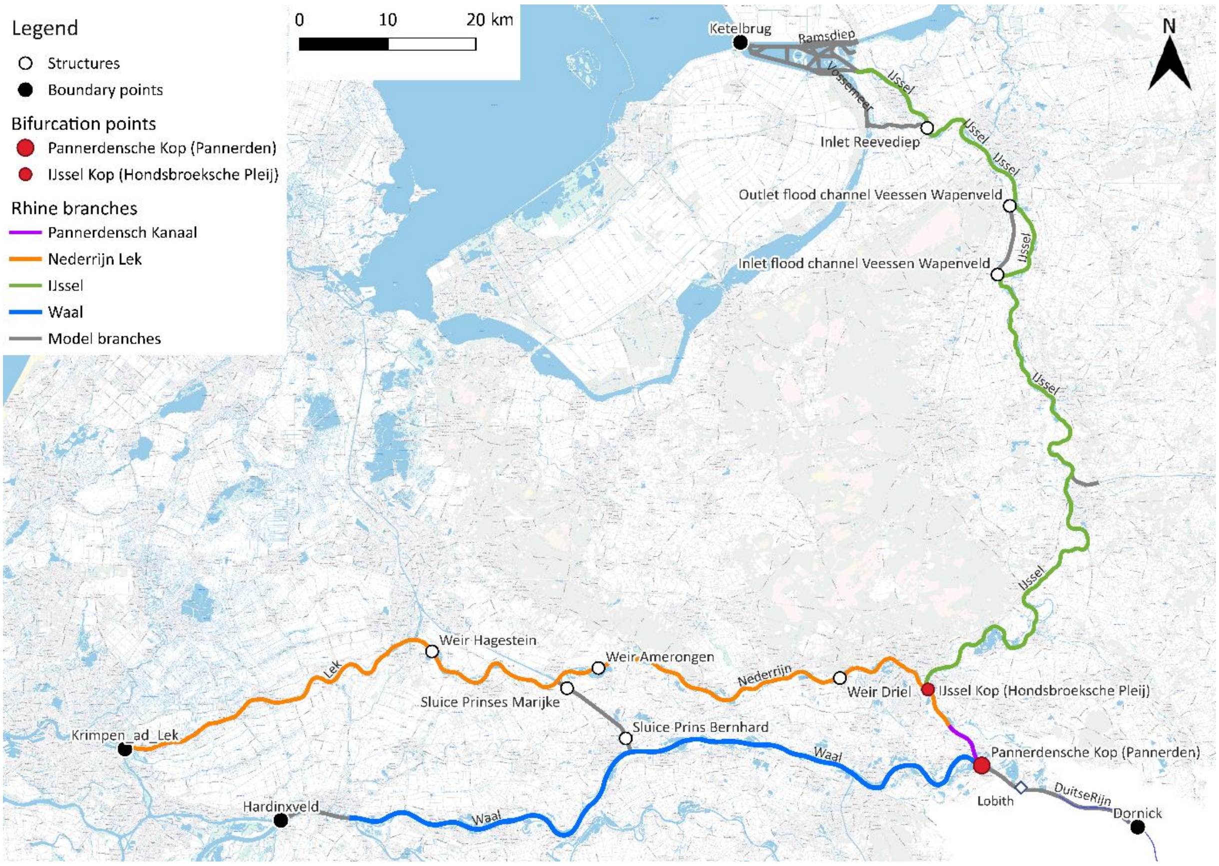

Figure 7: Study area. The Dutch Rhine branches including the two major bifurcation points

2.1 River branches

Rivers can be characterized by several parameters such as the channel width, channel slope, bed roughness, and sediment composition. Table 1 presents characteristics of the geometry of the Dutch Rhine distributaries. Information regarding the sediment composition is given in section 2.5.

Table 1: Characteristics of the Dutch Rhine distributaries, adapted from (Gensen et al., 2020)

Branch	Bankfull discharge [m^3/s]	Width main channel [m]	Mean width floodplain [m]	Length [km]
Bovenrijn	5,000	330-440	850	14
Waal	3,400	260-370	550	94
Pannerdensch Kanaal	1,600	130-200	400	11.5
Nederrijn-Lek	900	130-200	400	110.5
IJssel	700	80-120	500	127.5

The Rhine bifurcates into three distributaries. The river Waal has the largest main channel and floodplain and can discharge more water than other bifurcates. Next, the Waal is the shortest and steepest branch, which makes the Waal the quickest way for water to reach the sea. The water levels on the Nederrijn-Lek are controlled by three weirs and need 20 to 25 m^3/s to maintain the water levels (Schulte & van Winden, 2024). The IJssel is the longest bifurcate and has relatively the largest floodplains.

2.2 River bifurcations

Figure 8 shows the discharge distribution in a high flow situation and a low flow situation. The left part of the figure shows that during high flows, the Waal is entitled to 2/3 of the discharge, the Pannerdensch Kanaal 1/3 of the discharge and the water levels upstream of the bifurcation are increased through the effect of back water curves. The right side of the figure shows that during low flows the Waal receives relatively more discharge, and the Nederrijn-Lek receives only a fraction of the upstream discharge.

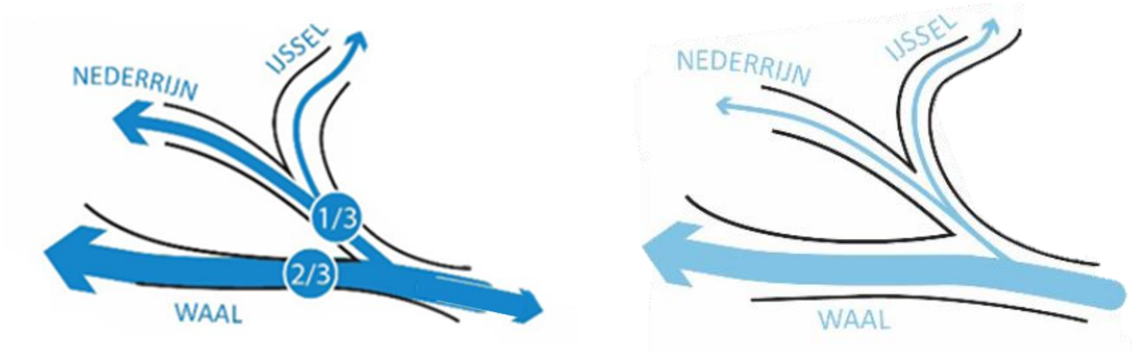

Figure 8: Discharge distribution during high flows (left) and low flows (left) (Klijn et al., 2022)

The distribution of discharge in the Rhine branches is a matter of legal determination, dating back to the 18th century (Ministerie van Infrastructuur en Waterstaat, 2024). In the 15th century, floods led to an increase in discharge from the Rhine to the Waal and sedimentation of the IJssel. To prevent the avulsion of the IJssel, the Pannerdensch Kanaal was dug. This ensured continued discharge in the IJssel (Gensen et al., 2020). In the late 18th century, the water distribution changed because of a combination of the widening of the Pannerdensch Kanaal and sediment deposition in the IJssel. Because of this, the Nederrijn-Lek received much more water, and several dikes were breached. One year later, a treaty was signed in which the water distribution among the Rhine branches was agreed upon (Ministerie van Infrastructuur en Waterstaat, 2024).

The agreed distribution is currently under pressure because of changing discharge patterns. The Expertise Network Flood Safety (ENW) advised to not further increase the discharge on the Nederrijn-Lek as the branch is relatively narrow and the adjacent areas are prone to flooding. The ENW advised a maximum discharge of 3,376 m^3/s, deviating from the legal determination (van den Top & ENW, 2021). Nowadays, the discharge distribution at the two bifurcation points is steered through static hydraulic structures and the weir near Driel.

2.3 Structures

There are three weirs constructed in the Nederrijn-Lek, two hydraulic control structures at the bifurcation points and two flood channels in the IJssel.

Figure 7 shows the locations of the three weirs in the Nederrijn-Lek. The weirs near Driel, Hagestein (Figure 9) and Amerongen regulate the water levels in the branch.

The hydraulic control structures Pannerden (Figure 10) and Hondbroeksche Pleij at the bifurcation points Pannerden Kop and IJssel Kop are static control structures. Each year, the number of concrete beams placed in the structure is determined and this determines the discharge distribution during high flows.

The flood channel (Figure 11) and flood channel Reevediep were constructed in the IJssel to lower the water levels near Deventer, Kampen and Zwolle under extreme water level conditions. As the IJssel is connected to the IJsselmeer, the water levels are sensitive to wave set-up due to northwest wind. The Reevediep allows for quicker water discharge.

Figure 9: Weir Hagestein (*Sluis Hagestein | Binnenvaart in Beeld*, 2025)

Figure 10: Control structure Pannerden (*Regelwerk Pannerden*, 2022)

Figure 11: Flood channel Veessen-Wapenveld. (Left) not in use. (Right) flood channel in use during high flows (Waterschap Vallei en Veluwe, n.d.)

2.4 Downstream boundaries

The study area has three downstream boundaries, which are presented in Figure 7. One downstream boundary marks the connection between the IJssel and the IJsselmeer and two downstream boundaries connect the Waal and Nederrijn-Lek to the North Sea.

2.4.1 IJsselmeer

The IJsselmeer is the largest freshwater reservoir in the Netherlands. The IJsselmeer is enclosed by the Afsluitdijk. The level of the IJsselmeer is regulated using pumps in the Afsluitdijk. The water level is dependent on the season, see Table 2. Possible lake levels in the future are elaborated on in section 3.5.2.

Table 2: Current IJsselmeer level (Mens et al., 2020)

IJsselmeer level [m+NAP]	Period
-0.1	Summer in preparation for dry periods
-0.2	Summer
-0.3	Summer during dry periods
-0.4	Winter

2.4.2 North Sea

The current mean sea level is about 0.0m+NAP. The tides from the North Sea extend upstream of the rivers. The tides impact the water levels in the downstream sections of the Waal and Nederrijn-Lek, contributing to variations in flow and water elevation throughout the day and month. Due to climate change, the sea level and the rate of sea level rise are increasing. The expected sea levels in future climate scenarios are listed in chapter 3.5.2.

The Knowledge Programme Sea Level Rise (Kennisprogramma Zeepsiegelstijging) is working on strategies to cope with sea level rise. They have published an interim report in which they describe four conceptual perspectives. These perspectives also affect the riverine areas. The four types are 'protect open', 'protect closed', 'seaward' and 'accommodate' (Sea Level Rise Knowledge Programme, 2023). Figure 12 shows a conceptual view of the four perspectives. The perspective protect open is in line with the current strategy. In this perspective, the current coastline is maintained, allowing the river water to flow freely to the sea. However, the water levels especially in the lower areas will increase as the sea level rises. In this research, the perspective protect open is maintained.

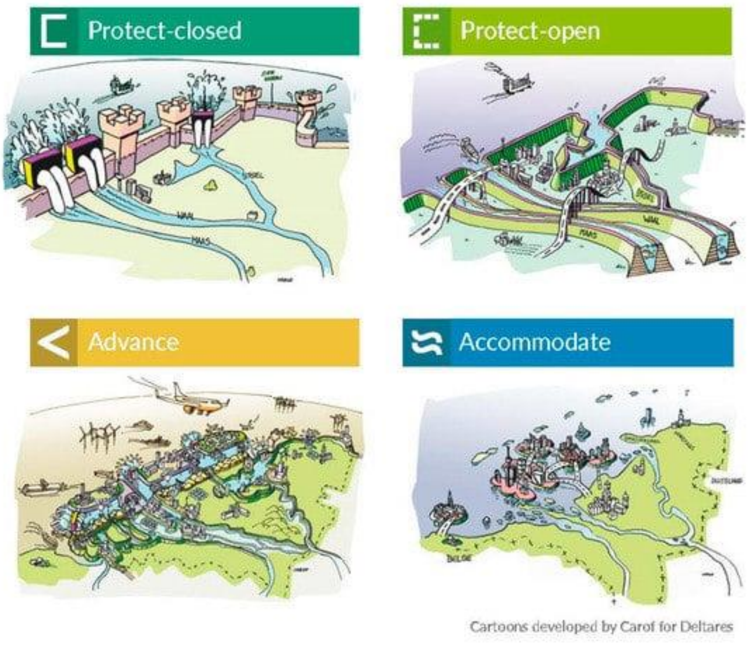

Figure 12: Four conceptual perspectives for the Netherlands in the event of strong sea level rise (Sea Level Rise Knowledge Programme, 2023)

2.5 Bed level and roughness

In the study area, two distinct roughness values can be attributed to the main channel and the floodplain. First, floodplains are hydraulically less smooth, as there is less vegetation and there are fewer obstacles in the main channel. Moreover, because of the vegetation and obstacles, the variation in roughness in the floodplains is larger than the variation in roughness in the main channel. The roughness in the main channel is dependent on the sediment characteristics and the bedforms.

The sediment on the bed of the Waal and Nederrijn-Lek is predominantly medium-sized sand and the sediment in the Pannerdensch Kanaal and IJssel is mostly fine to coarse gravel (Arcement & Schneider, 1989; Frings & Kleinhans, 2008). The bed surface around the bifurcations continues to coarsen, however, the downstream-migrating coarsening wave in the Rhine is seemingly not affected by climate change (Ylla Arbós et al., 2023). In addition to this, the current degrading trend of the Waal is 1 cm/year while the 2100W+ scenario from the KNMI'06 report forecasts a degrading trend of 1.5 cm/year (M. F. M. Yossef & Sloff, 2011).

3. Methodology

To achieve the research aim of this study, a research method is made, as illustrated in Figure 13. For the first research question (orange blocks, section 3.1), the method from Wieringa (2014) is adapted to design a Multi-Criteria Analysis (MCA) to compare the performance of river functions in the Rhine system across different scenarios. Subsequent steps involve using a hydraulic model to translate the expected river discharges at Lobith into water levels, water depths and water discharges along each river branches.

In the second research question (green blocks, section 3.2), the impact of climate change on the performance of river functions is assessed using the MCA. The third research question (blue blocks, section 3.3) involves determining two alternative discharge distributions, which are then implemented in the model, followed by a comparison of the results using the MCA. In the fourth research question (yellow blocks, section 3.4), three river widening measures are implemented in the model and the model results are again compared using the MCA.

Finally, the chapter provides a description of the data used (white squares) in section 3.5 and a description of the hydraulic model employed 3.6. The last section of this Chapter provides an overview of model runs per research question.

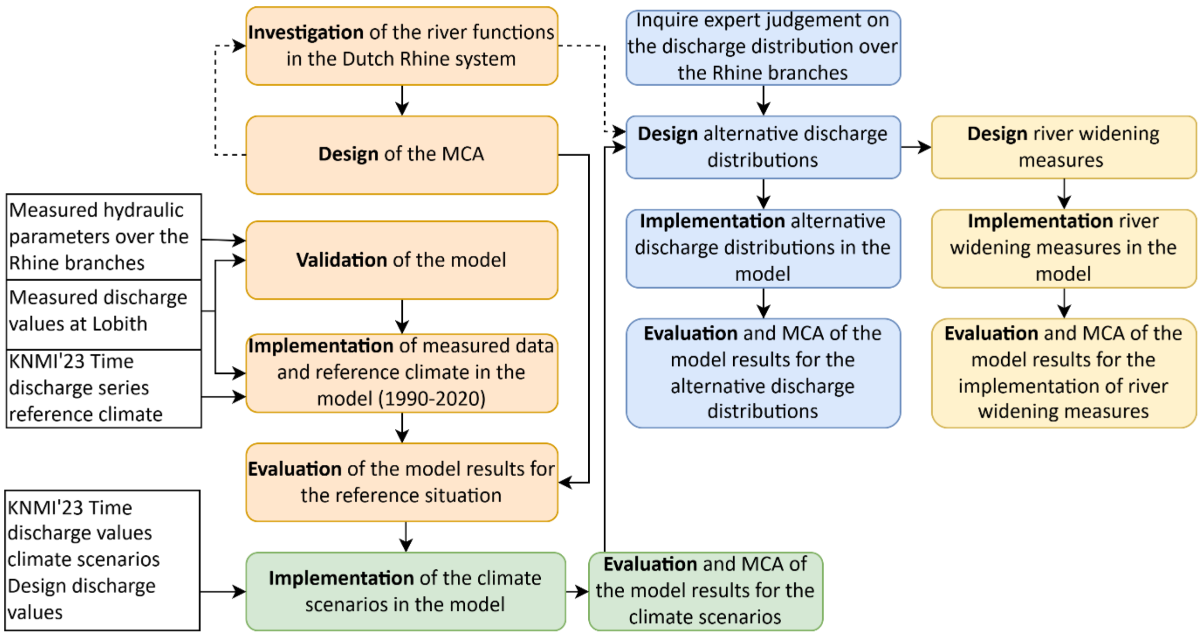

Figure 13: Visualization of the research method. The white squares indicate the data used. The steps for the first research question are shown in orange, the steps for the second research question are shown in green, the steps for the third research question are shown in blue, and the steps for the fourth research question are shown in yellow

3.1 RQ1: Performance indicators of river functions

The primary objective of the first research question is to define the performance indicators for river functions. To this end, a method combining the design and engineering cycle in design science research was used. This method has the capacity to yield a solution that addresses the problem in a specific area but can be generalized to other areas as well (Wieringa, 2014). Therefore, the MCA can be adapted for implementation in other river systems in the future.

The design and engineering cycle is comprised of five phases: investigation, design, validation, implementation, and evaluation. The temporal sequence of these phases is delineated in Figure 13.

3.1.1 Investigation

First, the Rhine system and the river functions were investigated by literature research. Using the literature review, a list of performance indicators to include in the MCA was made per river function.

3.1.2 Design

The subsequent process phase consisted of consolidating the information gathered in the previous step and translating them into performance indicators and if applicable limits for the performance indicators. For instance, in the context of water-borne transportation, a specific value was determined for the minimum navigation depths.

3.1.3 Model validation

In the third step, the hydraulic model is validated to check if the model is suitable to answer the research objective. The model including the discharge distribution is already calibrated by Deltares on discharges ranging from 500 m^3/s to 18,689 m^3/s (Deltares, 2024). Section 3.6 provides more information regarding the model.

In addition to the calibration report of Deltares, the model is validated for the period 2024. The input for the validation was the daily discharge values measured at Lobith. Section 3.5.1 provides more information regarding this data. The results of the model are compared to the measured discharges and water levels in 2024 using the correlation coefficient (Equation 1). It can be used to assess the differences between the simulated and observed values. The correlation is stronger for a correlation coefficient close to 1. A value of 0 indicates that there is zero correlation.

$$R^2 = (r)^2 = \left(\frac{cov(x,y)}{s(x)s(y)}\right)^2 = \left(\frac{\frac{\sum\left((x_i-\bar{x})(y_i-\bar{y})\right)}{(N-1)}}{s(x)s(y)}\right)^2 \qquad \textbf{Equation 1}$$

Where:
R^2 = Correlation coefficient
r = Correlation coefficient
$cov(x,y)$ = Covariation
$s(\,)$ = Standard variation
N = Sample size
x_i = Value for the i^{th} observation
$\bar{x}$ = Mean value for the i^{th} observation
y_i = Value for the i^{th} prediction
$\bar{y}$ = Mean value for the i^{th} prediction

3.1.4 Implementation

In the fourth step, the current climate is compared to the reference scenario published by Deltares, this regards the period 1991-2020. For this, nine model runs are done. The input for one model run is the series of measured daily discharge values at Lobith during 1991-2020. The input for the other eight model runs are the time discharge ensembles for the period 1991-2020. Elaborate information on the data and model used can be read in sections 3.5 and 3.6 respectively.

The time step of the model is 5 minutes and the input is daily. Therefore, the discharge values are interpolated. The linear interpolation method showed the best fit for daily discharge data and is therefore used to run the measured and synthetical daily discharge values over the period of 30 years. In addition, to guarantee the right initial conditions in the model, the initial discharge value of the 30-year discharge series is taken and used as a constant value over the warm-up period of one week, see appendix A for more elaboration.

The output of the hydraulic model gives values of hydraulic variables at observation points along the river branches. These values are to quantify the river performance indicators.

3.1.5 Evaluation

The implementation was followed by evaluation of the performance indicators following the MCA. In this step, scenarios are compared to each other for each function and assigned a rank. The ranks are summed after which a conclusion can be made on which scenario scores better. The MCA is equal weighted, this means that all functions are of equal importance in the assessment. Moreover, the evaluation of the historical period and the reference period should conclude the same on the river performance during this period. This is because the reference climate consisting of 8 ensembles resemble the historical climate 1991-2020.

3.2 RQ2: Climate scenarios

This section describes the method used to answer the second research question. The aim of the second research question is to investigate how the river functions will be affected by climate change. The performance indicators concluded on in the first research question are used in the MCA. Section 3.2.1 describes how the climate scenarios are implemented in the model. Thereafter, section 3.2.2 describes how the results of the model are compared.

3.2.1 Implementation

Four climate scenarios have been implemented in the model by changing the boundary conditions. The scenarios include the climate in 2100 ranging from drier climate to wetter climate and from medium CO_2 emissions to high CO_2 emissions.

The model boundaries at the Ketelbrug, Krimpen aan de Lek and Hardinxveld are a function of water level and discharge (Q-h relation) which means that given a discharge, a predefined water level is set at the boundary (Deltares, 2019). The downstream boundaries of the Waal and the Nederrijn-Lek have been adjusted to match the expected sea level rise in 2100 for both emission scenarios. Next to this, the downstream boundary at the IJssel has been adjusted to match the expected lake level rise in 2100. The values of the expected water level rise have been added to the water levels in the Q-h relation to change the downstream boundary. Section 3.5.2 provides more information on the expected sea level rise and lake level rise.

The upstream boundary of the model is located just upstream of Lobith at Dornick and the input is a timeseries. The model is run with a warmup period of one week (Appendix A: Determination warm up period) and linear interpolation is used to interpolate daily discharge values. First, the upstream boundary has been set equal to the design discharge a climate scenario. Second, the upstream boundary has been set to one of the ensembles of the climate scenario, the discharge values span a period of 30 years. Paragraph 3.5.2 describes the discharge series in more detail.

In total, three model runs were performed with the static design discharge and 40 (5 climate scenarios with each 8 ensembles) model runs with time varying discharge conditions.

3.2.2 Evaluation

The results of the model runs were evaluated by the river performance indicators of the first research question and a MCA. First, the discharge distribution per scenario is determined. Thereafter, the performance indicators of river function under future climate are evaluated per scenario. For a comparison between the results, a Multi Criteria Analysis (MCA) was used assigning ranks per scenario and function. The ranks were then summed after which the most and least favourable climate scenario were determined.

The evaluation of the water level dynamics in the floodplains included another step. In this research, an 1D model is used. The output of the model is for each location along the branches is one water level across the cross section, thus for both the main channel and floodplains. It is assumed that there is no water flowing in the floodplain if the water level in a branch is lower than the level of the minor embankments. Contrary, if the water level in a branch is higher than the minor embankment, it is assumed that the water depth in the floodplain is equal to the water level in the river minus the flood plain base level. Figure 14 shows a schematisation of the main channel and floodplain in the model. Moreover, the model includes a transition height of 0.5 metres. The transition height is included to avoid numerical oscillations and ensures that the flow area and storage area behind the minor embankment are gradually taken into computation (Deltares, 2023).

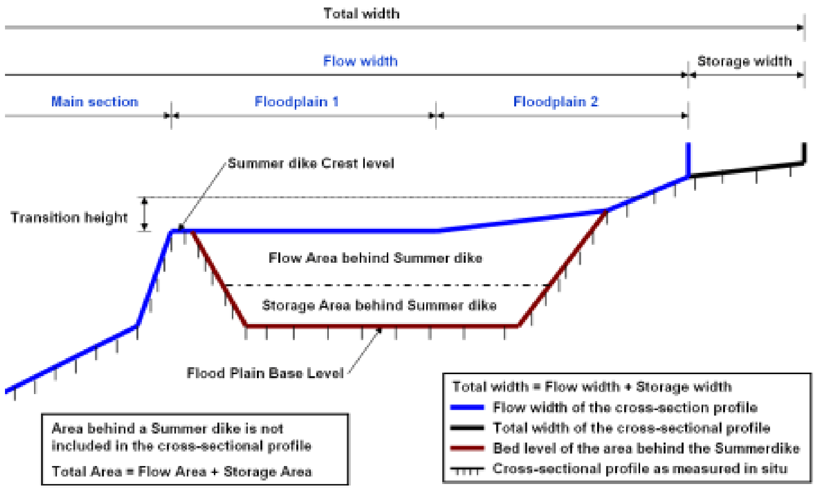

Figure 14: Schematisation of a minor embankment in the model (Deltares, 2023)

3.3 RQ3: Alternative discharge distributions

The goal of the third research question is to explore the effects of alternative discharge distributions on the river functions. First, two redistributions of the additional 2,000 m^3/s design discharge were determined based on the literature review, expert judgement and the results from the second research question. Section 3.3.2 describes how the alternative discharge distributions are implemented in the model. Thereafter, section 3.3.3 describes how the results of the simulations are compared to each other using the MCA.

3.3.1 Design

Building upon the previously determined redistributions of the discharge, adjustments needed to be made to the system to achieve this. First, changes were implemented to the weir policy near Driel. Second, altering the roughness coefficients of either or both the main channel and the floodplains did alter the hydraulic conditions including the discharge distribution at the bifurcations. By systematically varying the parameters and observing the resulting effects, an optimized design for the discharge distributions was found.

3.3.2 Implementation

Two alternative discharge distributions have been implemented by altering the roughness coefficients in the main channel. Figure 15 shows a schematisation of this at the red dotted lin.

The Manning coefficients for the Waal in the model range from [0.020,0.040], Nederrijn-Lek [0.016,0.044], IJssel [0.020,0.042] and Pannerdensch Kanaal [0.025,0.07]. These roughness values indicate a sand bed in the Waal and Nederrijn-Lek and a gravel bed in the Pannerdensch Kanaal and IJssel. Moreover, these ranges of Manning coefficients are used in the calibration of the model to ensure the correct water levels and discharge distribution in the model (Kosters et al., 2022). Therefore, the values for the manning coefficient differ over the chainages and have different values per flow regime.

The roughness values in the roughness-main.ini file have been adjusted over a length of 1 kilometre upstream of the bifurcations to reach the desired discharge distribution using a Python script.

3.3.3 Evaluation

Lastly, the result of the model runs of the alternative discharge distributions were evaluated based on the performance indicators from the first research question. For a comparison between the results, a Multi Criteria Analysis (MCA) was used assigning ranks per scenario and function.

3.4 RQ4: River widening measures

This section describes the method used to answer the fourth research question. The aim of the fourth research question is to propose three river widening measures in the IJssel to create space in the scenario where the IJssel will receive more discharge and investigate how these affect the river functions. Section 3.4.1 describes the three river widening measures, section 3.4.2 describes how this has been implemented, and section 3.4.3 describes how they are compared using the MCA.

3.4.1 Design

The measures dike relocation, lowering of the floodplain and lowering of the main channel have been investigated. Figure 15 presents a schematisation of the alterations to the model by the red arrows. In each of these measures, the size, the additional flow area is determined based on the following equation.

$$A = \frac{Q}{u} \qquad \textbf{Equation 2}$$

Where:
A = flow area [m^2]
Q = discharge [m^3/s]
u = flow velocity [m^2/s]

The flow velocity in the IJssel in the reference scenario is about 1.4 m/s. In the scenario where the IJssel receives and additional 800 m^3/s discharge, an additional flow area of 600 m^2 is preferable. The cross sections in the model are symmetrical, thus the floodplains on both sides on the main channel are identical. The main channel of the IJssel is on average 100 metres wide. Therefore, the main channel is lowered by 6 metres. Next to this, the measures include a dike relocation of 300 metre and excavating of both floodplains to create an additional flow area of 300 m^2.

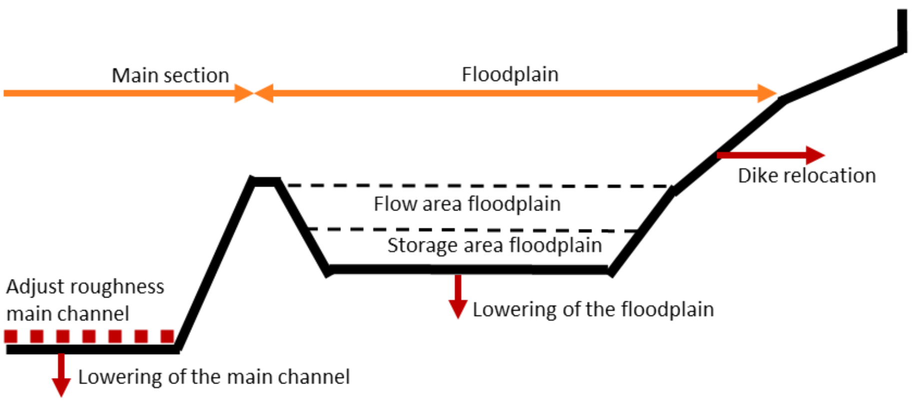

Figure 15: Schematisation of the model adjustments

3.4.2 Implementation

The river widening measures have been implemented by adjusting the CrossSectionDefinitions.ini file by a Python script. All cross sections named IJssel were altered either on the flow widths and total widths, base level, and flow area and total area.

3.4.3 Evaluation

Lastly, the results of the simulations of the river widening measures were evaluated based on the river performance indicators of the first research questions. Each result was assigned a rank per value after which they are summed in the MCA. These river widening measures also affect the discharge distribution, thus this should also be considered in the evaluation of the scenarios.

3.5 Data

The data used in this study is measured data and climate scenario data. The following section provides a description of the measured data including an explanation for the application. Thereafter, section 3.5.2 highlights the data used to model climate scenarios in the Rhine system.

3.5.1 Measured data

For the model validation (section 3.1.3), the hydraulic conditions in 2024 were retrieved. In addition to this, discharge values of the period 1991-2020 at Lobith were retrieved to compare the historical period with the reference climate made by Deltares.

Measured water data is accessed from the website waterinfo.rws.nl from Rijkswaterstaat and the service ddply (Rijkswaterstaat, 2024b). This service allows users to download measured hydraulic conditions via a Python script based on locations, parameters and periods (Veenstra, 2019/2024).

The parameters measured vary per measurement station. The parameters retrieved for the use of this study include water level and discharge. There are seven discharge measurement stations in the study area, their locations are shown in Figure 16 (red dots). The highest registered discharge at Lobith was 12,600 m^3/s in 1926 and the second highest peak discharge was 12,060 m^3/s in 1995 (*KNMI - Hoogwater Rijn en Maas 1995*, 2020). Next to this, there are about 30 locations at which the water levels are measured in the study area, the locations are shown in Figure 16 (red and white dots).

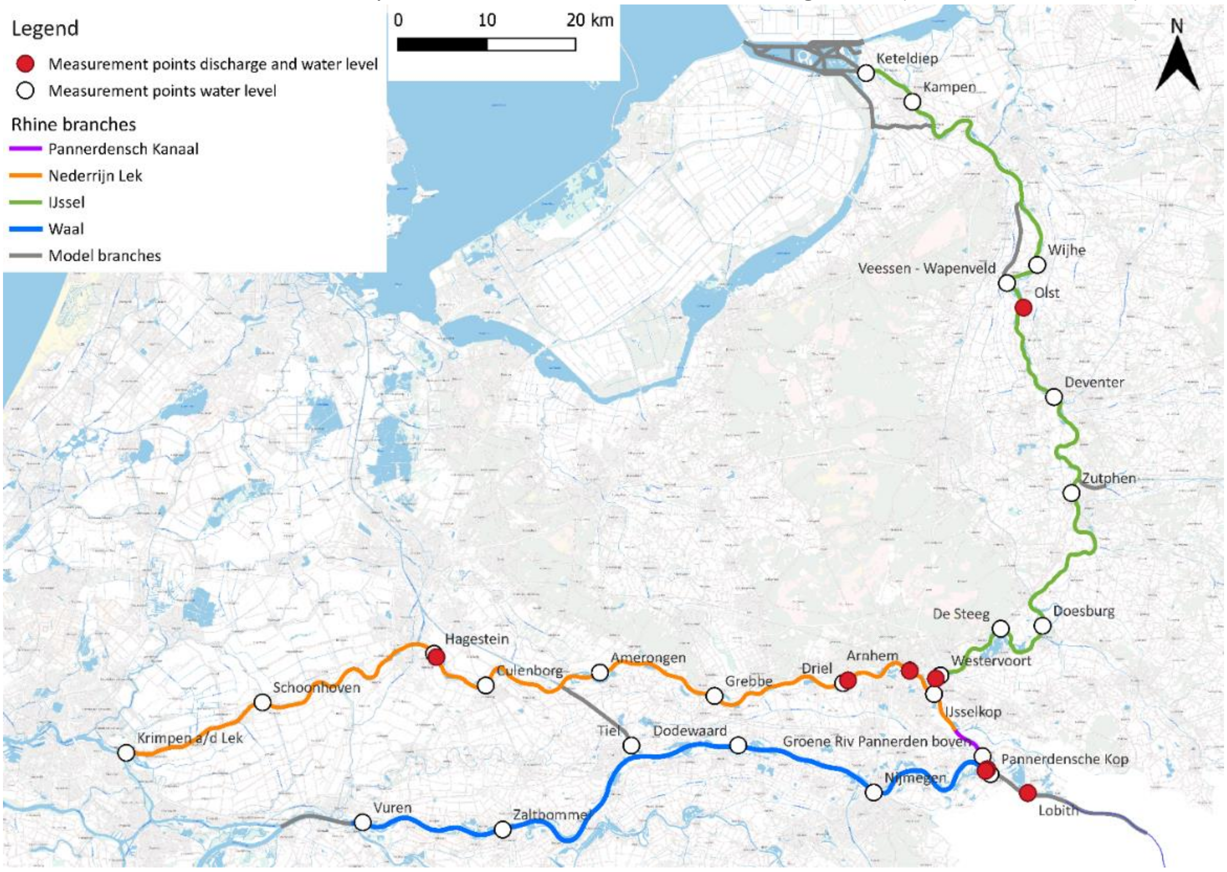

Figure 16: Locations of water level and discharge measurement stations in the Dutch Rhine branches. The red discharge measurement locations also measure water levels

The data is pre-processed before using. The measurements date far back and historically, water levels and discharges were only measured once every few days while nowadays they are measured every ten minutes. To account for the differences in measurement frequency, the daily average values are taken. Also, some measurements were incomplete, double, or contained a faulty input. Therefore, incorrect values were removed from the data set.

3.5.2 Climate scenario data

Deltares translated the KNMI scenarios into two types of data concerning the discharge on the Rhine: extreme discharge values and a time discharge series for a period of 30 years resembling the climate (Buitink et al., 2023).

First, Table 3 provides an overview of the extreme discharge values and the corresponding return periods. These values will increase. KNMI'14 also provided expectation for the extreme discharge values and corresponding return periods for each climate scenario. However, these are not yet published in the KNMI'23 version and are therefore also left out of the table. Also, the current and expected design discharge is presented. The design discharge will increase from 16,000 m^3/s to 18,000 m^3/s in 2100 (van den Top & ENW, 2021).

Table 3: Predicted discharges with corresponding return periods (Klijn et al., 2015)

Scenario	T10 [m^3/s]	T100 [m^3/s]	T1,000 [m^3/s]	T10,000 [m^3/s]	Design discharge [m^3/s]
Reference	9,000	13,000	15,000	16,250	16,000
2050					17,000
2100					18,000

Second, Deltares has translated the KNMI'23 scenarios into time discharge scenarios. For each climate scenario, an ensemble was made consisting of 8 series of 30 years. Thus, in total there is 240 years of discharge values available per climate scenario (Deltares et al., 2024).

3.4.2.1 Expectation Sea Level Rise

It is uncertain how fast the sea level will rise. According to the climate scenarios from the KNMI, the sea level will rise with 44 centimetre in the low emission scenario, with 59 centimetre is the medium emission scenario and 82 centimetre in the high emission scenario by 2100. Table 4 provides an overview of the expected sea level rise in 2100 and the bandwidths for the period 2086-2115. However, it is also found in literature that during the life span of investments, a sea level rise of 1.2 metres is advised for design purposes in line with the high emission scenario (Sea Level Rise Knowledge Programme, 2023). In the model, both the sea level rise of 59 centimetre and 82 centimetre have been implemented.

Table 4: Median of sea level rise in 2100 relative to 1995-2014 for the Dutch coast. The values between the brackets indicate the band width of the sea level rise as the climate in 2100 resembles the period 2086-2115 and the sea is rising in between the period.

	KNMI scenario 2100L SSP1-2.6	KNMI scenario 2100M SSP2-4.5	KNMI scenario 2100H SSP5-8.5
Sea level rise [cm]	44 (26 to 73)	59 (40 to 95)	82 (59 to 124)

3.4.2.2 Expectation lake level rise

The lake level of the IJsselmeer is expected to increase by 60 centimetres (Groenendijk et al., 2023; Staf Deltacommissaris, 2023). The lake level of the IJssel is regulated using pumps in the Afsluitdijk barrier, therefore, climate change does not have a direct effect on the lake level of the IJsselmeer. However, as the sea is rising, it is becoming more difficult to discharge water under gravity. The expected lake level rise is predominantly the result of sea level rise and a small result from the increased maximum discharges from the IJssel and an increase in precipitation (Groenendijk et al., 2023).

3.6 Rhine model

Initially, an evaluation of the available Rhine branch models is conducted, leading to the selection of a model that aligns with the objectives outlined in this research and results of research question 1. This study makes use of a SOBEK 3 Rhine model (version sobek-rijn-j24_6-v1a) to simulate the hydraulics in the Rhine branches under time varying discharge conditions.

The available models include a geographical information system (GIS) model, a 1D model (SOBEK), a 2D model (dflowfm2d), with no 3D model currently available (Rijkswaterstaat, 2024a).. The GIS model serves as the foundational layer, this model contains all geographical information of the Rhine system. The 1D model is derived from the 2D model and schematizations are as completely as possible copied from the 1D model. For instance, the weirs in 2D model are simulated in both the main channel and floodplains, however, in the 1D model weirs in the floodplains are absent (Deltares, 2024). The calculation time to model one week is about 30 seconds for the 1D model and 7 hours in the 2D model (Berends et al., 2022; Kosters et al., 2022).

The 1D model is selected for this research considering the available time and research objectives. The 1D model has short calculation times enabling modelling extended time periods such as the 30-year climate scenarios from Deltares. Furthermore, the primary focus of this research is to analyse the variations in water levels and discharges across the Rhine branches over time rather than the differences in the transverse direction.

3.6.1 Sobek-rijn-j24_6-v1a

The SOBEK model is node-branch structured. The model contains computational grid nodes every 500 metres with exception of areas near structures. The model grid near the hydraulic structures is finer, around 10 metres. The geometry of the river has been defined every 500 metres and the model linearly interpolated the geometries and properties of the summer dikes, main section and floodplains between these locations (Deltares, 2023, p. 3). The model includes the large river branches, the Ketelmeer, the flood channels Veessen-Wapenveld and Reevediep. In addition, the canals Twentekanaal and het Betuwepand connecting the Waal to the Amsterdam-Rijnkanaal via the Nederrijn-Lek are included too.

Furthermore, to reduce the run time, the output files are written less frequently than the time step of the model of 5 minutes. The time step of the Sobek model may not be larger than five minutes as this will create model instabilities (Deltares, 2023).

3.6.1.1 Structures

In the SOBEK model, several structures are included. First three large weirs in the Nederrijn-Lek at Driel, Amerongen and Hagestein (Figure 9) are included as real time controls (RTCs). The RTCs use upstream water levels and discharges as input. Based on this information, the RTCs determine how far the weirs should be opened to discharge water via the weirs.

Next to this, the flood channel Veessen-Wapenveld is included (Figure 11). This flood channel is built to lower the water levels on the IJssel in case of high flows. This is modelled as an inlet which opens gradually controlled by the RTC. Another structure is the spillover structure Reevediep which is built and controlled by an RTC to redirect water from the city Kampen for high flows. Last, the static controls the Hondbroeksche Pleij and Pannerden are not included in the 1D model (Figure 10).

3.6.1.2 Boundary nodes

The SOBEK model has one upstream boundary and three downstream boundaries. These boundaries can be assigned either a constant discharge, constant water level, water level series, discharge series or a water level discharge relationship. The upstream boundary node is located near the village Dornick in Germany. In this study, a discharge times series is assigned. The downstream boundary at the Waal is located at the Hardinxveld, on the Lek at Krimpen aan de Lek and on the Ketelmeer near the Ketelbrug. At these locations, a water level discharge relationship is the downstream boundary.

3.7 Overview model runs

An overview of the model runs done in SOBEK during this study is given in Table 5 and Table 6. All these runs are used to analyse the effects of climate change, an alternative discharge distribution and river widening measures. Table 5 is an overview of the model runs used to conclude on the discharge distribution and the water level rise from an additional discharge. Table 6 gives an overview of the simulations on the time varying conditions used to quantify the functions: water supply, habitat, and transportation.

Table 5: Overview of the simulations run with static upstream conditions (8 runs)

RQ	Scenario	Description	**Upstream condition**	**Downstream condition**
1	Reference	The current design discharge	16,000 m^3/s	
2	2100M	The expected design discharge in 2100 for the medium emission scenario	18,000 m^3/s	SLR +0.59m LLR +0.60m
	2100H	The expected design discharge in 2100 for the high emission scenario	18,000 m^3/s	SLR +0.82m LLR +0.60m
3	2100H 80-20	In this scenario, the scenario 2100H is adjusted by altering the roughness to obtain a discharge distribution of the additional discharge 80% to the Waal and 20% to the IJssel	18,000 m^3/s	SLR +0.82m LLR +0.60m
	2100H 60-40	In this scenario, the scenario 2100H is adjusted by altering the roughness to obtain a discharge distribution of the additional discharge 60% to the Waal and 40% to the IJssel	18,000 m^3/s	SLR +0.82m LLR +0.60m
4	2100 60-40 dike	In this scenario, the scenario 2100H 60-40 is changed by relocating the dike along the IJssel to create more room for the additional discharge	18,000 m^3/s	SLR +0.82m LLR +0.60m
	2100 60-40 floodplain	In this scenario, the scenario 2100H 60-40 is changed by lowering the floodplains along the IJssel to create more room for the additional discharge	18,000 m^3/s	SLR +0.82m LLR +0.60m
	2100 60-40 main channel	In this scenario, the scenario 2100H 60-40 is changed by lowering the main channel of the IJssel to create more room for the additional discharge		

Table 6: Overview of simulations run with time varying upstream conditions (10*8 + 2 = 82 runs)

RQ	Scenario	Description	Upstream boundary	Downstream boundary
0	2024	Measured discharge series in 2024 at Lobith		
	Historical	Measured discharge between 1991-2020 at Lobith		
1	Reference	Current climate 1991-2020	8x (30-year discharge series)	
2	2100Md	Medium emission, dry climate scenario 2086-2115	8x (30-year discharge series)	SLR +0.59m LLR +0.60m
	2100Mn	Medium emission, wet climate scenario 2086-	8x (30-year discharge series)	SLR +0.59m LLR +0.60m
	2100Hd	High emission, dry climate scenario 2086-2115	8x (30-year discharge series)	SLR +0.82m LLR +0.60m
	2100Hn	High emission, wet climate scenario 2086-	8x (30-year discharge series)	SLR +0.82m LLR +0.60m
3	2100H 80-20	High emission, dry climate scenario 2086-2115 with an alternative discharge distribution (80% Waal and 20% IJssel)	8x (30-year discharge series)	SLR +0.82m LLR +0.60m
	2100H 60-40	High emission, dry climate scenario 2086-2115 with an alternative discharge distribution (60% Waal and 40% IJssel)	8x (30-year discharge series)	SLR +0.82m LLR +0.60m
4	2100 60-40 dike	High emission, dry climate scenario 2086-2115 with an alternative discharge distribution. This scenario includes a dike relocation of 300 metres along both sides of the IJssel.	8x (30-year discharge series)	SLR +0.82m LLR +0.60m
	2100 60-40 floodplain	High emission, dry climate scenario 2086-2115 with an alternative discharge distribution. This scenario includes the lowering of the floodplains to create an additional 600m^2 in the floodplains.	8x (30-year discharge series)	SLR +0.82m LLR +0.60m
	2100 60-40 main channel	High emission, dry climate scenario 2086-2115 with an alternative discharge distribution. This scenario includes the excavation of the main channel to create 600m^2 additional flow area.	8x (30-year discharge series)	SLR +0.82m LLR +0.60m

4. Results

This chapter presents the results for each of the research questions.

4.1 RQ1: Performance indicators of river functions

The following four sections provide a comprehensive analysis on the river functions resulting from the literature study. Each section is concluded with a set of performance indicators for the MCA. For a comprehensive overview of all the parameters listed, refer to the table in conclusions section 6.1. Section 4.1.5 presents the results of the model validation for the historical period.

4.1.1 Conveyance

The term conveyance refers to the ability of a river to discharge water smoothly. This concept is evaluated by examining the relationship between the discharge and water levels.

The conveyance capacity of a river is closely related to flood safety in the area; however, flood safety is not a function of a river. However, increased conveyance capacity reduces the water levels in a river. If the water levels decrease, the flooding probability and the consequences of flooding will also decrease. Increasing the conveyance capacity thus indirectly increase the flood safety along a river stretch (Asselman & Klijn, 2016; Klijn, Asselman, & Wagenaar, 2018).

The conveyance capacity of a river branch is small if an increased discharge will lead to large increments of the water level (this is characterized by a steep Q-h relationship). This situation causes an increase in failure probabilities of the dikes near the river such as the probability of overtopping, piping, and macro stability. On the contrary, if the conveyance capacity of a river is large, an increase in the upstream discharge will not lead to a large increase in water levels.

Enlarging the conveyance capacity of a river branch does not mean that more water is flowing through the main channel and/or the floodplains. The conveyance capacity refers to how the river reacts to the additional discharge. For example, taking two river systems, the system with a larger conveyance capacity (usually the wider and hydraulic smoother channel) observes less increase in water levels. Thus, the conveyance capacity gives rise to a feedback mechanism between the water levels and the discharge distribution (Gensen et al., 2020).

In addition to this, literature uses decimation heights (DH) to give an impression of the Q-h relationship along a river branch. Decimation heights are the differences in the calculated water levels for flood return periods of 10, 100, 1.000 and 10.000 years along the length of the river (Klijn, Asselman, & Mosselman, 2018). Similarly, in this research the increase in water level between the current and expect design discharge is calculated and used to quantify the conveyance.

In short, the performance indicators for conveyance are the water level increase for the increasing design discharge along the lengths of the river branches.

4.1.2 Water supply

Rivers supply fresh water to downstream areas. The parameters used in this study to quantify fresh water supply are the values of low flows and the return periods.

In the Netherlands, fresh water is used for the water level management in for example polders, to counteract salt water intrusion from the North Sea, for the irrigation of fields and withdrawals for drinking and industrial water (Klijn et al., 2022). Many users and functions are thus depended on the supply and quality of the fresh water from the rivers.

The river IJssel supplies the IJsselmeer area with fresh water. The IJsselmeer, together with the Markermeer and the Randmeren supply fresh water in the northern region of the Netherlands, thereby functioning as a large fresh water reservoir (Mens et al., 2020). The rivers Nederrijn-Lek and

Waal supply the mid-west and south-west regions of the Netherlands. In addition to the fresh water supply from the rivers, functions and users are also depended on precipitation. Fresh water shortages occur in the case of a simultaneously low discharge from the river and precipitation deficits. Research into the return periods of low flows has proposed a method that accounts for three important aspects of low flows: discharge, duration and interdependency between low flows (van Brenk, 2022).

Concentrations of salt and other substances in water can be detrimental to both the environment and human health. Drinking water companies are responsible for monitoring the quality of water at the intake points. Intake points extract either ground or surface water. Should concentrations of the substances exceed the established limits, additional costs must be made to meet the drinking water quality requirements. Two examples of significant indicators for the drinking water quality are Carbamazepine (max 0.1µg/l) and Chloride (max 150 to 200mg/l) (Mens et al., 2020). Carbamazepine is a psychopharmaceutical measured in surface water in the Netherlands by the RIVM (Maastricht University, 2024). Both substances can be harmful to aquatic ecosystems and can affect human health when it ends up in the drinking water. Also, when one pharmaceutical is found in the water, this indicates that it is likely that other pharmaceuticals will be present as well. As the model is not able to model concentrations, this is left out of the comparison between scenarios.

Thus, the performance indicators for fresh water supply in this research are the 1-day, 7-day, 30-day, 90-day and 180-day flows and their return periods.

4.1.3 Habitat

A river system contributes to the development of nature by providing habitats for both flora and fauna. The conditions in the floodplains are most important for the preservation and development of (semi-) aquatic environmental values (Klijn et al., 2022). According to the system review of the Rhine branches, the development of nature can be improved through the implementation of the following four objectives (Asselman & Klijn, 2022):

- Increasing the area of nature
- More natural river dynamics
- Large diversity of environments
- Increased connectivity between nature- and function areas

The first objective implies nature will benefit from more areal destined to be nature. A measure to achieve this goal could therefore be to allocate current agricultural land as nature.

In the second objective, the term river dynamics refers to both the hydro dynamics and the morpho dynamics in the river. Hydro dynamics describe the differences in water levels as well as the variations in flow velocities. The variations in flow velocities in turn determine the morpho dynamics and with this also the variability in type of sediment on the riverbed ranging from gravel to sand or silt. The hydrodynamics can be investigated by looking at the inundation areas as well as the typical water level differences associated with the discharge regime. The difference between 95% and 5% percentile values of the water levels offer a coarse indication of the ecological state of the river (Asselman & Klijn, 2022). Natural river dynamics can be improved by relocating dikes and giving more room to the river.

Third, a large diversity of environments will lead to biotic diversity and to greater survival chances of species. Fourth, increased connectivity between the diverse environments will lead to larger changes of survival. A connection between full habitat areas and a connection between function areas for day-to-day activities (foraging, resting) and throughout the full life cycle (spawning, maturity) is preferable.

Soil organisms and plant species can disappear when flood plains dry up has. If the flood plains dry up with a frequency of every two or three years, the period of recovery is insufficient for the return of species. Furthermore, side channels are designed to flow for 11 months of the year (Schulte & van Winden, 2024). To ensure sufficient flow in a side channel, a minimum water depth of 50 centimetres is required. The model used in the study is a 1D model and is therefore not able to capture these small scale dynamics in the side channels of the floodplains. Thus, this is not included in the MCA.

Warm, turbid water is detrimental to fish populations. The Water Framework Directive (WFD) target is a water temperature of no more than 25 degrees Celsius to achieve a good ecological status. In addition to this, there is an increase in traffic intensity on the Waal during periods of low flow due to a reduction in loading depth and a decrease in available water. Consequently, the probability of a collision between ship propellers and fish increases for low water levels (Schulte & van Winden, 2024).

Furthermore, the operation of hydropower plants increases the mortality rates of fish migrating downstream (Schulte & van Winden, 2024). Therefore, it is recommended that the hydropower plant on the Waal should only commence generation from a discharge of 50 m^3/s to ensure that fish mortality does not exceed 10%. The number of days during which the fish ladder is operational can also be considered, although this is a highly specific matter and interventions could, of course, be made at the fish ladder.

To conclude, the habitat suitability of the river system will be quantified on the total nature area and the river dynamics in the floodplains.

4.1.4 Transportation

Both goods and people are transported via the water using different kind of vessels. The function transportation along a river branch can be qualified on the minimum water depths and their recurrences. Also, the ease of transportation depends on the flow velocities and the number of shipping locks.

Waterways in the west of Europe are classified according to the Conference of European Ministers of Transport (CEMT) classes since 1992. This is done based on the maximum loading capacity, length, width and maximum draught of the vessels the waterway can transport (cbs, 2023). The rivers IJssel, Nederrijn-Lek and Pannerdensch Kanaal fall into the category up to V. This category can transport vessels with a maximum length of 189 metres, width of 11.40 metres and draught of 4 metres (EuRIS, 2024). If these vessels are empty, the minimum draught is 1.75 metres (Nilson, 2021). The Amsterdam Rijnkanaal and the rivers Waal and Rhine fall into CEMT class up to VI. These stretches allow transportation for wider and longer vessels as the maximum length is 270 metres, maximum width of 22.80 metres and they have the same draught being 4 metres when loaded and 1.75 metres when not loaded.

According to the Royal Dutch Inland Navigation sector, the transportation of bulk cargo is hindered in bodies of water with a water depth of less than three metres. Moreover, transport becomes problematic at water depths smaller than 2 metres and the threshold for navigation is 1.40 meter. The Royal Dutch Inland Navigation sector however also noted that low flows are common and that problems arise mostly when the low flow conditions persist over extended periods (G. Snoeij, personal communication, 6 August 2024). For example, if the water depths are limited, vessels can transport partial loads. However, this leads to additional costs and the logistics sector gets disrupted if the low flows continue over time.

In the transportation sector, both time and fuel consumption are factors which significantly influence the costs. Therefore, it is preferable for vessels to have minimum waiting times at locks and to navigate on rivers with low flow velocities to minimize the transport time. However, navigation locks ensure sufficient water depths during periods of low flow and are thus beneficial to the function navigation in low flow period.

The capacity of vessels during low flows can be improved through resilient vessel design: increasing the length and width while minimizing the draught. Low flows are seen as the major threat for inland shipping. Other threats are high flow velocities, heat (expanding structures (non-functioning bridges)) and extreme weather events (G. Snoeij, personal communication, 6 August 2024).

In addition to the minimum draught and waiting times, the Agreed Low Discharge (OLA) is also used to quantify the navigability of the Rhine. The OLA is the discharge which is not exceeded for 20 days per year based on a long term average of a period of 100 years (Comité Infrastructuur en Milieu, 2021). The OLA is set every 10 years for every river branch. Currently, the OLA is 1020 m^3/s at Lobith, 194 m^3/s for the Pannerdensch Kanaal, 826 m^3/s for the Waal, 24 m^3/s for the Nederrijn-lek and lastly 70 m^3/s for the IJssel (Comité Infrastructuur en Milieu, 2021). However, experts expect the agreed minimum discharge to drop to 915 m^3/s in the most extreme scenario from KNMI'23 scenarios and to 960 m^3/s in the low-emission KNMI'23 scenario in 2050 (ter Maat et al., 2024). Last, the current Agreed Low Waterlevel (OLR) is set based on a minimum water depth of 2.80m in the Bovenrijn, Waal, Pannerdensch Kanaal, and Nederrijn-Lek and on a minimum water depth of 2.50m in the IJssel (Comité Infrastructuur en Milieu, 2021). Adaptation measures to cope with higher high flows and longer and lower low flows include both immobile and mobile infrastructure. Measures for immobile infrastructure include relocation of bridges and canalization and measures for a change in mobile infrastructure include a change in barge size (Kriedel, 2022).

To conclude, the performance indicators for transport in the river system is based on the minimum water depths in the main channel and the recurrences. The indicators for navigation are the non-exceedances of the minimum water depths for navigation and the values for the OLA.

4.1.5 Validation model

The hydrographs in Figure 17 show the model validation for the period 2024. The graphs show the discharge over time. The locations of the graphs can be seen in the titles including the statistical metric. The R^2 value is higher than 0.9 for each location. This shows a good agreement between model results and measured results.

Visually, a small lag can be observed at Lobith (top graph). This can be accounted to the fact that the upstream boundary and thus the input location of the model is located near the German village Dornick. The observation station however is situated near the Dutch village Lobith. These villages are 15 kilometres from each other apart.

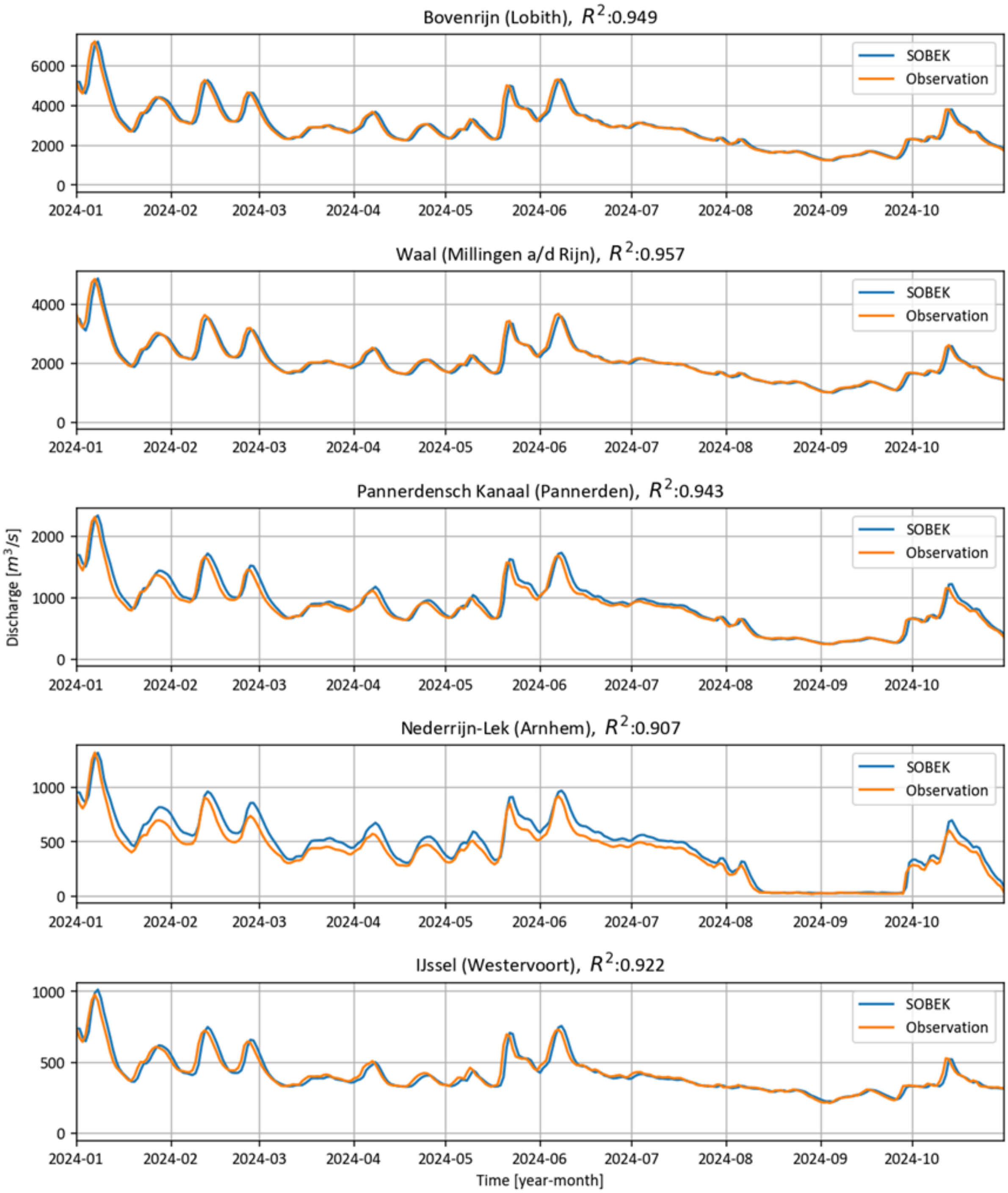

Figure 17: Model validation of the discharge distribution in the Dutch Rhine branches. The blue lines indicate the simulated SOBEK discharge per Rhine branch and the orange line indicates the observed discharge values. The input of Sobek were the discharges at Lobith for January 2024 till November 2024 (10 month).

4.2 RQ2: Climate scenarios

The following sections show the results for the second research question; in which ways the Dutch Rhine system will be affected by climate change. The next four sections show the effects of climate change per function and section 4.2.5 compares the climate scenarios in a MCA.

Table 7 shows the absolute and relative discharge distribution. The table shows that the design discharge will increase by 2,000 m^3/s; the expected discharge with a return period of 1 in 1250 years at Lobith is 18,000 m^3/s in 2100. Additionally, Figure A-37 in Appendix D: Discharge distribution over the complete flow range shows that the relative discharge distribution varies for the flow ranges.

Table 7: Discharge distribution in SOBEK for the reference scenario with design discharge of 16,000 m³/s, and for the climate scenarios with design discharge of 18,000 m³/s

Scenario	Distributary	Discharge [m^3/s]	Percentage [%]	Distribution additional design discharge [%]
Reference (16,000 m^3/s)				
	Waal	10,117	63	-
	Nederrijn	3,359	21	-
	IJssel	2,525	16	-
2100H and 2100M (18,000 m^3/s)				
	Waal	11,250	63	57
	Nederrijn	3,809	21	23
	IJssel	2,941	16	20

4.2.1 Conveyance

Figure 18 shows that the maximum water levels in the Waal, Nederrijn-Lek and the IJssel will increase for all climate scenarios due to the increased river discharges and increased sea level. The maximum water levels on the Waal will increase the most with 0.6 metres on average, followed by the maximum water levels on the Nederrijn-Lek with 0.5 metres on average. The maximum water levels on the IJssel will increase by 0.4 metres on average.

Next, the figure shows that the increase in maximum water levels is larger near the downstream boundaries. The increase in maximum water levels near the downstream boundaries is consistent with the rise in sea level rise and lake level. Moreover, the backwater curve resulting from sea level rise is the longest on the Nederrijn-Lek followed by the Waal. The effects of lake level rise only increase the water levels over a stretch of three kilometres upstream of the IJsselmeer, reaching as far as Keteldiep.

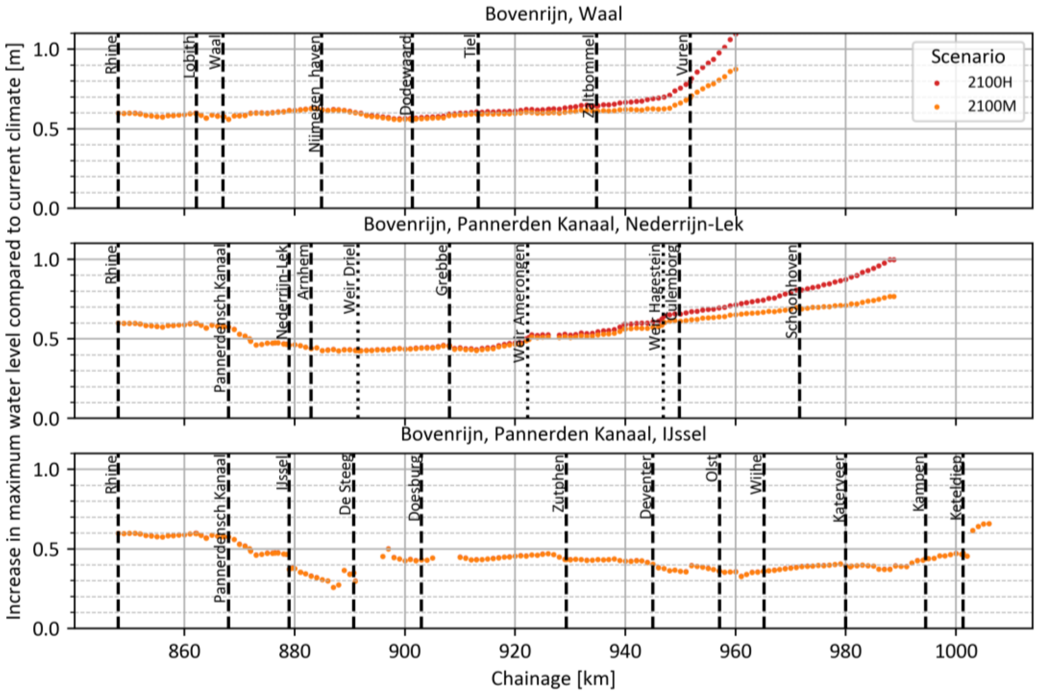

Figure 18: Increase in maximum water levels in the climate scenarios

4.2.2 Water supply

The boxplots in Figure 19 provide insight in the variability of the low flow durations in the reference climate and the climate scenarios 2100Md, 2100Mn, 2100Hd and 2100Hn. Each column represents a scenario, and each row resembles a river branch. The location of the upper row is the Waal (Nijmegen), the location of the middle row is Nederrijn-Lek (Arnhem), and the location of the lowest row is IJssel (Doesburg). In addition to the boxplots with low flow durations, Figure 20 presents the return periods of the low flow periods per river branch in these scenarios.

Each climate scenario consists of 8 ensembles of 30 years. This gives 240 years of data (points) per climate scenario. The boxplot presents the variability of the lowest 1-day discharge, lowest 7-day discharge, lowest 30-day discharge, lowest 90-day discharge and lowest 180-day discharge. The lower edge of the box indicates the 25th percentile of the data and the upper edge of the box indicates the 75th percentile of the data. The stripe inside the box indicates the median of the 50% data. This is therefore an indication of the skewness of the data. Furthermore, the lines show the spread of the low discharges. Lastly, the circles indicate outliers (values which are significantly lower or higher than the other data points. When looking at the figure it should be noted that the limits of the axis for the locations differ.

The boxplots show that the values for the 1-day low flow and 7-day low flow per location and scenario are nearly equivalent. This indicates that the low flows maintain for at least a period of one week. Thus, the Dutch Rhine system is characterized by prolonged durations rather than sharp peaks.

Moreover, the median of the low flow gradually increases over the periods for the Waal and the IJssel. The low flows in the Nederrijn-Lek show a steep increase from the 30-day low flow. This is the result of the weir policy. The weirs are closed during low flows and gradually open with rising discharges measured at Lobith.

The dry climate scenarios show an overall decrease in the low flow values. Here the high emission scenarios show a larger decrease than the medium emission scenarios.

The wet scenarios show an increase in the variability in the low flows. The medium emission scenario however shows a larger increase in variability than the high emission scenario.

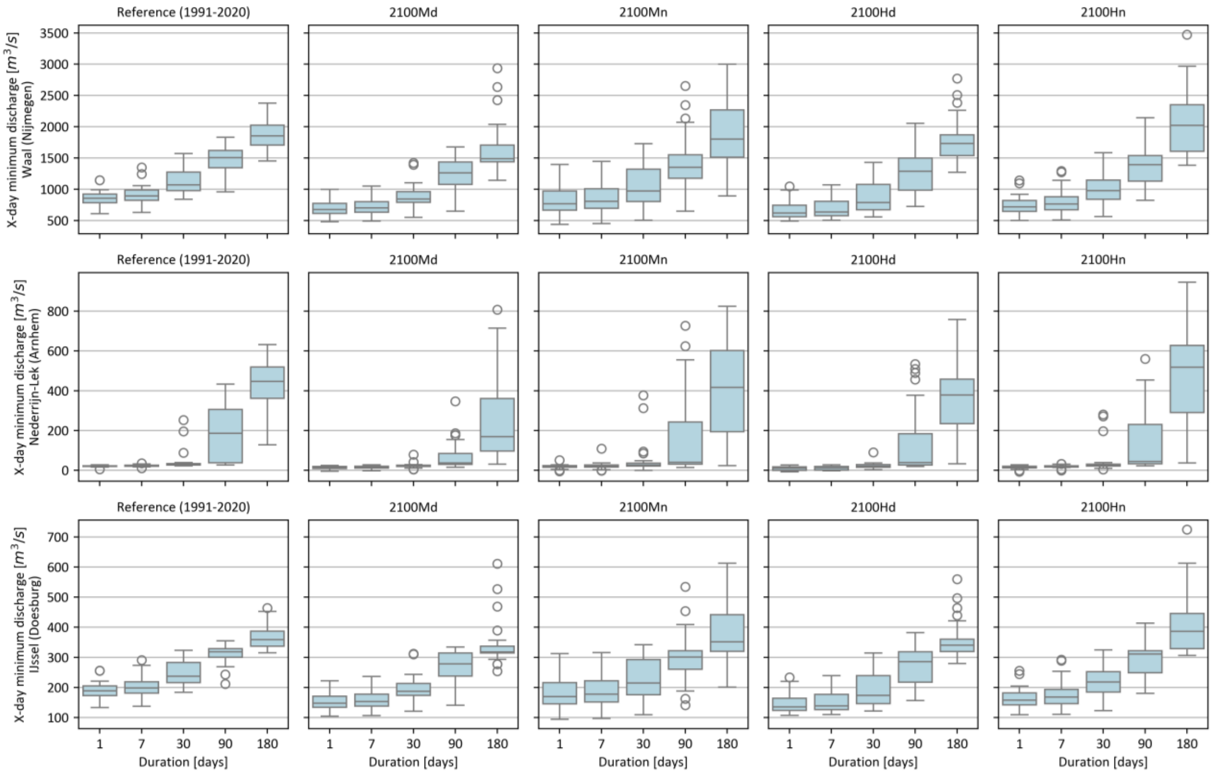

Figure 19: Boxplots of annual minimum low flows for different durations for the Waal (top row), Nederrijn-Lek (middle row) and IJssel (lower row) in the reference, 2100Md, 2100 Mn, 2100Hn, 2100Hd scenario

Figure 20 presents the return periods of the annual minimum discharges per climate scenario and river branch. The subplots are presented on a logarithmic scale, the x-axis presents the discharge, and the y-axis presents the accompanying return periods ranging from 10 to 1 years.

The figure shows that the low flows will be lower in the future and that the low flow occur more often in all climate scenarios. Moreover, the scenario 2100Mn shows the smallest change in low flows. The climate scenarios 2100Md and 2100Hn show similarities. Last, the climate scenario 2100Hd shows the largest decrease in the low flow and the largest increase in return period.

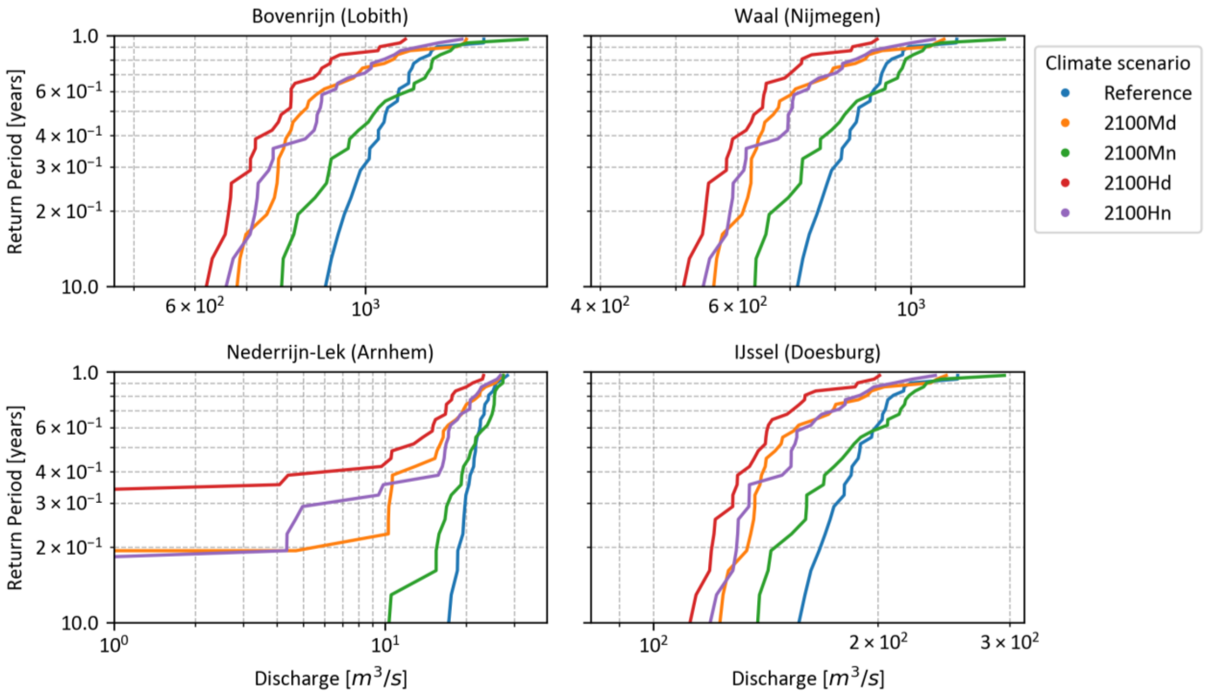

Figure 20: Return periods of the annual minimum discharges per climate scenario

4.2.3 Habitat

Figure 21 shows the dynamics in the floodplains in the climate scenarios, this is expressed as the difference between the 95% water levels and the 5% water levels in the floodplains. In the comparison between the contribution to the development of nature per branch, the area and length of the floodplains are considered as well (Table 1). The IJssel is the longest with 128 kilometres followed by the Nederrijn-Lek which is 111 kilometre and last the Waal is the shortest branch with 94 kilometres.

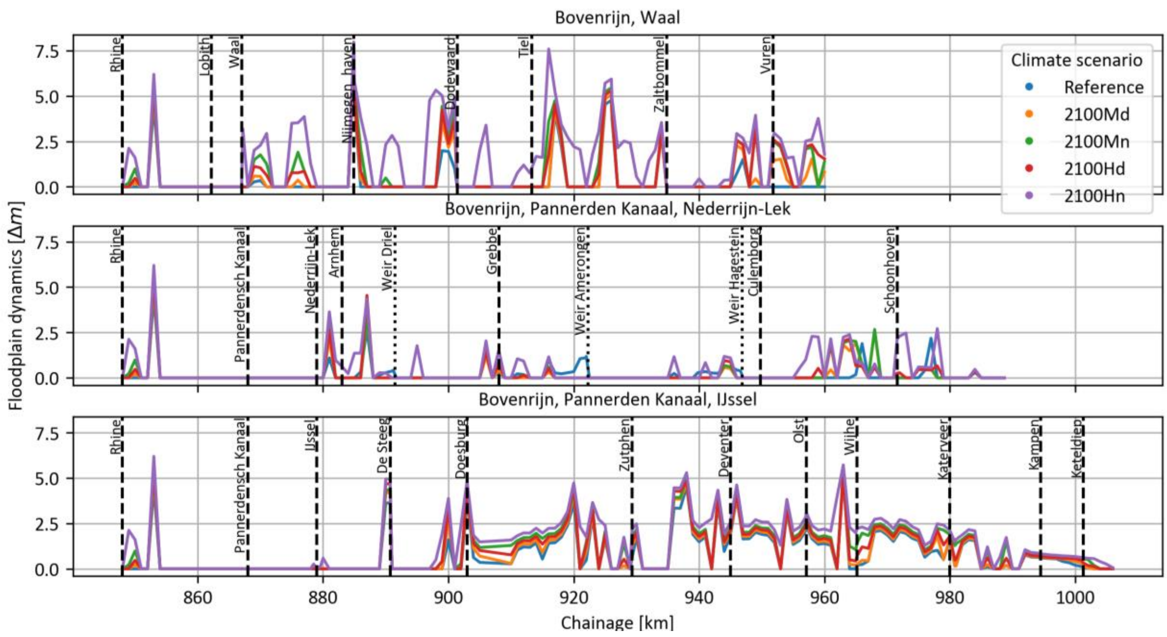

Figure 21: Water level dynamics in the floodplains along the Dutch Rhine tributaries for the climate scenarios

The total dynamics in the floodplain per scenario is equal to the average floodplain dynamics in Figure 21 times the length and width of the floodplain. The lengths and widths of the floodplains are shown in Table 1. Table 8 shows the average and total water level dynamics in the floodplains per river branch. The table shows that the average dynamics in floodplains of the Nederrijn-Lek are smallest. The average dynamic in the floodplains in the climate scenarios 2100Mn and 2100Hd are comparable while the climate scenario 2100Hn shows the largest dynamics in the floodplains. Moreover, the total floodplain dynamics in the scenario 2100Hn for the Waal and IJssel are comparable as the total dynamics is defined as the average dynamics times the length and the average width of the floodplains. The IJssel is 17 kilometres longer, and the mean width of the floodplain of the Waal is 50 metres larger which makes them comparable.

Table 8: Floodplain dynamics in the climate scenarios (based upon 122 observation points)

Average dynamics [Δm]	**Reference**	**2100Md**	**2100Mn**	**2100Hd**	**2100Hn**
Waal	0.38	0.53	0.77	0.71	1.55
Nederrijn-Lek	0.17	0.16	0.2	0.19	0.41
IJssel	0.81	0.92	1.13	1.03	1.43
Total dynamics [m^3]	158	187	242	222	380

4.2.4 Transportation

Figure 22 shows the minimum simulated water depths over the Dutch Rhine branches in 240 years per climate scenario. Section 4.1.4 concluded that navigation is problematic at water levels lower than 2 meter and that impacts are noticeable at water depths smaller than 3 metres. Moreover, the agreed minimum water depth on the Waal and Nederrijn-Lek is 2.8 metres and 2.5 metres on the IJssel. The area between 2 meter and the agreed minimum water depth is shown by the shaded red area.

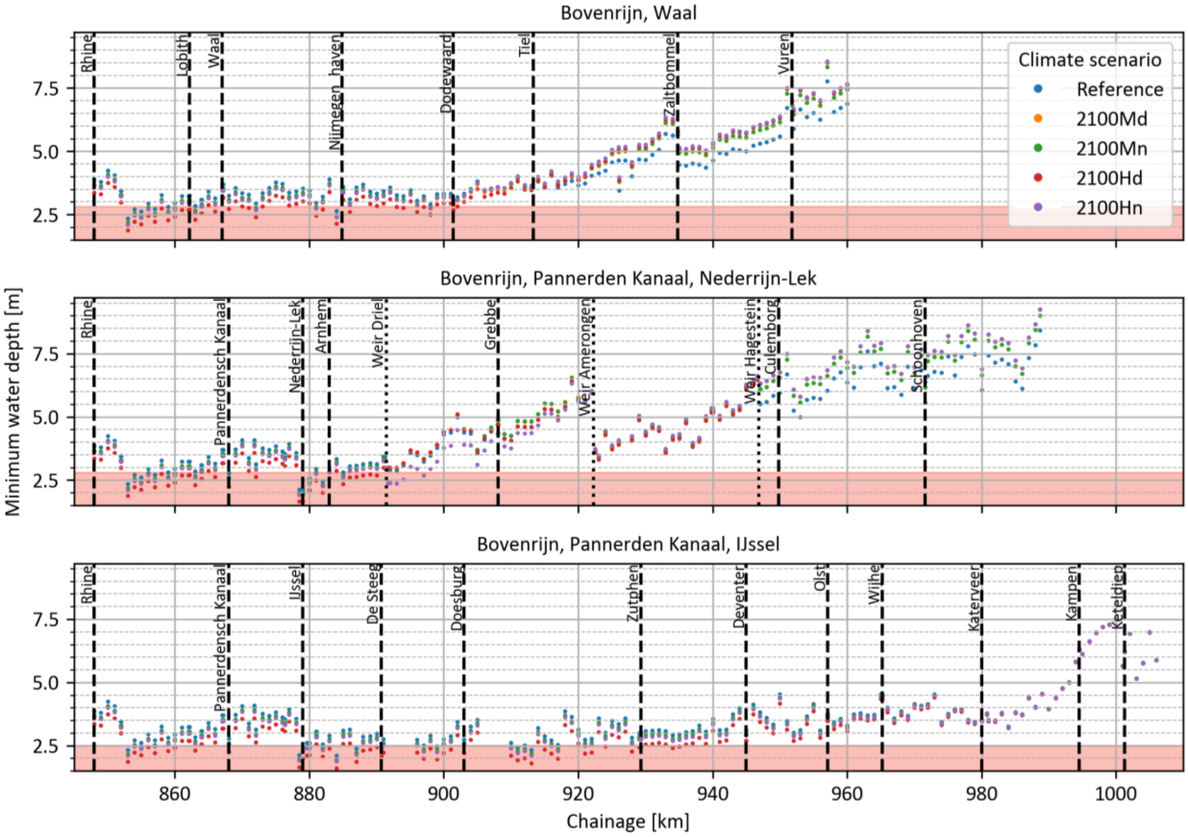

Figure 22: Minimum water depths in the Dutch Rhine branches for five climate scenarios. The red shaded area indicates the region where the agreed minimum water depths (2.80m Waal and Nederrijn-Lek, 2.50m IJssel) are not reached (Comité Infrastructuur en Milieu, 2021)

Table 9 shows how many days per year water depths are lower than the minimum water on average per climate scenario. All scenarios show an increase in days on which the water levels do not exceed the critical navigation depths. The table shows that the Waal is navigable most days of the year, followed by the IJssel and the Nederrijn-Lek is navigable for the least days per year. Also, the water levels are in all scenarios almost never lower than 2 metres. Furthermore, the table shows that the climate scenario 2100Mn shows least increase in the non-navigable days per day. The scenarios 2100Md and 2100Hn have similar results on the navigability of the river branches. Last, the scenario 2100Hd shows the largest increase in non-navigable days per year.

Table 9: Exceedances of the minimum navigation depths in [average days per year]

	Reference	2100Md	2100Mn	2100Hd	2100Hn
Water depth below 2m (Waal)	0	0	0	0	0
Water depth below 2.8m (Waal)	1	6	3	18	7
Water depth below 2m (NR-Lek)	0	1	0	3	1
Water depth below 2.8m (NR-Lek)	11	30	19	54	28
Water depth below 2m (IJssel)	0	1	1	4	1
Water depth below 2.5m (IJssel)	4	14	9	34	16
Maximum exceedance	11	30	19	54	28

Table 10 shows the expectations for the OLA in each of the river branches. The table shows that in each climate scenario, the minimum discharge occurring 20 days per year will be lower depending on the climate scenario. Moreover, the high emission scenarios and the dry scenarios show the largest decrease in low flow.

Table 10: Expectations for the Agreed Low Discharge under climate change

	Reference [m³/s]	2100Md [m³/s]	2100Mn [m³/s]	2100Hd [m³/s]	2100Hn [m³/s]
Lobith	1197	1023	1145	890	1067
Waal	958	823	919	719	857
Nederrijn-Lek	28	19	24	13	22
IJssel	212	182	204	158	190

4.2.5 Evaluation

Table 11 shows the results of the MCA on the performance of the river functions for the climate scenarios. The results show that the scenarios showing a trend towards a wetter future put least pressure on the river system while the high emission scenario with a trend towards a drier future 2100Hd puts a lot of pressure on the river functions. The next sections provide detailed results per river function and climate scenario.

Table 11: MCA performance river functions in climate scenarios (rank 1 = best)

	Reference	2100Md	2100Mn	2100Hd	2100Hn
Conveyance	1	2.5	2.5	4.5	4.5
Water supply	1	3.5	2	5	3.5
Habitat	5	4	2	3	1
Transportation	1	3.5	2	5	3.5
Sum rank	8	13.5	8.5	17.5	12.5

4.3 RQ3: Alternative discharge distribution

The following sections present the results for the third research question. The objective of this research question was to propose alternative distributions of the additional design discharge and evaluate the impact of these distributions on the river functions. The following section describe the choice for investigated alternative discharge distributions. Thereafter, sections 4.3.1 until 4.3.4 describe the results per river function. Section 4.3.5 compares the alternative discharge distributions using a MCA.

First, the Dutch Expert Network of Flood safety advised to spare the Lek for increasing discharges (van den Top & ENW, 2021). The results of the conveyance of the river under climate change showed that the water levels in the Nederrijn-Lek increase relatively the most with an increasing discharge. Next, Klijn et al. (2024) concluded that the strategy to spare the Lek is still the best alternative and presented multiple reasons including the slope of the river, the large flood risks and the geographical location. Alternative discharge distributions for the additional 2,000 m^3/s should therefore be distributed over the Waal and IJssel.

In total, three scenarios are compared in which the increase in design discharge is distributed following the current discharge distribution, redistributed 80% towards the Waal and 20% towards the IJssel, and redistributed 60% to the Waal and 40% to the IJssel. The distributions are compared for the scenario 2100Hd.

Table 12 shows the absolute and relative distribution of the design discharge for the abovementioned scenarios. The table shows that the alternative discharge distributions were obtained (by a change in the main channel roughness). Figure A-38 in Appendix D: Discharge distribution over the complete flow range shows the variations of the discharge distribution over the complete flow range.

Table 12: Discharge distribution in SOBEK for the reference scenario (upstream discharge of 16,000 m^3/s) and the climate scenarios (upstream discharge of 18,000 m^3/s)

Scenario	Distributary	Discharge [m^3/s]	Total percentage [%]	Distribution additional design discharge (2,000 m^3/s) [%]
Reference 16,000 m^3/s				
	Waal	10,120	63	-
	Nederrijn	3,360	21	-
	IJssel	2,530	16	-
2100Hd 18,000 m^3/s				
	Waal	11,250	63	57
	Nederrijn	3,810	21	23
	IJssel	2,940	16	21
2100Hd 18,000 m^3/s 80-20				
	Waal	11,700	65	79
	Nederrijn	3,360	19	0
	IJssel	2,950	16	21
2100Hd 18,000 m^3/s 60-40				
	Waal	11,330	63	61
	Nederrijn	3,370	19	1
	IJssel	3,310	18	39

4.3.1 Conveyance

Figure 23 presents the increase in the maximum water levels over the Waal, Nederrijn-Lek and IJssel for future climate and altered discharge distributions (18,000 m^3/s) compared to current climate (16,000 m^3/s). The water level increase resulting from climate change is minimized on the Nederrijn-Lek by alternative discharge distributions. The Nederrijn-Lek will not receive additional discharge in both scenarios compared to the current climate. The figure shows that the maximum water levels resulting from the proposed changes to the discharge distribution will increase on the Bovenrijn, Waal and IJssel. Moreover, the figure shows that the maximum water levels in the Nederrijn-Lek do not increase in the scenario of the alternative discharge distributions, however, the effects of climate change on the maximum water levels downstream are however still up to 0.5 meter.

First, the maximum water levels on the Bovenrijn slightly increase in the scenario 60-40 and do increase 0.1 to 0.2 metres in the scenario 80-20. The roughness in the main channel is increased over a length of one kilometre upstream of the Pannerdensch Kop in the scenario 80-20. Increasing the roughness has an increasing effect on the water levels, therefore, the water level increase in the

Bovenrijn in the scenario 80-20 is possibly an effect of the model implementation in the alternative discharge distribution.

Second, the water levels around the IJsselkop increase by 0.5 meter in the scenario 60-40. In this scenario, the roughness in the main channel of the Nederrijn-Lek just upstream of the IJsselkop is increased to reach the desired discharge distribution. Increasing the roughness has an increasing effect on the water levels, therefore the water level increase around the IJsselkop in the scenario 60-40 is rather an effect of the model implementation in the alternative discharge distribution.

The maximum water levels on the Waal increase by 0.05m in the distribution 60-40 and with 0.2m in the distribution 80-20 compared to the current distribution.

Last, the redistribution of the additional design discharge toward the partitioning 80-20 gives the same increase in maximum water levels. However, the redistribution 60-40 shows that the maximum water levels will increase by 0.4m compared to the current distribution. This is the result of an additional discharge of 400 m^3/s.

In conclusion, if the Nederrijn-Lek is spared for additional discharge, the water levels on the Nederrijn-Lek will not increase by 0.5m. However, this will lead to an increase in water levels on the Waal and the IJssel. The proposed distribution 80-20 will lead to an increment in the maximum water levels of 0.2m and the second proposed distribution 60-40 will lead to an increase in the maximum water levels in the IJssel by 0.4m.

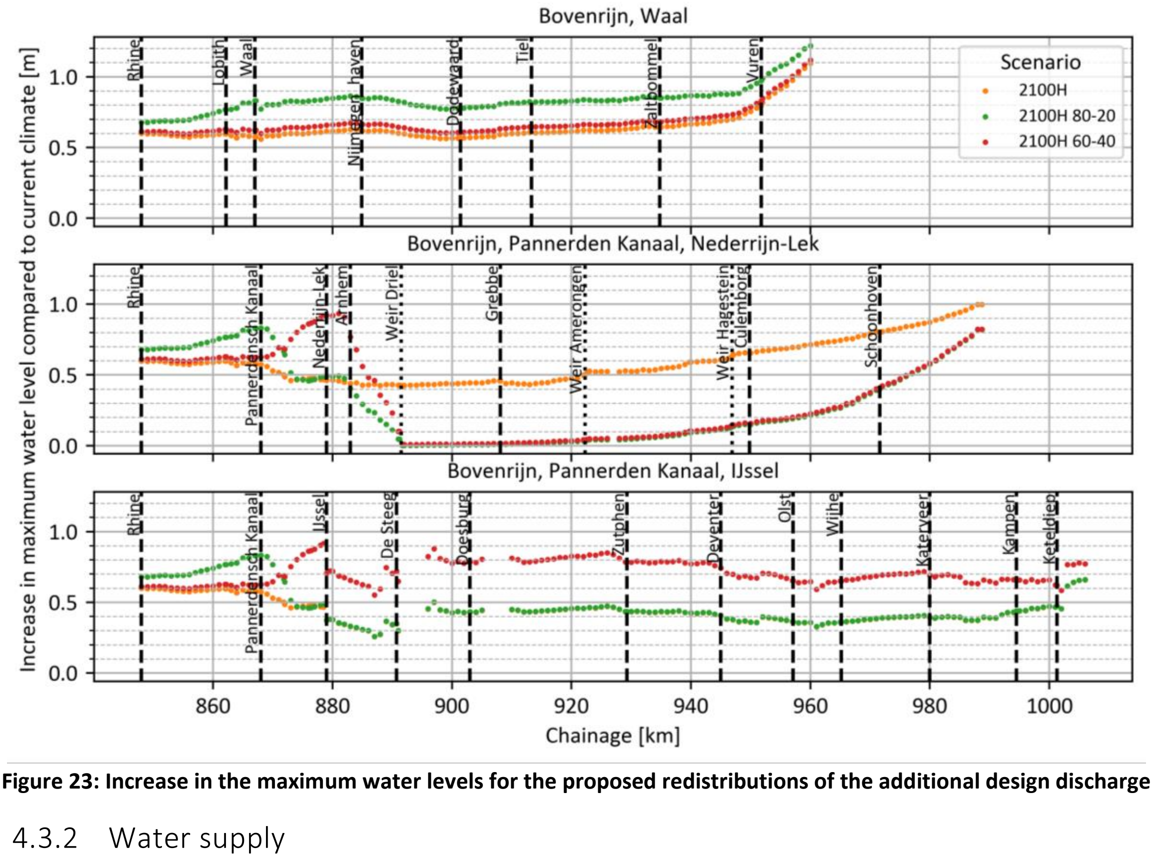

Figure 23: Increase in the maximum water levels for the proposed redistributions of the additional design discharge

4.3.2 Water supply

Figure 24 provides insight in the variability of the low flow durations in the reference climate, 2100Hd and for the two proposed alternative discharge distributions. Additionally, Figure 25 presents the return periods of the minimum annual low flow periods.

The box plots for the low flow durations indicate that the proposed alternative discharge distributions increase the variability in the 180-day discharge. Furthermore, the discharge in the Waal in the scenario 80-20 is higher than the discharge in the scenario 60-40. The difference is however small compared to the total discharge. The low flows in the Nederrijn-Lek in the scenarios 60-40 and 80-20 are almost identical. This observation can be accounted to the weir policy at Driel.

Thirdly, the variability in low flow discharge increases in the alternative discharge distribution scenarios. Also, in the 60-40 scenario the low flow discharges in the IJssel are found to be higher than in the other scenarios which is expected for an increase in discharge towards the IJssel.

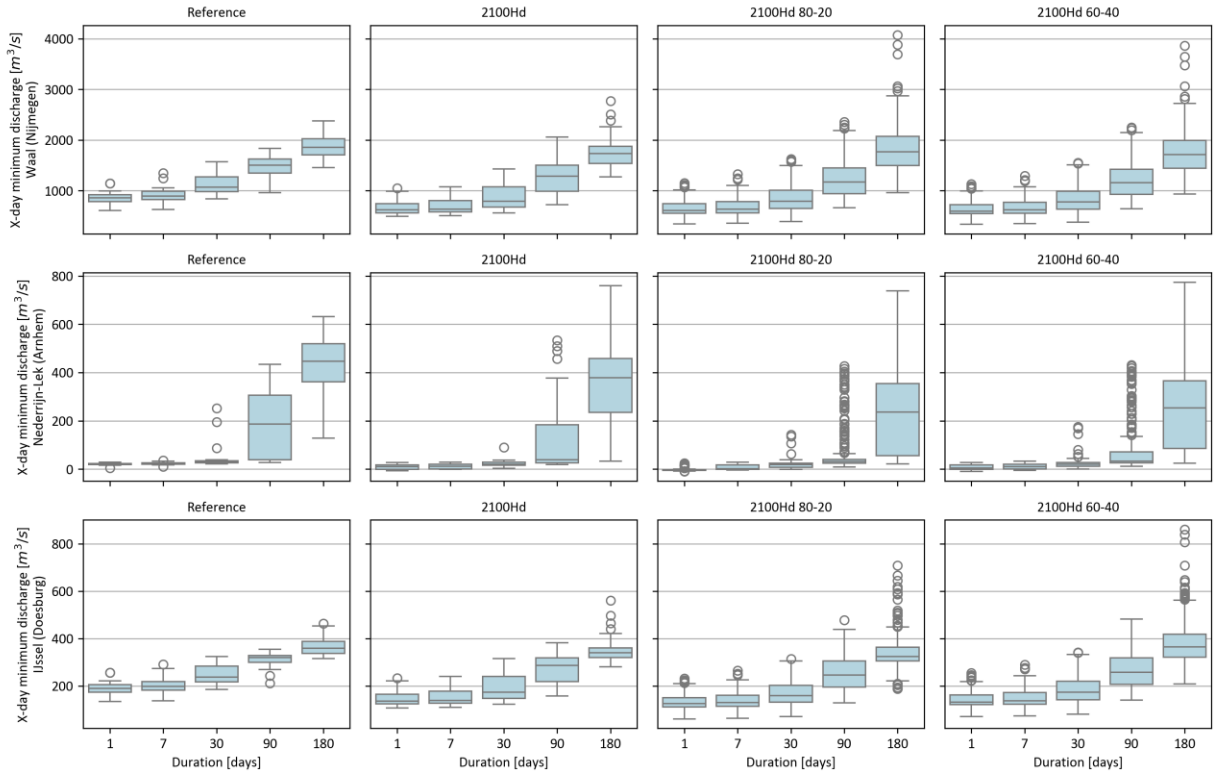

Figure 24: Boxplots for the low flow durations for the Waal (top row), Nederrijn-Lek (middle row) and IJssel (lower row) in the reference and 2100Hd scenario and the redistribution of additional design discharge scenarios

Figure 25 presents the return periods of the annual minimum discharges in the reference and alternative discharge distribution scenarios. The figure indicates that the average annual 1-day minimum discharge is not altered by a redistribution of the additional design discharge. The redistributions of the discharge were focussed on the high flows and obtained by a change in the roughness of the main channel over a length of one kilometre of the bifurcations. Thus a change in the roughness coefficients have no visible influence on the distribution of the low flows.

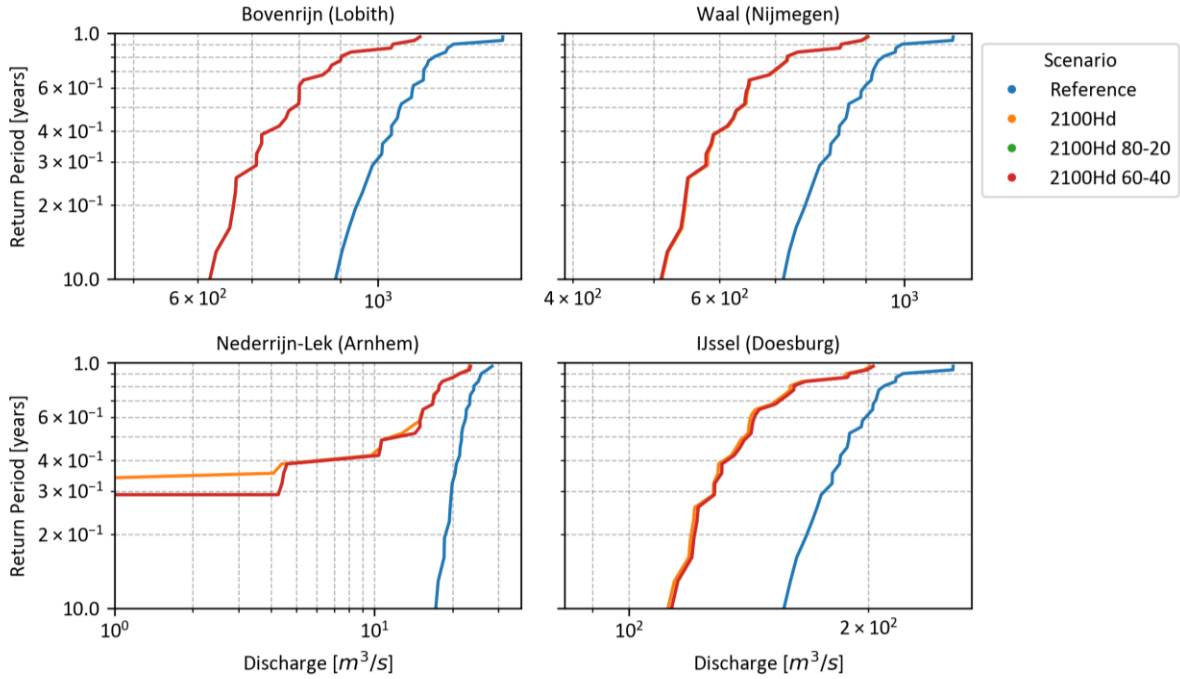

Figure 25: Return periods of the annual minimum discharges for the current climate scenario, and three different discharge distributions for future climate

4.3.3 Habitat

Figure 26 shows the dynamics in the water levels in the floodplains for the proposed alternative discharge distributions. The figure shows no large differences in the floodplain dynamics along the Nederrijn-Lek for climate change and the proposed discharge distributions. Next, the floodplain dynamics in the Waal will increase most in the scenario 80-20. This can be attributed to the additional discharge which will cause higher water levels. Furthermore, the water level dynamics in the floodplain of the IJssel are largest for the scenario 60-40 as the IJssel receives most discharge in this scenario.

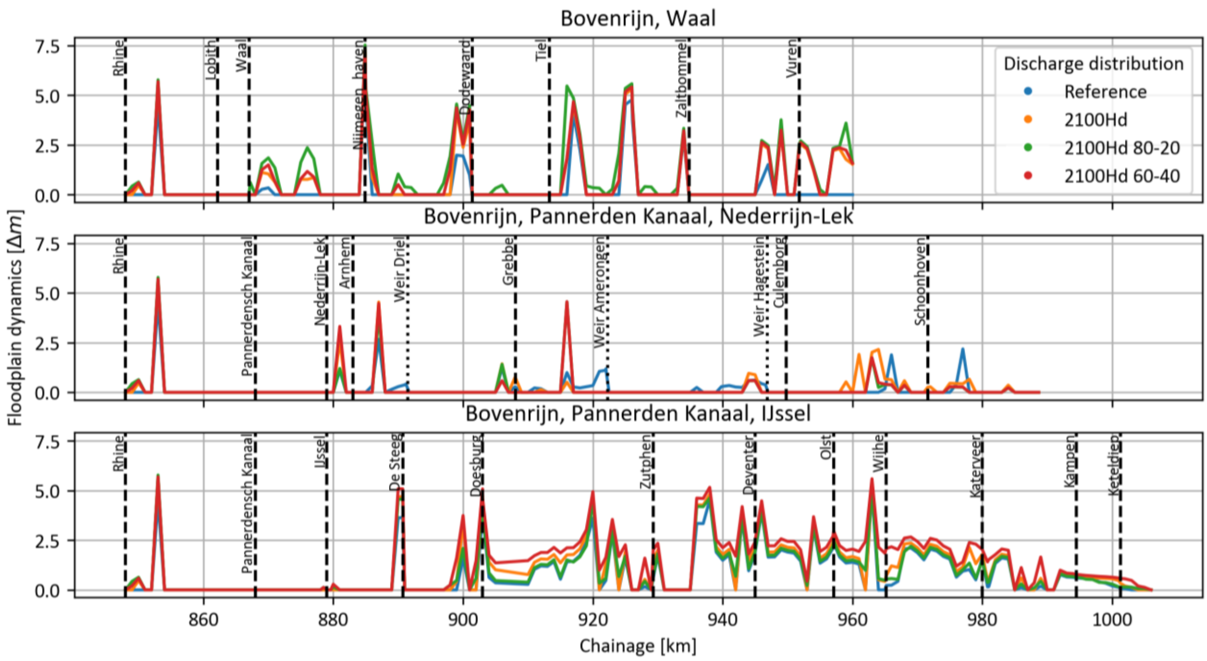

Figure 26: Water level dynamics in the floodplains along the Dutch Rhine tributaries in the reference scenario, climate scenario 2100Hd and for the proposed alternative discharge distributions

Table 13 shows the values for the average water level dynamics along the river branches for the alternative proposed discharges as well. The table concludes that the dynamics in the floodplains of the rivers will increase in the scenario 2100Hd and that the alternative discharge distributions will create overall more river dynamics. The floodplain dynamics are the largest in the alternative discharge distribution 60-40. This is concluded by taking the sum of the multiplication per branch length, average floodplain width and the dynamics. The increase in floodplain dynamics is contributed to an increasing difference between water levels.

Table 13: Floodplain dynamics for alternative discharge distributions

Average dynamics [Δm]	**Reference**	**2100Hd**	**2100Hd 80-20**	**2100Hd 60-40**
Waal	0.38	0.71	0.95	0.76
Nederrijn-Lek	0.17	0.19	0.15	0.16
IJssel	0.81	1.03	0.94	1.31
Total	158	222	232	260

4.3.4 Transportation

Figure 27 shows the minimum simulated water depths over the Dutch Rhine branches in the reference scenario, 2100Hd climate scenario and the proposed alternative discharge distributions in the 2100Hd climate scenario. The figure shows only minor differences between the alternative discharge distributions and the current discharge distribution in the 2100Hd climate scenario compared to the difference between reference climate and 2100Hd climate.

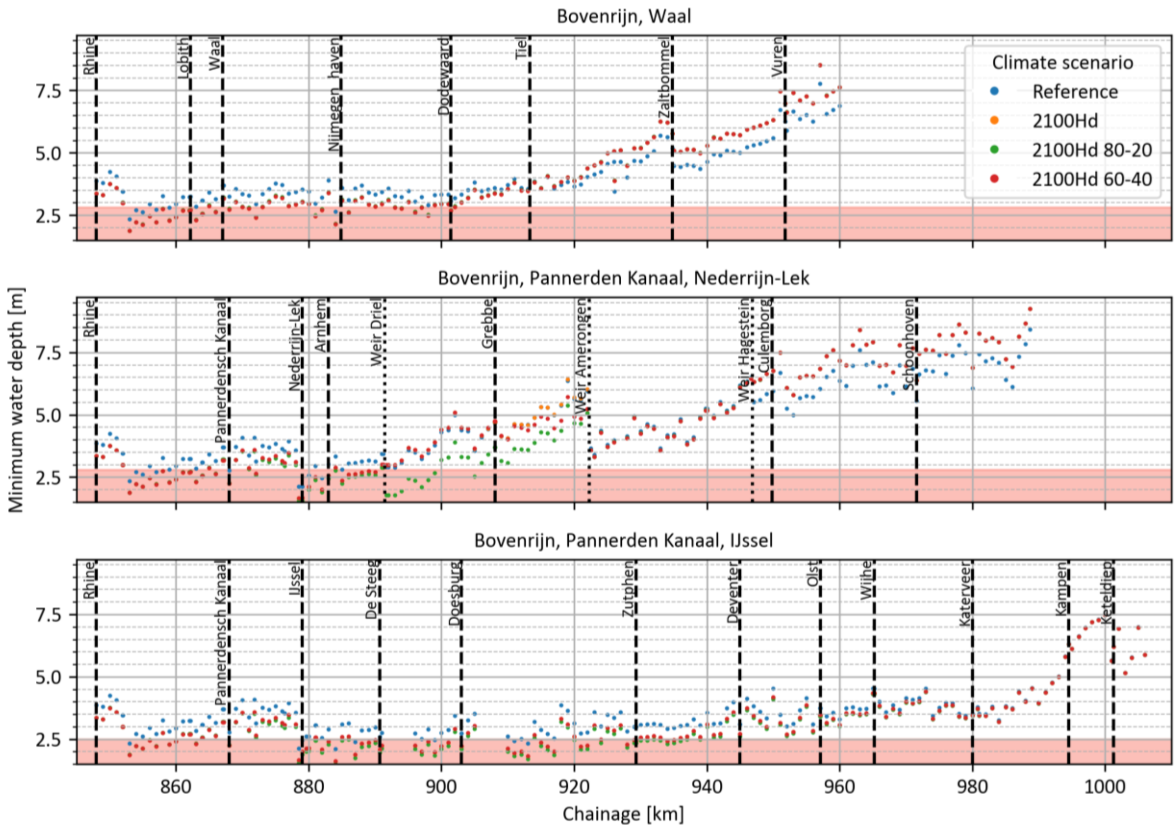

Figure 27: Minimum water depths in the scenario of alternative discharge distributions. The red shaded area indicates the region where the agreed minimum water depths (2.80m Waal and Nederrijn-Lek, 2.50m IJssel) are not reached (Comité Infrastructuur en Milieu, 2021)

Table 14 presents how many days per year the water depths do not exceed the minimum water depths. The table suggests that the number of non-navigable days per year in the scenario 80-20 does increase compared to the current and 60-40 distributions. Next to this, the table shows that the Waal is most reliable for transportation followed by the IJssel and the Nederrijn-Lek is least reliable for transportation in all scenarios.

Table 14: Exceedances of the minimum navigation depths

[Average days per year]	Reference	2100Hd	2100Hd 80-20	2100Hd 60-40
Water depth below 2m (Waal)	0	0	1	0
Water depth below 2.8m (Waal)	1	18	16	18
Water depth below 2m (NR-Lek)	0	3	9	3
Water depth below 2.8m (NR-Lek)	11	54	66	53
Water depth below 2m (IJssel)	0	4	10	4
Water depth below 2.5m (IJssel)	4	34	45	33
Maximum exceedance	11	54	66	53

Table 15 adds on the expectations for the OLA in each of the river branches for the proposed alternative discharge distributions. The table shows a relatively large decrease in the OLA in the Waal in the alternative distribution 60-40. This difference is the result of a change in the main channel roughness.

Table 15: Expectations for the Agreed Low Discharge under climate change and for river widening measures

	Reference [m^3/s]	2100Hd [m^3/s]	2100Hd 60-40 [m^3/s]	2100Hd 80-20 [m^3/s]
Lobith	1197	890	890	890
Waal	958	719	732	718
Nederrijn-Lek	28	13	7	14
IJssel	212	158	148	160

4.3.5 Evaluation

Table 16 shows the results of the MCA for the proposed alternative discharge distributions. The table shows that an alternative discharge distribution increases the total conveyance as the scores are lower than the scenario 2100Hd with the current discharge distribution. All three discharge distributions show equal ranks for the water supply as the upstream conditions and thus the total discharge is not changing. Furthermore, both discharge redistributions indicate that the habitat suitability of the floodplains do increase. Fourth, the average number of days per year on which the minimum water depths do not exceed the required navigation depths are equal for the scenario 60-40 and increase for the scenario 80-20. Overall, the alternative distribution 60-40 puts least pressure on the river functions. The next sections provide the results per function and scenario in detail.

Table 16: MCA performance river functions in alternative discharge distributions (range sum rank [4(best), 16(worst)])

	Reference	2100Hd	80-20	60-40
Conveyance	1	4	3	2
Water supply	1	3	3	3
Habitat	4	3	2	1
Transportation	1	2.5	4	2.5
Sum	7	12.5	12	8.5

4.4 RQ4: River widening measures

The following sections present the results for the last research question; in which ways spatial measures in the IJssel (Figure 15) will affect the river functions in Rhine. The next sections show the effects of river widening measures per river functions. Section 4.4.5 compares the river widening measures in a MCA.

Table 17 shows the absolute and relative discharge distributions for the proposed river widening measures. The table shows that the river widening measures have a large influence on the discharge distributions during high flows. A dike relocation and excavation in the floodplain do have an effect on discharges above bankfull width. Next to this, lowering of the floodplain affects the discharge distribution at all flow ranges. The relative discharge distribution over the full range can be seen in Figure A-39 in Appendix D: Discharge distribution over the complete flow range.

Increasing the flow area in the IJssel will lead to an increase in discharge towards the IJssel and a decrease in discharge to the Waal and Nederrijn-Lek compared to the current distribution. The discharge distribution shifts most to the IJssel in the scenario in the scenario in which the main channel is excavated followed by a relocation of the dikes and least for the excavation of the floodplains. The negative values in the last column of the table below indicate that the river widening measure results in a smaller discharge towards the branch (Nederrijn-Lek) compared to the current discharge distribution.

Table 17: Discharge distribution at high flows in SOBEK for the implementation of river widening measures in climate scenario 2100Hd

Scenario	Distributary	Discharge [m^3/s]	Total percentage [%]	Distribution additional design discharge (2,000 m^3/s) [%]
2100Hd 18,000 m^3/s 60-40				
	Waal	11,330	63	61
	Nederrijn-Lek	3,370	19	1
	IJssel	3,310	18	39
2100Hd 18,000 m^3/s 60-40 dike				
	Waal	11,170	62	53
	Nederrijn-Lek	2,930	16	-22
	IJssel	3,900	22	69
2100Hd 18,000 m^3/s 60-40 floodplain				
	Waal	11,240	62	56
	Nederrijn-Lek	3,110	17	-13
	IJssel	3,660	20	57
2100Hd 18,000 m^3/s 60-40 main channel				
	Waal	11,130	62	51
	Nederrijn-Lek	2,800	16	-28
	IJssel	4,070	23	77

4.4.1 Conveyance

Figure 28 shows the increase in maximum water levels over the Dutch Rhine distributaries for the 60-40 distribution including proposed river widening measures in the IJssel (18,000 m^3/s) compared to current climate (16,000 m^3/s). The figure shows that the increase in maximum water level in the Waal for each of these scenarios is about the same, around 0.6 metres. Next, the figure shows that the maximum water levels in the Nederrijn-Lek are decreasing in the case of river widening measures in the IJssel. Last, lowering the main channel results in a smaller increase in maximum water levels along the IJssel.

First, a dike relocation, excavation of the floodplains and the lowering of the main channel all have a small lowering effect on the maximum water levels in the Bovenrijn. Also, all scenarios have an increased effect on the water levels near the IJsselkop. This is a result of the implementation of the alternative discharge distributions as the roughness values in the Nederrijn-Lek just downstream of the IJsselkop are increased in the scenario 60-40.

Second, the river widening measures implemented in the model each affect the discharge distribution (Table 12). All three implemented river widening measures show an increase in discharge directed to the IJssel. As a result, less discharge is directed to the Waal and Nederrijn-Lek. Therefore, the maximum water levels are lower on the Waal and Nederrijn-Lek.

Lastly, Figure 28 shows that despite the increase in discharge in the IJssel, the maximum water levels show no large differences for the stretch between De Steeg and Katerveer from the scenario without a river widening measure. This shows that a dike relocation and floodplain excavation do have a positive effect on the conveyance of the river. Moreover, the excavation of the main channel shows a large difference in increase in maximum water levels from the scenario without a river widening measure.

The main channel of the IJssel was excavated with 6 metres and received compared to the reference climate 1,500 m³/s much more discharge (+60%). The maximum water levels only increased by 0.1 to 0.3 metres.

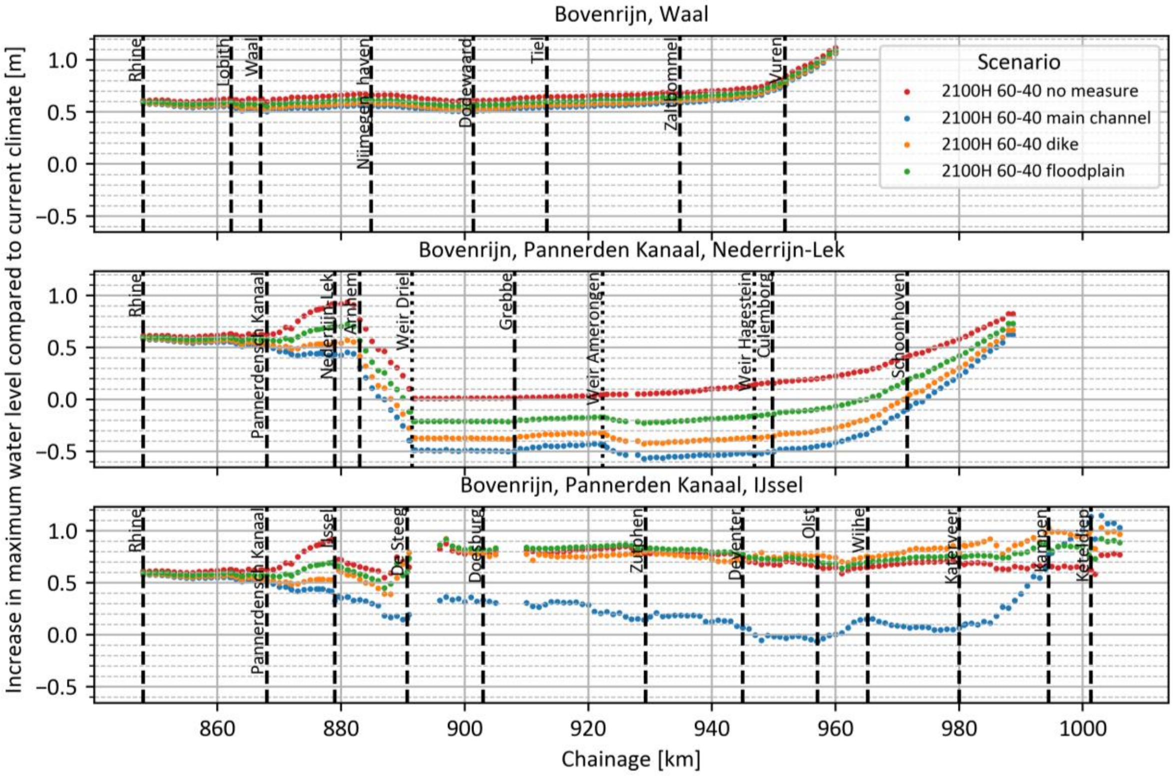

Figure 28: Increase in the maximum water levels for the proposed redistribution of the additional design discharge and river widening measures along the IJssel

4.4.2 Water supply

Figure 29 shows the boxplots for the low flow durations in the reference climate and alternative discharge distribution 60-40 as well as the implementation of river widening measures.

The boxplot provides insight in the variability in low flow discharges after the implementation of river widening measures. These river widening measures affect the discharge distribution. The dike relocation and excavation of the floodplain do not have an effect on the distribution of low flows as these do not exceed the bankfull discharge. Furthermore, the excavation of the floodplain causes an increase in discharge towards the IJssel at the expense of the other branches. The low flows of the Waal and Nederrijn-Lek show therefore a decrease while the low flow discharge towards the IJssel increases.

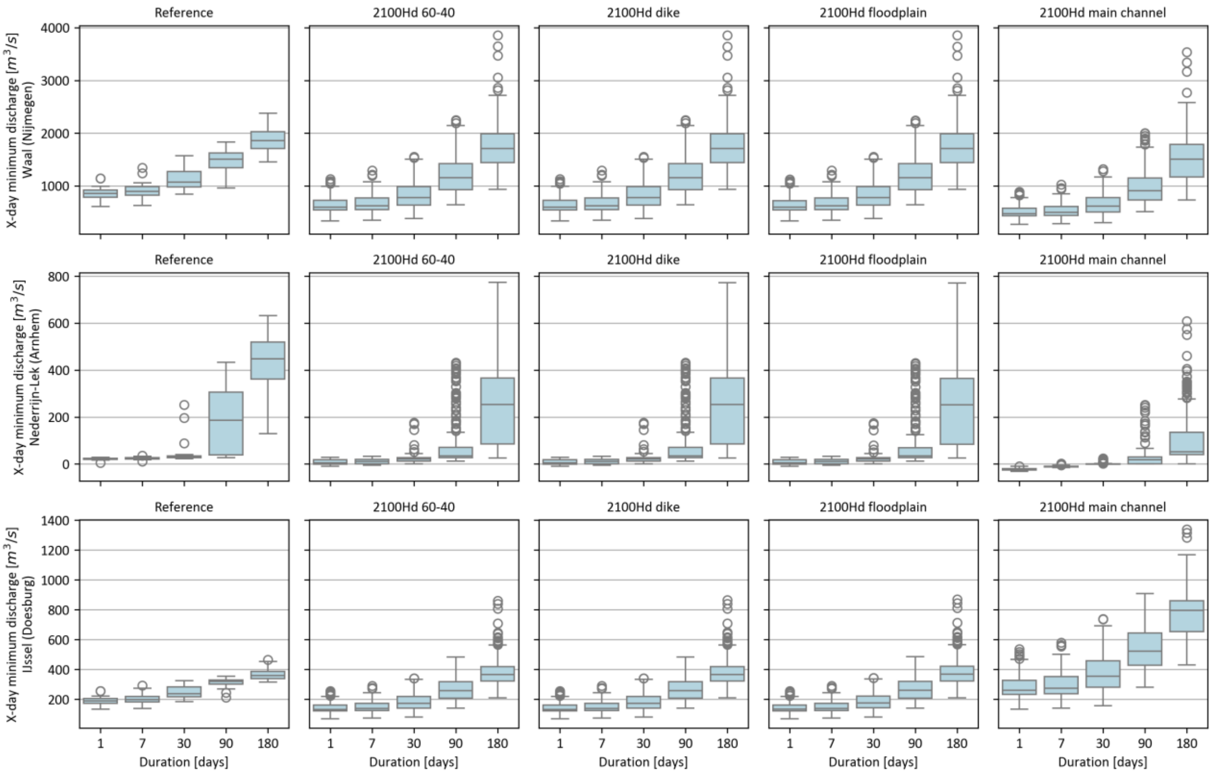

Figure 29: Boxplots for the low flow durations for the Waal (top row), Nederrijn-Lek (middle row) and IJssel (lower row) in the reference and 2100Hd 60-40 and for the river widening scenarios

Figure 30 presents the return periods of the annual minimum discharges for river widening scenarios. The figure indicates that due to climate change, the low flows will be lower and that low flows will occur more often. Moreover, the scenarios in which the dike is relocated, and the floodplain is lowered, there is no change in low flows and their return period. However, the low flows will get lower and occur more often in the Waal in the scenario of lowering the main channel. In addition, the low flows will increase, and the return periods will decrease in the IJssel in the scenario of lowering the main channel.

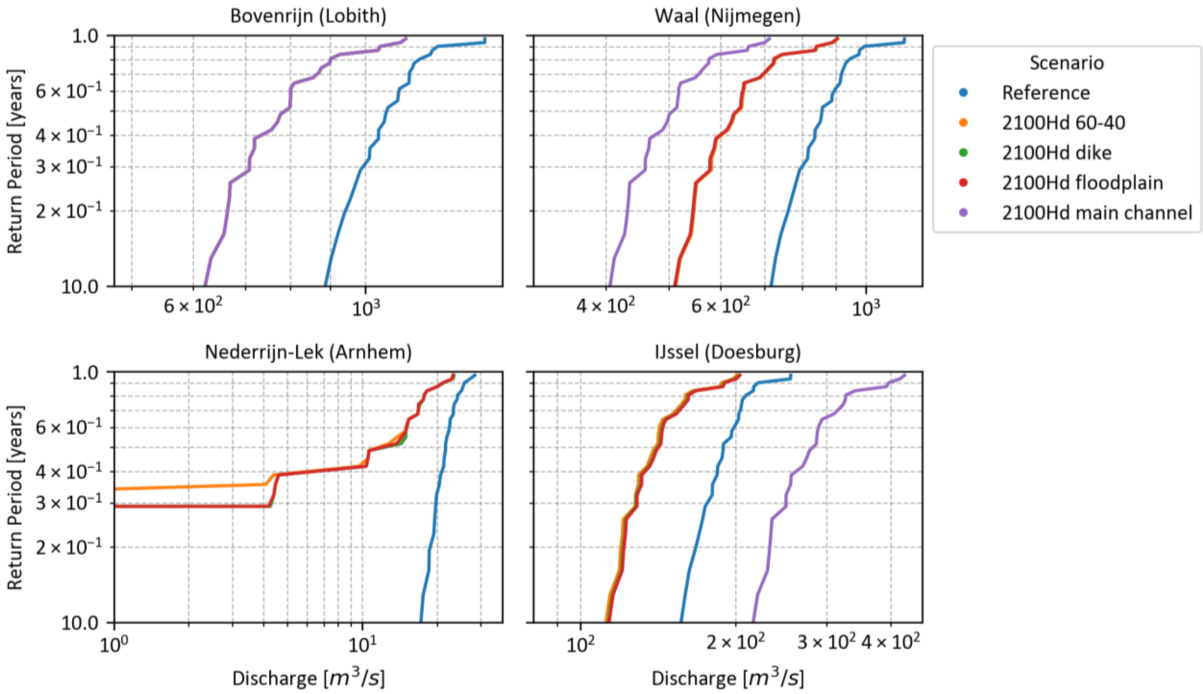

Figure 30: Return periods of the annual minimum discharges for the reference climate, future climate and river widening measures

4.4.3 Habitat

Figure 31 shows the water level dynamics in the floodplain for the implementation of the river widening scenarios in the IJssel. The figure shows large differences along the IJssel. First, the figure shows that the dike relocation does not seem to have an effect on the dynamics in the floodplains. However, the area of the floodplains is larger as the dikes on both sides have been relocated with 300 metres and this is also taken into account in the MCA. Secondly, excavating the floodplains do increase the dynamics in the floodplains as the differences between the water levels and the base level of the floodplain are larger. Third, the excavation of the main channel led to a decrease in the floodplain dynamics despite an increased proportion of the upstream discharge towards the IJssel. Excavating the floodplains thus increased the dynamics in the main channel and not in the floodplains.

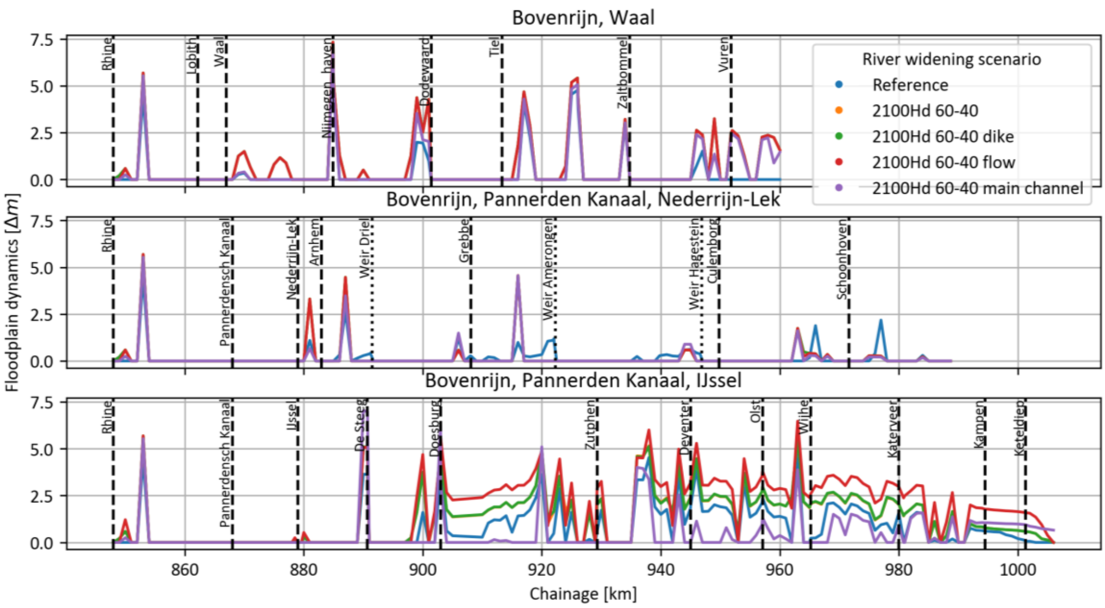

Figure 31: Water level dynamics in the floodplains along the Dutch Rhine tributaries for the implementation of river widening measures

Table 8 shows the average water level dynamics in the floodplains per river branch. The results showed that a dike relocation causes a large increase in the floodplain dynamics. The dikes are relocated by 300 metres and the floodplains near the IJssel will thereby increase from 500 meter to 800 meter on average. Next, excavating the floodplains will also increase the water level dynamics in the floodplains as during high flows the vertical water level difference will be larger. Last, lowering of the floodplain will decrease the water level dynamics in the floodplain despite the increased discharge towards the IJssel. When lowering the main channel, the floodplains will be flooded less frequent.

Table 18: Floodplain dynamics for river widening implementations

Average dynamics [Δm]	**Reference**	**2100Hd**	**2100Hd dike**	**2100Hd flow**	**2100Hd main channel**
Waal	0.38	0.76	0.76	0.76	0.58
Nederrijn-Lek	0.17	0.16	0.16	0.16	0.13
IJssel	0.81	1.31	1.31	1.76	0.53
Total	158	222	361	318	139

4.4.4 Transportation

Figure 32 shows the minimum simulated water depths over the Dutch Rhine for the river widening interventions in the IJssel. The figure shows a clear difference between the reference and 2100Hd climate. However, the figure does not show a difference for each of the river widening measures in the IJssel.

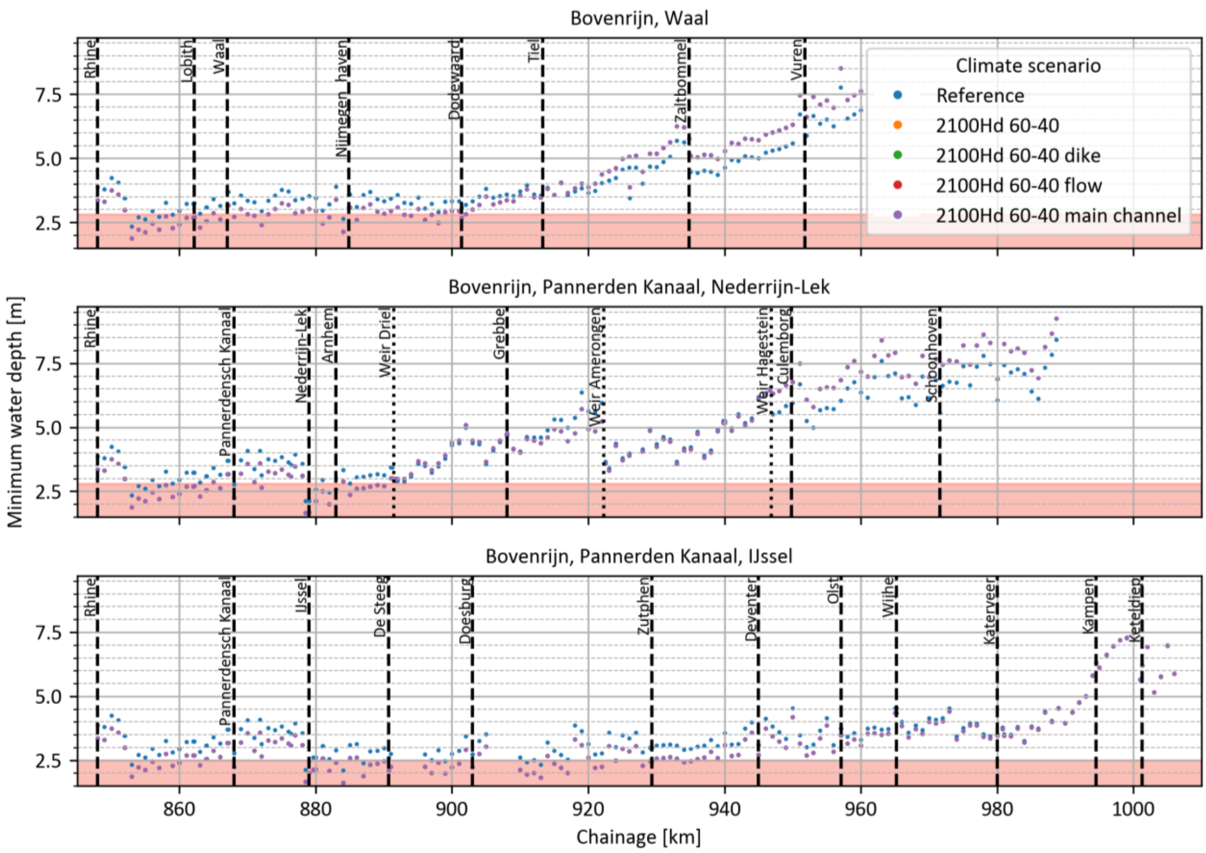

Figure 32: Minimum water depths in the Dutch Rhine branches for river widening measures. The red shaded area indicates the region where the agreed minimum water depths (2.80m Waal and Nederrijn-Lek, 2.50m IJssel) are not reached (Comité Infrastructuur en Milieu, 2021)

Table 19 presents the number of days on average on which the water depths do not exceed the minimum navigation depths. The table does show a decrease in the navigability of the river branches compared to the reference scenario. Moreover, the scenario in which the main channel is excavated by 6 metres shows a large increase in days on which the water depths do not exceed the critical navigation depth for the Waal and Nederrijn-Lek. Excavation of the IJssel will however ensure that the IJssel will be navigable all days throughout the year on average.

Table 19: Exceedances of the minimum navigation depths for river widening measures [average days per year]

	Reference	2100Hd 60-40	2100Hd 60-40 dike	2100Hd 60-40 flow	2100Hd 60-40 main channel
Water depth below 2m (Waal)	0	0	0	0	1
Water depth below 2.8m (Waal)	1	18	18	18	51
Water depth below 2m (NR-Lek)	0	3	3	3	177
Water depth below 2.8m (NR-Lek)	11	53	53	53	223
Water depth below 2m (IJssel)	0	4	4	4	0
Water depth below 2.5m (IJssel)	4	33	33	34	0
Maximum exceedance frequency	11	53	53	53	223

Table 20 adds on the expectations for the OLA in each of the river branches for the proposed river widening measures in the IJssel. The table shows that the lowering of the main channel causes a large shift in the discharge distribution towards the IJssel on the cost of discharge towards the Waal.

Table 20: Expectations for the Agreed Low Discharge under climate change and for river widening measures

	Reference [m^3/s]	2100Hd 60-40 [m^3/s]	2100Hd 60-40 dike [m^3/s]	2100Hd 60-40 flow [m^3/s]	2100Hd 60-40 main channel [m^3/s]
Lobith	1197	890	890	890	889
Waal	958	718	718	717	569
Nederrijn-Lek	28	14	14	13	11
IJssel	212	160	160	161	324

4.4.5 Evaluation

Table 21 shows the results of the MCA for the proposed river widening interventions. The table shows that the overall conveyance capacity is the largest when the main channel of the IJssel is excavated. Furthermore, a dike relocation is most beneficial for the habitats in the river system. Next, excavation of the main channel in the IJssel increases the average days on which the river is not navigable and is therefore the worst alternative for the transportation function. In summary, the alternatives dike relocation and lowering of the floodplain put the least pressure on the river functions. The next sections provide the results per function and scenario in detail.

Table 21: MCA performance river functions for river widening interventions (range sum rank [5(best), 20(worst)])

	Reference	2100Hd 60-40	Dike	Floodplain	Main channel
Conveyance	1	5	4	3	2
Water supply	1	3.5	3.5	3.5	3.5
Habitat	4	3	1	2	5
Transportation	1	3	3	3	5
Sum	7	14.5	11.5	11.5	15.5

5. Discussion

The study explored the performance of the river functions conveyance, water supply, habitat, and transportation for the KNMI reference climate scenario, and the climate scenarios 2100Md, 2100Mn, 2100Hd, and 2100Hn. Two alternative discharge distributions for the increasing design discharge have been proposed and investigated for the climate scenario 2100Hn. Also, three river widening measures have been implemented in the IJssel to compensate for the additional discharge. The 1D hydrodynamical model SOBEK is used. First, the key findings are summarized and compared to literature. Thereafter, the chapter discusses the limitations in methods and model used.

5.1 Comparison results to literature

The results on the river conveyance showed that an increase in design discharge and sea level rise will lead to an increase in the maximum water levels on all branches by 2100. The largest increase is expected in the Waal by 0.6m, followed in the Nederrijn-Lek by 0.5m and the least increase is expected in the IJssel by 0.4m. This amount is in line with the results of research conducted on the consequences of an increase in discharge on the water levels per river branch (Ubbels et al., 1999).

The results on water supply showed that the low discharges will be lower and occur more often in future climate scenarios compared to current climate. However, research by Van Brenk (2022) showed that climate scenarios showed higher discharges compared to the GRADE reference scenarios. An explanation for this difference can be attributed to the difference in the climate data and model used. The discharge with a return period of 10 years in the reference scenario is 900 m^3/s while in the research of van Brenk (2022) this is 650 m^3/s, this is a large difference. The values of the scenario 2100Mn show similarities with 2085GL, and the scenarios 2100Hn and 2100Md show similarities with 2085WH. Next, the low discharges with corresponding return periods show the largest change for a high emission scenario and a drier future climate. This is in line with the research of Van Brenk (2022).

The results suggest that nature will increase in all future climate scenarios compared to current climate and that nature in the system will benefit from an alternative discharge distribution as well as a dike relocation or floodplain excavation along the IJssel. The results show that deepening the summer bed of the river will put extra pressure on the nature. Literature agrees on the statement that climate change has a significant impact on habitat suitability of the riverine area. Moreover, the management of floodplains are more important than the changes in river discharges (Haasnoot et al., 2003). Literature also includes the return periods of drought in the floodplains and the expected fluctuations in the groundwater levels (Asselman & Klijn, 2022; Schulte & van Winden, 2024).

The results indicate that the agreed low discharges which are expected 20 days per year will decrease in a changing climate. The magnitude differs per climate scenario. In the most extreme scenario, the OLA will decrease from 1,197 to 890 m^3/s. However, the current OLA is 1,020 m^3/s. This is significantly lower than is calculated in this study (Van der Mark, 2022). Additionally, Van der Mark (2022) concluded that the OLA will drop to 850 m^3/s in 2085 according to the warm climate scenario. This is comparable to the results of this study.

5.2 Limitations in method

The study is subject the following limitations: the downstream boundary, the anticipated lake level rise and sea level rise, the feasibility of the proposed river widening measures, and the assessment of the alternative discharge distributions.

First, a fixed Q-h relation was used at the downstream boundaries in the model. However, the water levels at Krimpen aan de Lek and Hardinxveld depend on river discharge and sea level. Deltas have a damping effect on water levels from the sea. Therefore, the implementation of the sea level rise at the downstream boundaries is an overestimation of the effects of sea level rise at these points. A study by

Ylla Arbós et al. (2023), for example, used the empirical fit to the Bresse analytical solution of backwater equations to determine the effect of sea level rise at the downstream boundaries.

Second, the expected lake level rise of 0.6m in 2100 at the IJsselmeer were incorporated in the runs for the conveyance, but not in the time varying model runs used to quantify water supply, habitat, and transportation (Table 6). Consequently, this influences the results of the performance of these functions in the IJssel in future scenarios. Next, section *2.4.2 North Sea* elaborated on the possible strategies to cope with sea level rise. In this study, the current strategy protect closed is maintained in future scenarios. The strategies will not affect the discharge distribution but will impact the river functions as sea level rise does not influence the discharge distribution at the bifurcations but do influence the water levels downstream along the Nederrijn-Lek and the Waal.

Third, the study excluded morphological development in the Rhine branches. Literature has shown that the bed of the Rhine is coarsening over time (section 2.5 Bed level and roughness). Also, the Waal shows a degrading trend and that the peak flows of 1993 and 1995 mark a tipping point of the system, triggering an ongoing change in flow partitioning (Yossef & Sloff, 2011; Blom et al., 2024). The same model cross sections were used in all scenarios, the ongoing flow partitioning and bed degradation are, therefore, not included in future scenarios. If these processes were incorporated in the model, the discharge partitioning towards the Waal would have been larger in all climate scenario and the results of the performance for all functions would have been different.

Fourth, the study proposed large scale river widening interventions. The proposed dike relocation, floodplain excavation and main channel exaction raise significant considerations regarding their feasibility. While this study aimed to evaluate all three types, the scenario of main channel excavation by six metres is not realistic. It will not only pose challenges to morphological stability but will also lead to unforeseen ecological consequences.

The next sections highlight some of the limitations in the performance indicators from research question 1.

One of the performance indicators for habitat (the differences in water level) disregard the implications of water depths on the development stage of the present species (Asselman & Klijn, 2022; Schulte & van Winden, 2024). Thus, only including the difference in 95% and 5% water level in the comparison is a rough indication as a comprehensive metric for quantifying habitat.

Moreover, navigability of the river is linked to low flows conditions in this research. However, high flow periods present also challenges to inland navigation. Insufficient vertical clearance between the water and infrastructure can impede navigation during high flows. Additionally, high flow periods are often linked by larger bidirectional flow velocities, upstream transportation becomes more challenging. Incorporating the maximum bidirectional flow velocities as a performance indicator in the MCA will improve the assessment.

Last, the study evaluated the river performance of the alternative discharge distributions and the large-scale implementation of the river widening measures in the scenario 2100Hd. The alternative discharge distribution 60-40 scored better than the current discharge distribution. However, it is not investigated whether this is also the case for the other climate scenarios.

5.3 Limitations in model

The model employed in the study also introduced certain limitation. They are attributed to the model grid and the one dimensionality of the model as this limited the assessment of the river performances.

First, the distance between grid points in the model is 500 metres and the points in between are linearly interpolated. This spacing and method overlooks abrupt changes in floodplain widths and bed slope, which affect the conveyance of the river. Moreover, all cross sections in the model are symmetric while this is not the case for most river sections. For example, several cities are situated near the rivers. On these locations, the floodplain is wider on one side of the river than on the other side of the river. These bottlenecks are therefore not in detail included in the model.

Second, the method assessing the river function habitat simplifies the contribution for nature as it regards the floodplains as a flat rectangular plane. One value is found for the dynamics in the vertical water level, while the difference in water levels secondary channels in the floodplain deviates from other areas in the floodplain. Thus, the model cannot capture the diversity in habitat areas in the transverse direction of the flow. Moreover, the inundation in the floodplains is simplified. The water levels in the floodplains are calculated based on an if statement if the water levels are higher than the minor embankment. However, discharge may also overtop the minor embankment and flow through a small side channel in the floodplain and join the main channel more downstream. Moreover, filling the floodplains result in a bend in the Q-h relationship at a point in the river, however the 1D model is not able to reproduce this bend while a 2D is able to (Kosters et al., 2022).

In addition, SOBEK 3 is a one-dimensional model. This means that the discharges and flow velocities are only calculated in one direction. The model thus is not able to capture the flow velocities in the transverse direction. High transverse flow velocities increase the difficulty for navigation.

Lastly, the implementation of the alternative discharge distribution must be discussed. The hydraulic control structures Hondbroeksche Pleij and Pannerden are not included in the model. These structures were built to be able to influence the flow distribution during high flows. The flow area at these hydraulic control structures can be adjusted each year. Thus, this cannot be adjusted dynamically like the weir Driel influences the flow distribution at low flows. Therefore, in this study other measures are incorporated to redistribute the discharge. These measures like a change in main channel roughness and change of the geometry of a branch change the discharge distribution, however, this is also because the measures affect the water levels. The water levels are used in the assessment to quantify the conveyance, habitat, and transportation.

6. Conclusions and recommendations

The objective of the study was to explore the discharge distribution over the Dutch Rhine branches for climate scenarios and how they contribute to the performance of river functions. This chapter gives the main conclusions per research question and one overarching conclusion. The last section of this chapter gives recommendations for further research.

6.1 Conclusions

RQ1: Which performance indicators can be used to assess the performance of river functions along the Dutch Rhine branches under time-varying flow conditions?

Through literature research and research steps adapted from Wieringa (2014), a MCA with performance indicators per river function was set up. The MCA is used in the second and third research questions. Table 22 shows the indicators on which the four river functions are quantified.

Table 22: Performance indicators to quantify the rivers functions

River function	Performance indicators
Conveyance	Branch length [m] Water level increase [Δm]
Water supply	○ 1-day minimum yearly discharge [m^3/s] ○ 1-week minimum yearly discharge [m^3/s] ○ 1-month minimum yearly discharge [m^3/s] ○ 3-month minimum yearly discharge [m^3/s] ○ 6-month minimum yearly discharge [m^3/s] Return period low flow
Habitat	Area flood plain (Length branch * floodplain width) [m^2] Floodplain dynamics (5% water depth in the floodplains - 95% water depth in the floodplains) [Δm]
Transportation	Critical navigation depth [m] Exceedance minimum water depth [days/year] OLA [m^3/s]

In this study, an equal weighted ranking MCA has been used as the relative importance of the considered river functions is difficult to quantify objectively due to their differing natures and stakeholders' perspective. This ensures that no function is prioritized over another in the conclusions.

RQ2: In what ways will climate change affect the conveyance, water supply, habitat, and transportation in the Dutch Rhine system by the year 2100?

The second research question explored how the expected river discharges at Lobith for several climate scenarios in 2100 compared to the current river discharges in the MCA on the Rhine branches. Table 11 is again presented below and shows the conclusions for this research question.

Table 11: MCA performance river functions in climate scenarios (range sum rank [5(best),20 (worst)])

	Reference	2100Md	2100Mn	2100Hd	2100Hn
Conveyance	1	2.5	2.5	4.5	4.5
Water supply	1	3.5	2	5	3.5
Habitat	5	4	2	3	1
Transportation	1	3.5	2	5	3.5
Sum	8	13.5	8.5	17.5	12.5

First, it was found that the conveyance of the river will be faced with increased water levels along all river branches. There is a difference in increase in maximum water level rise between the medium and high emission scenarios for the difference in the rate of sea level rise in these scenarios. An increase in discharge shows the largest increase in water levels in the Waal followed by the Nederrijn-Lek. The water levels in the IJssel increase the least in both emission scenarios.

Second, dry periods in the Dutch system are characterizable by the prolonged durations of 7-day or longer droughts instead of 1-day peak minimum flows. In all climate scenarios, the low flows, and the return periods decrease. The largest decrease is observed in the scenario 2100Hd. Furthermore, the 180-day discharge show a larger variability in the climate scenarios compared to the reference scenario, especially in the wet scenarios.

Third, the results showed that the habitat suitability of the floodplains increase in all climate scenarios. Furthermore, the total floodplain dynamics are largest along the IJssel.

Fourth, the results showed that the minimum navigation depths per year will be exceeded more often. Inland navigation will be most hindered in the high emission scenarios and especially in combination with the dry climate scenarios. This is attributed due to the large decrease in OLA.

RQ3: What are alternative discharge distributions and how do these affect the conveyance, water supply, habitat, and transportation in the Dutch Rhine system by the year 2100?

The third research question explored how the performance of the river functions change per river branch for the current discharge distribution. Table 16 is again presented below and shows the conclusions for this research question.

Table 16: MCA performance river functions in alternative discharge distributions (range sum rank [4(best), 16(worst)])

	Reference	2100Hd	80-20	60-40
Conveyance	1	4	3	2
Water supply	1	3	3	3
Habitat	4	3	2	1
Transportation	1	2.5	4	2.5
Sum	7	12.5	12	8.5

First, from now till 2100, the current design discharge is expected to change by 2,000 m^3/s. This discharge can be distributed following the agreements, or 80% to the Waal and 20% to the IJssel or 60% to the Waal and 40% to the IJssel.

The increase in design discharge will increase the maximum water levels in the Dutch Rhine branches. However, the results have shown that an alternative discharge distribution in which the Nederrijn-Lek is spared, the water levels on the Nederrijn-Lek will increase less.

Third, in comparing the fresh water supply in the alternative discharge distributions, it is shown that the low flows and return periods per river branch are affected by an alternative discharge distribution. However, the Dutch Rhine system total discharge is the same. Therefore, the future climate scenarios were assigned an equal rank and score worse than the reference climate.

Fourth, according to the results, the alternative discharge distributions 60-40 and 80-20 do have a good influence on the nature. Also, relocating the dike or excavating the floodplain in the IJssel show a large increase in nature. However, an excavation of the main channel does negatively affect the total river nature.

Last, the discharge distribution 80-20 shows an increase in non-navigable days per year compared to the current discharge distribution. The distribution 60-40 however showed a decrease in non-navigable days in the river system. Furthermore, a dike relocation and excavation of the floodplain did not show change. Excavating the main channel of the IJssel will put a lot of pressure on the Dutch navigation sector as the Nederrijn-Lek will be non-navigable for many days in the year.

RQ4: River widening measures can be used to account for the additional discharge on a river branch resulting from the proposed alternative discharge distributions. How do these affect the conveyance, water supply, habitat, and transportation in the Dutch Rhine system by the year 2100?

The fourth research question explored how the performance of the river functions change for implementation of three river widening measures in the alternative discharge distribution 60-40. A dike relocation, excavation of the floodplain, and excavation of the main channel are implemented to create additional flow area in the IJssel. Table 16 is again presented below and shows the conclusions for this research question.

Table 16: MCA performance river functions for river widening interventions (range sum rank [5(best), 20(worst)])

	Reference	2100Hd 60-40	Dike	Floodplain	Main channel
Conveyance	1	5	4	3	2
Water supply	1	3.5	3.5	3.5	3.5
Habitat	4	3	1	2	5
Transportation	1	3	3	3	5
Sum	7	14.5	11.5	11.5	15.5

First, an increase in design discharge will increase the maximum levels in the Dutch Rhine branches. Implementation a large-scale river widening interventions is beneficial for the conveyance of the river.

Additionally, the fresh water supply for river widening measures was assigned an equal rank in the MCA as the total discharge in the system was not changed.

Third, the dike relocation and excavation of the floodplain are beneficial for the habitat suitability of the river function as this creates additional flow area which is a rough estimate for the ecological status of the river system. Moreover, excavating the main channel by 6 metres will have a negative effect on the habitats in the river system for the water will be discharged via the main channel and the dynamics in the floodplains will decrease.

Last, the dike relocation and excavation of the floodplains show no change for the transportation function of the river. This is because these large-scale interventions only affect the flows above bankfull discharge. Moreover, excavation of the main channel has probably a negative effect on the transportation, however, this is probably the result of the changed discharge distribution rather than the river widening measure.

Aim – To explore the desired discharge distribution of the Dutch Rhine at the bifurcations Pannerdensche Kop and IJsselkop at Lobith in 2100 for the KNMI climate scenarios and how they contribute to the performance of river

Climate change places increasing pressure on the river functions conveyance, habitat, and transportation. However, the water level dynamics in the floodplains of the rivers do increase which is a metric for the development of nature but it is not a guarantee.

The design discharge will increase from 16,000 m^3/s to 18,000 m^3/s in 2100. Options are investigated for this discharge distribution for the current distribution, 80% Waal – 20% IJssel and 60% Waal – 40% IJssel. The alternative discharge distribution put less pressure on the river functions, they put equal pressure on the river functions in the case of equal ranking. However, the ranking per functions differs, therefore it could be questioned whether conveyance or habitat is more important in the Dutch Rhine system.

Last, three river widening functions have been investigated. The performance indicators in the MCA showed that the excavation of the main channel will have a negative effect on the river functions. However, a dike relocation and excavation of the floodplain show great potential in alleviating the pressure on the river functions.

6.2 Recommendations

6.2.1 Recommendations for policy makers

The results showed that alternating the discharge distribution of the additional 2,000 m^3/s to the partition 60-40 yields a better performance of the overall conveyance, habitat, and transportation than the agreed discharge distribution or the 80-20 distribution. With this option, the Lek will be spared as advised by (Top & ENW (2021) and more discharge will be directed to the relatively wide IJssel. It is however very important to evaluate both the technical feasibility of this alternative and to evaluate the effects in depth.

The second recommendation is allocating enough space for the river in the zoning plan. The results have shown that a dike relocation and lowering of the floodplain do have positive impacts on the conveyance, habitat and transportation in the Dutch Rhine system. Therefore, it is both important to not build on all land adjacent to the river, but also not to build in the floodplains as an intervention in the floodplain has also shown to benefit the river functions.

6.2.2 Recommendations for future research

Last, future research in water engineering must consider the most recent research into climate change and a large range in scenarios. The results showed that the large uncertainty in climate change also results in a large variability in effects on the performance of the river functions for the several climate scenarios.

This study did not look at the technical feasibility of both the proposed discharge distributions and the large-scale river widening implementations. It is therefore advised to explore the technical feasibility of another discharge distribution as the feasibility on large scale river interventions in the IJssel. Also, it should be investigated whether multiple small river interventions can also yield the same result.

The results showed that of the three discharge distributions, the 60-40 puts the least pressure on the river functions in case of an equal ranking. It is important to further examine the implications of the proposed discharge distribution. For example, the morphological impacts should be investigated to be able to conclude on if the proposed discharge distribution results in a stable flow partitioning.

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Appendices

Appendix A: Determination warm up period

The warm up period of the model is four days based on an upstream discharge at Dornick of 18,000 m^3/s. Figure A-33 shows the discharges in time in the model and Figure A-34 shows the water level on seven locations in time. The discharges and water levels are increasing over a period of four days and are constant after.

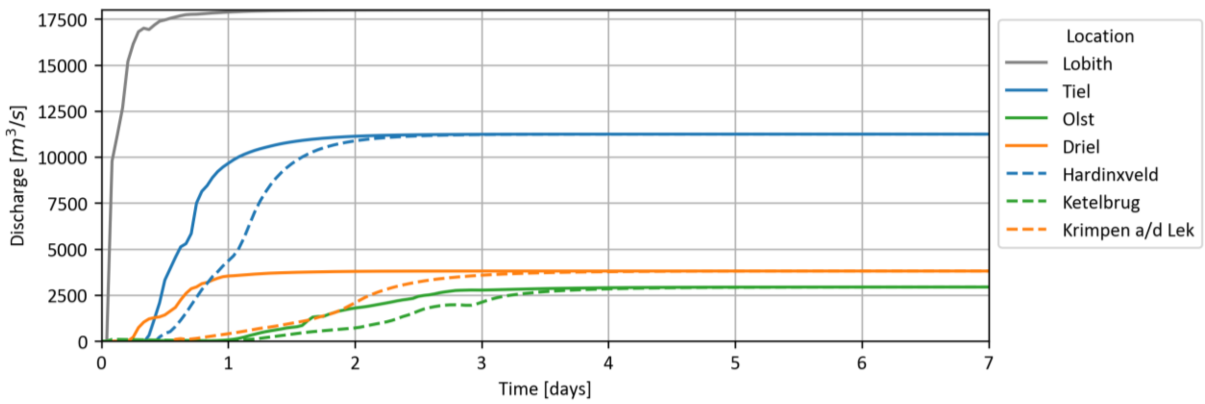

Figure A-33: Discharge over time for a constant upstream discharge of 18,000 m^3/s

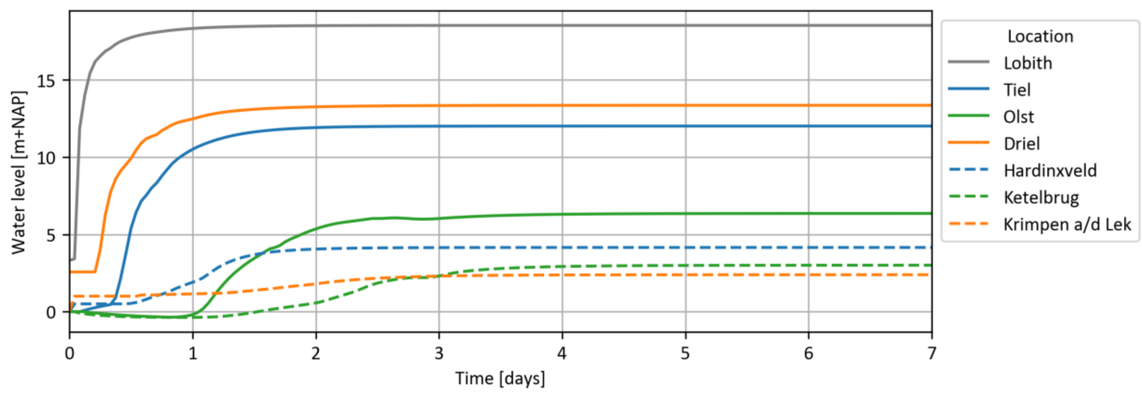

Figure A-34: Water level over time for a constant upstream discharge of 18,000 m^3/s

Appendix B: Altering the discharge distribution

For research question 3, an alternative discharge distribution is obtained by changing the model. Currently, the design discharge is 16,000 m^3/s. In 2100, due to climate change the design discharge is increased to 18,000 m^3/s (Staf Deltacommissaris, 2023). It is investigated how this discharge should be distributed for the additional 2,000 m^3/s. From the policy document ''Beleid Lek Ontzien'', report ''Meer afvoer veilig van Lobith naar Zee'' and an interview with Frans Klijn is concluded that the additional discharge should not be directed to the Nederrijn-Lek but distributed over the IJssel and the Waal (Klijn et al., 2024; van den Top & ENW, 2021).

In this research, 60% of the additional discharge (1,200 m^3/s) will be directed to the Waal and 40% of the additional discharge (800 m^3/s) will be directed to the IJssel. Table A-23 provides an overview of the distribution of the design discharge in the reference scenario, in the climate scenario and the goal.

Table A-23: Discharge distribution in SOBEK for an upstream discharge of 16,000 m³/s, 18,000 m³/s and the proposed discharge distribution for an upstream discharge of 18,000 m³/s

	Discharge [m^3/s]	Percentage [%]
Reference 16,000 m^3/s		
Waal	10,117	63
Nederrijn	3,359	21
IJssel	2,525	16
2100 Climate 18,000 m^3/s		
Waal	11,250	63
Nederrijn	3,809	21
IJssel	2,941	16
2100 Climate 18,000 m^3/s (60-40)		
Waal	11,317	63
Nederrijn	3,359	19
IJssel	3,325	18
2100 Climate 18,000 m^3/s (80-20)		
Waal	11,717	65
Nederrijn	3,359	19
IJssel	2,925	16

The roughness of the main channel has been changed by trial and error to obtain the required discharge distribution. It was found that the discharge distribution is more sensitive to a change in the roughness in the main channel than to a change in the floodplain roughness or a change in the steering policy of weir Driel. For this reason, only the roughness in the main channels were altered to find the proposed discharge distribution.

From Table A-24 can be concluded that a change in the main channel roughness has a larger effect for a branch with a larger width and thus larger flow width. Considering the differences in branch width, decreasing the roughness in one channel leads to approximately the same result as increasing the roughness in the other bifurcate.

Literature has shown that the main channel of the rivers are coarsening over time (Ylla Arbós et al., 2023). Therefore, it is expected that the roughness of the bifurcates will increase in time and therefore the preferred alternative is the alternative where the roughness increases.

To conclude, Table A-24 presents the results for obtaining the desired discharge distribution by trial and error. In the situation where the design discharge increases with 2,000 m^3/s and this is distributed 60-40 over the Waal and IJssel, the main channel of the Pannerdensch Kanaal should be smoothed and the main channel of the Nederrijn-Lek rougher.

First, the range of the Manning roughness in the model for Pannerdensch Kanaal was [0.025-0.070]. This corresponds with coarse sand, gravel, cobble and boulder (Arcement & Schneider, 1989). If the roughness decreases with 10%, the sediment types will also include sand. Next, the range of the Manning roughness in the model for the Nederrijn-Lek was [0.016-0.044]. This corresponds with sand and gravel. If the roughness does increase by 90%, the sediment type in the Nederrijn-Lek would consist of coarse sand, gravel, cobble, and boulder.

Table A-24: Discharge distribution for several situations in which the roughness in the main channel is changed

	Discharge [m³/s]	Percentage [%]
Roughness main channel Waal - 50%		
Waal	11,717	65
Nederrijn	3,566	20
IJssel	2,941	15
Roughness main channel Pannerdensch Kanaal +50%		
Waal	11,532	64
Nederrijn	3,662	20
IJssel	2,806	16
Roughness main channel Waal -50% and Roughness main channel IJssel -50%		
Waal	11,643	65
Nederrijn	3,356	19
IJssel	3,001	17
Roughness main channel Pannerdensch Kanaal +50% and Roughness main channel Nederrijn-Lek +50%		
Waal	11,532	64
Nederrijn	3,662	20
IJssel	2,806	16
Roughness main channel Waal -20% and Roughness main channel IJssel -20%		
Waal	11,422	63
Nederrijn	3,620	20
IJssel	2,959	16
Roughness main channel Pannerdensch Kanaal +10% and Roughness main channel Nederrijn-Lek +50%		
Waal	11,421	63
Nederrijn	3,601	20
IJssel	2,978	17
Roughness main channel Pannerdensch Kanaal +5% and Roughness main channel Nederrijn-Lek +70%		
Waal	11,411	63
Nederrijn	3,390	19
IJssel	3,199	18
Roughness main channel Nederrijn-Lek +70%		
Waal	11,378	63
Nederrijn	3,407	19
IJssel	3,215	18
Roughness main channel Pannerdensch Kanaal -10% and Roughness main channel Nederrijn-Lek +90%		
Waal	11,333	63
Nederrijn	3,363	19
IJssel	3,304	18
Roughness main channel Pannerdensch Kanaal +80% and Roughness main channel Nederrijn-Lek +40%		
Waal	11,701	65
Nederrijn	3,355	19
IJssel	2,944	16

Appendix C: Discharge in the climate scenarios

Figure A-35 and Figure A-36 show the probability density function, cumulative density function of the discharge series, and the average, minimum and maximum discharges throughout the year for the synthetic discharge series from (Deltares et al., 2024).

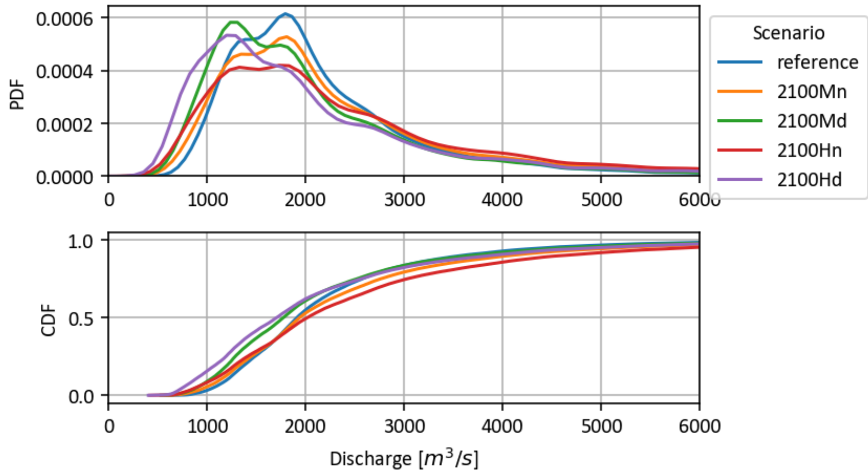

Figure A-35: Probability Density Function and cumulative Density Function of the discharge at Lobith in the reference and climate scenarios

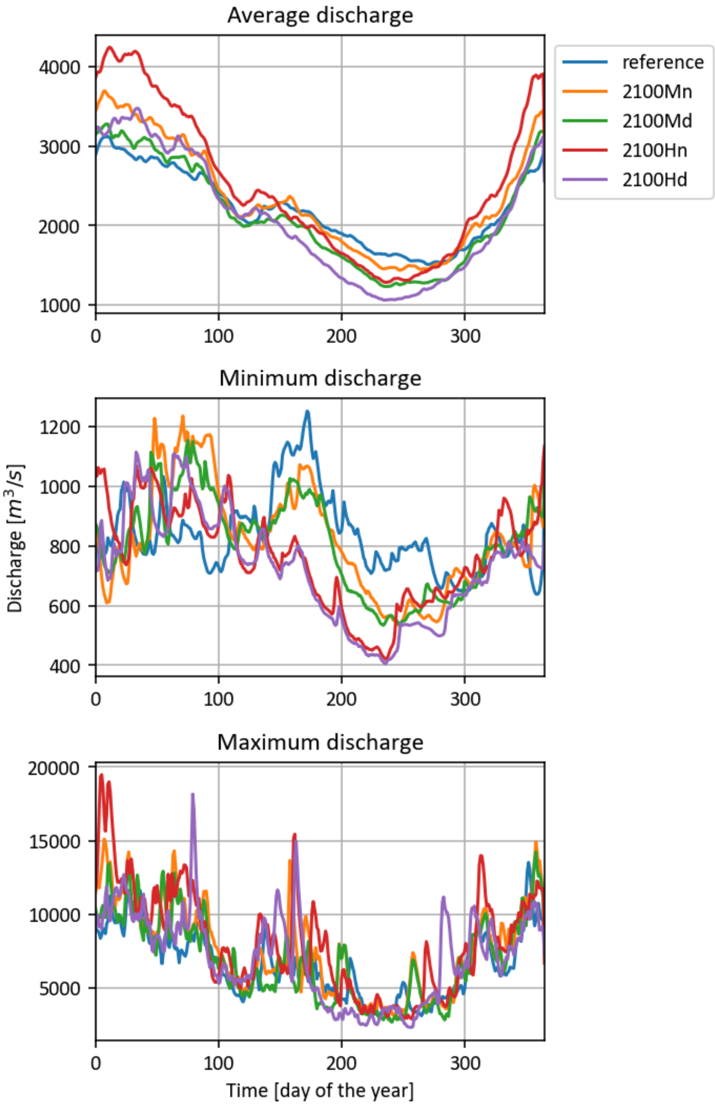

Figure A-36: Average, minimum and maximum discharge in Lobith for the climate scenarios (X-axis January till December)

Appendix D: Discharge distribution over the complete flow range

This section presents the distribution of the discharge at Lobith over the branches; the Waal (solid line), the Nederrijn-Lek (dotted line), and the IJssel (dashed line) for the full flow range.

Figure A-37 presents the discharge distribution in the reference scenario and the medium and high climate scenarios. This Figure shows that the discharge distribution is not affected by sea level rise and lake level rise.

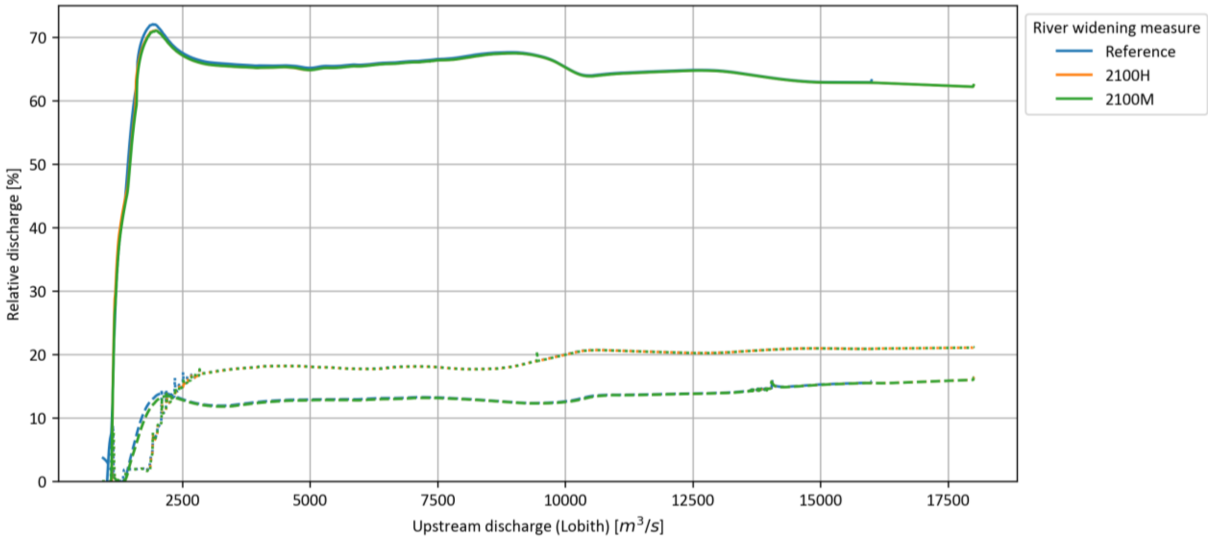

Figure A-37: Discharge distribution over the complete flow range for the climate scenarios

Figure A-38 shows the discharge distribution for the proposed alternative discharge distributions. In these scenarios, the expected additional discharge of 2,000 m^3/s is distributed over the Waal and IJssel, and the Nederrijn-Lek is spared. In the scenario 80-20, the relative discharge over the complete flow range is increased. The scenario 60-40 shows a large increase in the relative discharge toward the IJssel.

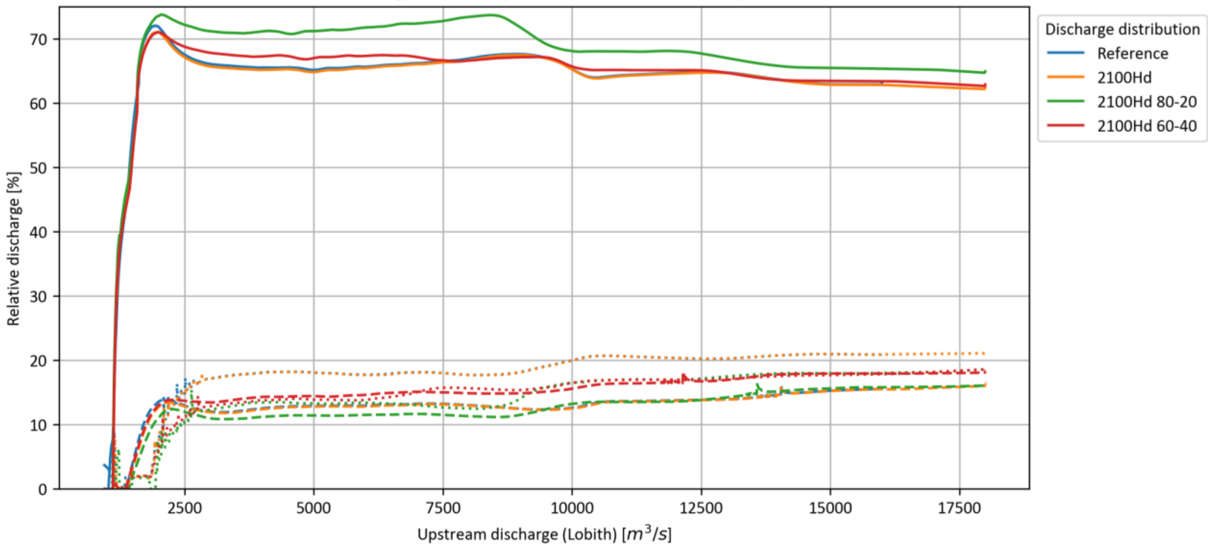

Figure A-38: Discharge distribution over the Dutch Rhine bifurcates for alternative discharge distributions

Figure A-39 shows the relative discharge distribution in the scenario where the additional discharge towards the IJssel is compensated by extra flow area. The scenario in which the main channel is excavated by 6 metres shows a large change in the relative discharge distribution especially in the lower flow regime. Additionally, the scenarios dike relocation and floodplain excavation show differences in the higher flow regimes. The bankfull discharge of the IJssel is about 700 m^3/s (Table 1). Consequently, a dike relocation and floodplain excavation will thus only affect the discharge distribution when the discharge in the IJssel is larger than this threshold.

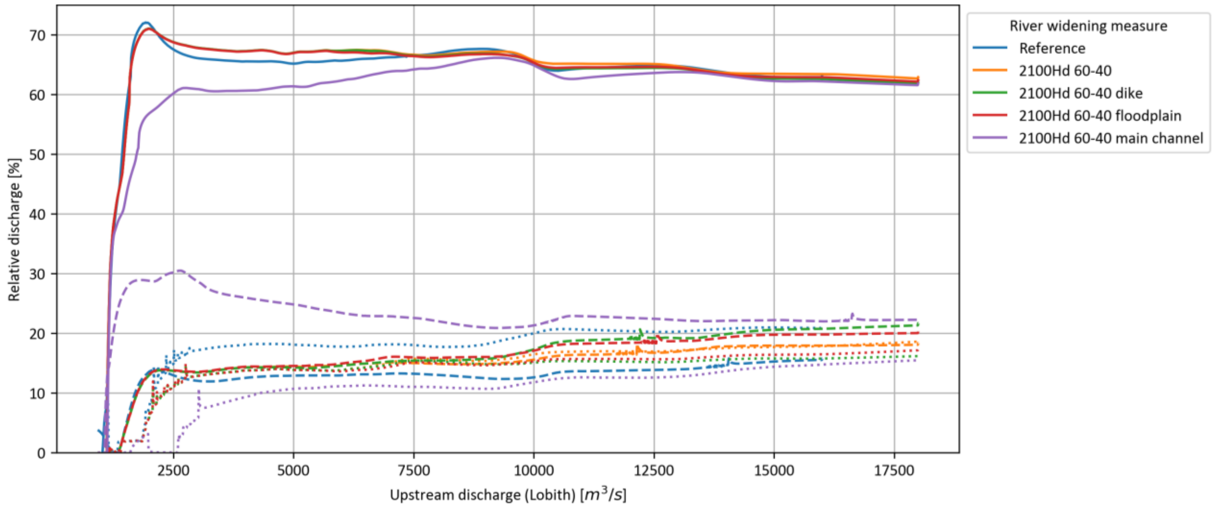

Figure A-39: Discharge distribution over the Dutch Rhine bifurcates for the proposed alternative discharge distribution and river widening measures