# Canalization of the River Waal

## Evaluating the Impact of Climate Change and Assessing the Necessity of Measures

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,

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Cover: Rotterdam at sunrise (Own work, 2018)

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# Preface

This thesis concludes my Master in Hydraulic Engineering at the faculty of Civil Engineering and Geosciences at the TU Delft. I feel grateful for having the opportunity to finish my study on the topic of inland shipping, which is important to me personally. A word of thanks is herein to be made to Otto Koedijk, who as lecturer at the TU Delft inspired me to approach inland shipping from an academic perspective. Later, in his position at Rijkswaterstaat, he created the thesis topic that eventually would be my graduation project.

Having said that, I would like to thank Rijkswaterstaat for having me as an intern and my colleagues for their support throughout the process. It was insightful to be introduced to the professional field for the first time and see how a government agency works. I would especially like to thank Jourian Ligtenberg and Frederik Vinke, for daily supervision of my project and as discussion partners, from which I learned a lot. Furthermore I want to express my gratitude to Mark van Koningsveld and Mark Voorendt as supervisor and committee members from the TU Delft. I am thankful to both for their enthusiasm and feedback throughout the process.

Lastly, I want to thank my beloved ones for their continuous support throughout my studies. Without them this wouldn't have been possible. I look forward to the adventures, opportunities and challenges ahead of me.

*Laurens Pomp*
*Delft, September 2024*

# Abstract

The Dutch system of waterways, of which the River Waal is the largest, allows for transport of cargo via inland navigation. Inland navigation as a transport mode contributes to the Dutch GDP and is indispensable for the Dutch strategic position in international world trade. Because inland navigation is river-based, it is dependent on natural conditions. Recent periods of drought, such as in 2018, have led to major financial impacts in the Netherlands and Germany. Due to climate change, periods of drought are expected to be more frequent, longer and more extreme in the future. Given the importance of inland navigation, measures are sought after to counteract these effects of climate change. Canalization of the River Waal is a last resort infrastructural measure to gain control over water levels on the river. To date, it is unclear whether climate change will eventually make it necessary to canalize the river for the benefit of inland navigation. In addition, it is unknown on the basis of what considerations such a decision should be made. This research attempts to answer these questions.

To investigate the necessity of canalization due to climate change, first the impact of climate change on inland shipping is determined on three different levels. First the hydrological development including occurrence of (low) discharges and corresponding water depths. Second the impact on individual vessel's loaded draught and loading rate, based on least available water depths on the River Waal in climate scenarios. Third the corridor cargo transport capacity, based on the occurrence of (low) discharges and the cargo transport performance of inland shipping in the past 10 years during similar discharge events. The development of these elements are the considerations in the debate on necessity of canalization of the River Waal from a shipping perspective. Whether these developments support the necessity of canalization is studied by means of limits which, if exceeded, may argue canalization. For the river's navigation function, requirements on navigability were identified based on prevailing international waterway management regulations (CCNR and TEN-T) as well as on previous Dutch canalization projects on the River Meuse and Lower-Rhine. The limits are projected on the analysed future development of the River Waal under climate change, to identify if and when they are met.

The hydrological development of the River Waal is assessed based on future discharge projections at Lobith under climate change. A range in scenario's is described, with a low emission and wet climate scenario 'Ln' on one side and a high emission and dry scenario 'Hd' on the other. In an Ln scenario, the future occurrence of days with low discharges (<1800 $m^3/s$) on average per year is similar to that of the reference scenario (past 30 years, 1990 - 2020). In contrast, an Hd scenario shows a steady increase in the days of low discharges until 2100 after which the trend stabilizes. Extreme low discharges <600 $m^3/s$ appear. Furthermore, the lowest annual discharge (generally speaking during summer) lowers to 1000 $m^3/s$ by 2150, which is 750 $m^3/s$ lower than in the reference scenario.

At Rhine Kilometer 885 near Nijmegen the lowest water depths occur. In an Ln scenario the number of days with low water depth (<2.8 meter) is similar to the reference scenario with 40 days, independent of time. In the Hd scenario the number of days with low water depth increases where <2.8 meter occurs up to 3x more as in the reference scenario and outliers of <1.6 meters appear, up to 10 days. The long term average lowest discharge during the year drops from 3.5 meters in the reference scenario to 3 meters in 2050 and <2.5 meters after 2100.

The analysis of discharges and water depths is used to describe the development of the transport function of the River Waal. The location with the lowest water depth on a route of a vessel determines the loading rate. The combination of loading rate and active fleet determines the total amount of cargo carried on a corridor. In an Ln scenario, there is little deviation from the reference scenario, but nonetheless, a large vessel 135x17.4 meter CEMT Class VI+ has a restricted loading rate for 7 months per year with a minimum of 50% of the maximum vessel loading capacity. In an Hd scenario the loading rate of vessels decreases and the period lasts longer. For a most common vessel 110x11.4 meter CEMT Class Va, an annual average minimum is observed of 60% in 2050 to 40% in 2150. The duration of restricted loading doubles and the steepest decline is observed between 2050 and 2100.

Based on historical performance (2010-2020) of inland navigation, linked to the occurrence of discharges, a first-order indication of the development of transport performance over the River Waal corridor under climate change is made. No absolute numbers can be determined on this basis, but a sense of trends can be obtained. Assuming no changes in the current fleet, the annual total weight that can be transported will decrease regardless of the climate scenario. The severity does depend on the climate scenario. Zooming in on cargo type does show a varying picture, where for dry bulk cargo there is an annual decrease of -3.0% cargo transport capacity in the most severe 2150 Hd scenario, while for liquid bulk cargo there is a steady decrease to -12.0% cargo transport capacity in 2150. This difference is explained by the number of trips made, where for dry cargo this theoretically rises to +25% in 2150 Hd, while for liquid cargo it can only increase +3%. Redundancy in the fleet can thus partially counteract the effects of climate change.

To reason the necessity of canalization, limits on navigability are identified, based on current navigational requirements and previous canalization practice. For the river's transport function, no clear limits where found, as a result of which no development could be identified that necessitates canalization. There are two regulations that apply to the navigability of the River Waal. TEN-T is a transport policy of the European Union and sets requirements for the quality of its network. On the River Waal, a guaranteed draught of 2.5 meters is required year-round. This is not met in the present (20 days undershoot in an average year) and will not improve in any climate scenario (up to 80 days in 2150 Hd). The CCNR is an association of five countries that is committed to the safety and interests of inland navigation on the Rhine. CCNR guidelines are leading for river management in the Netherlands. On the River Waal, 'OLR' (Agreed Low River Level) conditions require a water depth of 2.8 meters in the fairway, per definition a water depth that is undershot on average 20 days a year. This is not met in the present (40 days undershoot in an average year) and will not improve in any scenario in the future (>100 days in 2150 Hd).

Conditions on the River Meuse (1920) and Lower-Rhine (1960) before canalization were projected onto the present River Waal. If, as on the River Meuse, one want to accommodate a normative vessel CEMT VIc 6-barge push barge, there is at least 180 days of loading rate restrictions, now and in the future under all considered climate scenarios. The Lower-Rhine is canalized for the purpose of navigability of Lower-Rhine and River IJssel and to control freshwater distribution. Both Lower-Rhine and River IJssel did not meet the navigability requirements set at the time. The River Waal also does not meet its current stated navigability requirements (CCNR 2.8m: 40 days), but even in the extreme 2150 Hd scenario this is roughly only half (100) of the days as on the River IJssel and Lower-Rhine (2.7m: 190 and 225). The navigability requirements of that time did fit better with the draught of a most common vessel. The current most common vessel 110x11.4 meter CEMT Va experiences as many days (160) of insufficient water depth as on the River IJssel in all dry climate scenarios between 2033 and 2050. Compared to the Lower-Rhine, this is the case in an Hd scenario between 2050 and 2100 (180 days).

This research concludes is that from the inland shipping perspective there are two overarching considerations in the decision on canalization of the River Waal, the perspective of the navigability of the river and the perspective of it's capacity to allow cargo transport. The navigability, described in (low) discharges and water depth, deteriorates due to climate change. Clear thresholds as TEN-T and CCNR requirements are not met and there is not sufficient water depth to accommodate the normative vessel CEMT VI+ year round. Taking action in the form of canalization would guarantee these requirements to be met now and in the future. Uncertainty in climate conditions causes that no clear predictions can be given on how severe the impact on the transport function is. Furthermore the transport function is more complex, since it describes a spread of individual vessels, different cargo types and a corridor. It is not inconceivable that adjustments within the 'transport function', like alterations in the logistical chain or improvement of the fleet, could (partially) counteract the negative impacts of climate change, which subvert the necessity of canalization. Apart from that, this research concluded that for the transport function there are no uniform quantified goals. Goals mentioned are the added value to Dutch GDP, the role in other sectors, the model shift and (military) strategic. Since these goals are broadly formulated, but not well quantified, it is difficult to identify limits in the performance of the system under climate change which could argue the necessity of canalization. To make a deliberate decision on canalization based on it's capacity to allow cargo transport, it should first be defined and quantified what achievements should be made with the River Waal.

# Samenvatting

Het Nederlandse systeem van waterwegen, waarvan de rivier de Waal de grootste is, maakt vervoer van lading via de binnenvaart mogelijk. De binnenvaart draagt als transportwijze bij aan het Nederlandse BBP en is onmisbaar voor de Nederlandse strategische positie in de internationale wereldhandel. Omdat de binnenvaart gebruik maakt van rivieren, is zij afhankelijk van natuurlijke omstandigheden. Recente periodes van droogte, zoals in 2018, hebben geleid tot grote financiële gevolgen in Nederland en Duitsland. Door klimaatverandering zullen periodes van droogte in de toekomst naar verwachting vaker voorkomen, langer duren en extremer zijn. Gezien het belang van de binnenvaart is gezocht naar maatregelen om deze effecten van klimaatverandering tegen te gaan. Kanalisatie van de Waal is een laatste infrastructurele maatregel om controle te krijgen over de waterstanden op de rivier. Tot op heden is het onduidelijk of klimaatverandering het noodzakelijk zal maken om de rivier te kanaliseren ten behoeve van de binnenvaart. Bovendien is het onbekend op basis van welke overwegingen een dergelijke beslissing moet worden genomen. Dit onderzoek probeert deze vragen te beantwoorden.

Om de noodzaak van kanalisatie als gevolg van klimaatverandering te onderzoeken, is eerst de invloed van klimaatverandering op de binnenvaart op drie verschillende niveaus bepaald. Ten eerste de hydrologische ontwikkeling, inclusief het optreden van (lage) afvoeren en bijbehorende waterdieptes. Ten tweede het effect op de diepgang en beladingsgraad van een individueel schip, gebaseerd op de minst beschikbare waterdieptes op de Waal in verschillende klimaatscenario's. Ten derde de vervoerscapaciteit van de corridor, gebaseerd op het optreden van (lage) afvoeren en de vervoersprestaties van de binnenvaart in de afgelopen 10 jaar tijdens vergelijkbare afvoeren. De ontwikkeling van al deze elementen vormen de overwegingen in de discussie over de noodzaak van kanalisatie van de Waal vanuit scheepvaartperspectief. Of deze ontwikkelingen de noodzaak van kanalisatie ondersteunen, is onderzocht aan de hand van grenzen die, als ze worden overschreden, kunnen pleiten voor kanalisatie. Voor de navigatiefunctie van de rivier zijn de vereisten voor bevaarbaarheid geïdentificeerd op basis van de geldende internationale regelgeving voor vaarwegbeheer (CCR en TEN-T) en op basis van eerdere Nederlandse kanalisatieprojecten op de Maas en de Nederrijn. De grenzen worden geprojecteerd op de geanalyseerde toekomstige ontwikkeling van de Waal onder invloed van klimaatverandering, om vast te stellen of en wanneer er aan de grenzen wordt voldaan.

De hydrologische ontwikkeling van de Waal is beoordeeld op basis van toekomstige afvoerprojecties bij Lobith onder klimaatverandering. Een reeks scenario's is beschreven, met aan de ene kant een lage-emissie en nat klimaatscenario 'Ln' en aan de andere kant een hoge-emissie en droog scenario 'Hd'. In een Ln-scenario is het toekomstige aantal dagen met lage afvoeren (<1800 $m^3/s$) gemiddeld per jaar vergelijkbaar met dat van het referentiescenario (afgelopen 30 jaar, 1990 - 2020). Daarentegen laat een Hd-scenario een gestage toename zien van het aantal dagen met lage afvoeren tot het jaar 2100, waarna de trend stabiliseert. Er treden daarbij extreme lage afvoeren <600 $m^3/s$ op. Bovendien daalt de laagste jaarlijkse afvoer (over het algemeen in de zomer) tot 1000 $m^3/s$ in 2150, wat 750 $m^3/s$ lager is dan in het referentiescenario.

Bij Rijnkilometer 885 bij Nijmegen treden de laagste waterdieptes op. In een Ln-scenario is het aantal dagen met lage waterdiepte (<2,8 meter) vergelijkbaar met het referentiescenario (40 dagen), onafhankelijk van de tijd. In het Hd-scenario neemt het aantal dagen met lage waterdiepte toe waarbij <2,8 meter tot 3x meer voorkomt als in het referentiescenario en uitschieters van <1,6 meter komen voor, tot wel 10 dagen per jaar. De langetermijngemiddelde laagste afvoer gedurende het jaar daalt van 3,5 meter in het referentiescenario naar 3 meter in 2050 en <2,5 meter na 2100.

De analyse van het optreden van afvoeren en waterdieptes is gebruikt om de ontwikkeling van de transportfunctie van de Waal te beschrijven. De locatie met de laagste beschikbare waterdiepte op een route van een schip bepaalt de beladingsgraad. De combinatie van beladingsgraad en actieve vloot bepaalt de totale hoeveelheid lading die op een corridor wordt vervoerd. In een Ln-scenario is er weinig afwijking van het referentiescenario, maar toch heeft een groot Rijnschip van 135x17,4 meter

CEMT klasse VI+ een beperkte beladingsgraad gedurende 7 maanden per jaar met een minimum van 50% van de maximale scheepsbeladingscapaciteit. In een Hd-scenario neemt de beladingsgraad van schepen af en duurt de periode langer. Voor een meest gangbaar schip van 110 x 11,4 meter van de CEMT-klasse Va wordt een gemiddeld jaarlijks minimum waargenomen van 60% in 2050 tot 40% in 2150. De duur van de beperkte belading verdubbelt en de sterkste afname wordt waargenomen tussen 2050 en 2100.

Op basis van historische prestaties (2010-2020) van de binnenvaart, gekoppeld aan het optreden van toekomstige afvoeren bij Lobith, is een eerste-orde indicatie gegeven van de ontwikkeling van de vervoersprestatie over de Waalcorridor bij klimaatverandering. Op basis hiervan kunnen geen absolute getallen worden bepaald, maar kan wel een gevoel voor trends worden verkregen. Ervan uitgaande dat de huidige vloot niet verandert, zal het jaarlijkse totale gewicht dat kan worden vervoerd afnemen, ongeacht het klimaatscenario. De ernst hangt wel af van het klimaatscenario. Inzoomen op het vrachttype laat een variërend beeld zien, waar voor droge bulklading een jaarlijkse afname is van -3,0% vrachtvervoerscapaciteit in het uiterste jaar 2150 in een Hd scenario, terwijl er voor vloeibare bulklading een gestage afname is tot -12,0% vrachtvervoerscapaciteit in 2150. Dit verschil wordt verklaard door het aantal gemaakte reizen, waar dit voor droge lading theoretisch stijgt tot +25% in 2150 Hd, terwijl het voor vloeibare lading slechts +3% kan stijgen. Redundantie in de vloot kan de effecten van klimaatverandering dus gedeeltelijk tegengaan.

Om de noodzaak van kanalisatie te bepalen, worden de grenzen van de bevaarbaarheid vastgesteld op basis van de huidige internationale eisen aan bevaarbaarheid en eerdere kanalisatiepraktijken. Voor de transportfunctie van de rivier zijn geen duidelijke grenzen gevonden, waardoor er geen ontwikkeling kon worden geïdentificeerd die kanalisatie noodzakelijk maakt. Er zijn twee regelgevingen van toepassing op de bevaarbaarheid van de Waal. TEN-T is een transportbeleid van de Europese Unie en stelt eisen aan de kwaliteit van haar netwerk. Op de Waal is het hele jaar door een gegarandeerde diepgang van 2,5 meter nodig. Hieraan wordt nu niet voldaan (20 dagen in een gemiddeld jaar) en dit zal in geen enkel klimaatscenario in de toekomst verbeteren (tot 80 dagen in 2150 Hd). De CCR is een vereniging van vijf landen die zich inzet voor de veiligheid en belangen van de binnenvaart op de Rijn. De richtlijnen van de CCR zijn leidend voor het rivierbeheer in Nederland. Op de Waal vereisen 'OLR'-voorwaarden (Overeengekomen lage rivierstand) een waterdiepte van 2,8 meter in de vaargeul, per definitie een waterdiepte die gemiddeld 20 dagen per jaar wordt onderschreden. Hieraan wordt momenteel niet voldaan (gemiddeld 40 dagen onderschrijding per jaar) en dit zal in geen enkel toekomstscenario verbeteren (>100 dagen in 2150 Hd).

De omstandigheden op de Maas (1920) en de Nederrijn (1960) vóór de kanalisatie zijn geprojecteerd op de huidige Waal. Als men, zoals op de Maas, een maatgevend schip (nu CEMT VIc 6-baks duwbak) wil afladen, zijn er nu en in de toekomst onder alle beschouwde klimaatscenario's ten minste 180 dagen beperkingen voor de beladingsgraad. De Nederrijn is gekanaliseerd om de Nederrijn en de IJssel bevaarbaar te houden en om de zoetwaterverdeling te regelen. Zowel de Nederrijn als de IJssel voldeden niet aan de bevaarbaarheidseisen die destijds zijn gesteld. De Waal voldoet ook niet aan de huidige eisen voor bevaarbaarheid (CCR 2,8 m: 40 dagen), maar zelfs in het extreme 2150 Hd-scenario is dit ruwweg slechts de helft (100 dagen) van het aantal dagen als op de IJssel en de Beneden-Rijn (2,7 m: 190 en 225 dagen). De bevaarbaarheidseisen van die tijd pasten wel beter bij de diepgang van een meest gangbaar schip. Het huidige meest gangbare schip 110x11,4 meter CEMT Va ondervindt evenveel dagen (160) onvoldoende waterdiepte als op de IJssel in alle droge klimaatscenario's tussen 2033 en 2050. Vergeleken met de Nederrijn is dit het geval in een Hd-scenario tussen 2050 en 2100 (180 dagen).

De conclusie van dit onderzoek is dat er vanuit het perspectief van de binnenvaart twee overkoepelende overwegingen zijn bij de beslissing over kanalisatie van de Waal, namelijk het perspectief van de bevaarbaarheid van de rivier en het perspectief van de capaciteit van de rivier om vrachtvervoer mogelijk te maken. De bevaarbaarheid, beschreven in (lage) afvoeren en waterdiepte, verslechtert door klimaatverandering. Duidelijke grenswaarden zoals TEN-T en CCR eisen worden niet gehaald en er is niet voldoende waterdiepte om het maatgevende schip CEMT VI+ het hele jaar door af te laden. Het nu nemen van actie in de vorm van kanalisatie garandeert dat in de (nabije) toekomst aan deze eisen wordt voldaan. Onz ekerheid in klimaatomstandigheden zorgt ervoor dat er geen duidelijke voorspellingen kunnen worden gedaan over de ernst van de impact op de transportfunctie. Bovendien is de transportfunctie complexer, aangezien deze een diversiteit van individuele schepen, verschillende ladingtypes en een corridor beschrijft. Het is niet ondenkbaar dat aanpassingen binnen de ’transportfunctie’, zoals veranderingen in de logistieke keten of verbetering van de vloot, de negatieve gevolgen van klimaatverandering (deels) kunnen tegengaan, waardoor de noodzaak van kanalisatie minder wordt. Daarnaast concludeerde dit onderzoek dat er voor de transportfunctie geen uniforme gekwantificeerde doelen zijn. Doelen die worden genoemd zijn de toegevoegde waarde aan het Nederlandse BBP, de rol in andere sectoren, de modal shift en (militair) strategisch. Aangezien deze doelen breed zijn geformuleerd, maar niet goed gekwantificeerd, is het moeilijk om grenzen te stellen aan de prestaties van het systeem onder klimaatverandering die de noodzaak van kanalisatie zouden kunnen beargumenteren. Om een weloverwogen beslissing over kanalisatie te nemen op basis van de capaciteit om vrachtvervoer mogelijk te maken, moet eerst worden gedefinieerd en gekwantificeerd welke prestaties op de Waal moeten worden geleverd.

# Contents

# Nomenclature

## Abbreviations

| Abbreviation | Definition |
|---|---|
| ABS | Agent Based Simulation |
| CCNR | Central Commission for the Navigation of the Rhine |
| CHR | International Commission for the Hydrology of the Rhine Basin |
| DES | Discrete Event Simulation |
| ICPR | International Commission for the Protection of the Rhine |
| IPCC | The Intergovernmental Panel on Climate Change |
| IVS | Informatie- en Volgysteem voor de Scheepvaart, Information System for Inland Shipping |
| IWT | Inland Waterway Transport |
| MGD | Minst Gepeilde Diepte, Lowest Measured Depth |
| NAP | Normaal Amsterdams Peil, Dutch chart datum |
| OLA | Overeengekomen Lage Rivierafvoer, Agreed Low River Discharge:<br>”*The Agreed Low River Discharge (OLA) is the discharge on the Rhine that is not undershot during a long-term period over an average of 20 days per year without ice.*” |
| OLR | Overeengekomen Lage Rivierstand, Agreed Low River Level:<br>”*The Agreed Low River Level (OLR) is the water level that, in relation to the agreed low discharge, is 20 days per year below the average discharge value measured over years on the Rhine.*” |
| RCP | Representative Concentration Pathway |
| RKM | Rhine Kilometer |
| SSP | Shared Socioeconomic Pathways |
| TEN-T | Trans-European Network for Transport |
| UKC | Under keel clearance |

# 1

# Introduction

## 1.1. Research motivation

The drought in the summer of 2018 and accompanying low water levels on the River Rhine lead to an economic loss estimated at 2.7 billion euro's in Germany and the Netherlands (Streng & van Saase, 2020). This event showed the vulnerability of the inland shipping and transport sector in Western Europe to extreme low discharges on the River Rhine. This event is not an incident, as the River Waal has not complied with requirements set for the waterway for years (Schulz, 2018). Climate change is expected to increase the frequency, intensity and duration of periods of droughts in the future, which asks for measures to counteract the negative effects on inland shipping. One of these measures is canalization, where the river discharge is managed using control structures in the form of weirs and locks.

This research aims to provide a broad view on the necessity of canalization, serving as guidance on the basis of which such a decision for canalization can be made. In this chapter the topic and research setup is introduced.

## 1.2. Problem analysis

This research focuses on the River Waal, the Dutch section of the River Rhine and largest river of the Dutch waterways. This section introduces this system, puts it in the context of climate change and investigates the leap in knowledge.

### 1.2.1. Inland waterway transport

The Netherlands is characterized by an extensive system of waterways consisting of normalised rivers and man-made canals. Over the past decades engineers used their skills and knowledge to shape these systems in order to use them for our benefits. The rivers have various functions which are categorized and ordered in the Dutch 'Waterwet' (Water law) under article 2.9 as the 'verdringingsreeks' (order of importance). These categories are Safety, Utilities, Small-scale high-value and Remaining interests. Economic interests is one of the remaining functions which includes inland shipping. Inland shipping is an important modality for the transport of cargo, accounting for roughly 20 percent of cargo transport by weight in the Netherlands (Centraal Bureau voor de Statistiek, 2021), adding more than 2 billion euro to the Dutch economy annually (Centraal Bureau voor de Statistiek, 2022). As a mode of transport it's efficient for specific types of cargo, including (dry/liquid) bulk, containers and large structures/special transport due to it's large loading capacity, volumetric as well as weight (Bureau Voorlichting Binnenvaart, 2023). The transport capacity per vessel is larger than other modes of transport such as a train or truck, which gives the benefit of economies of scale, lowering the cost per tonne cargo transported. Furthermore this large transport capacity brings down the relative emissions per tonne-kilometer, making inland shipping a relative sustainable mode of cargo transport, as shown in Figure 1.1.

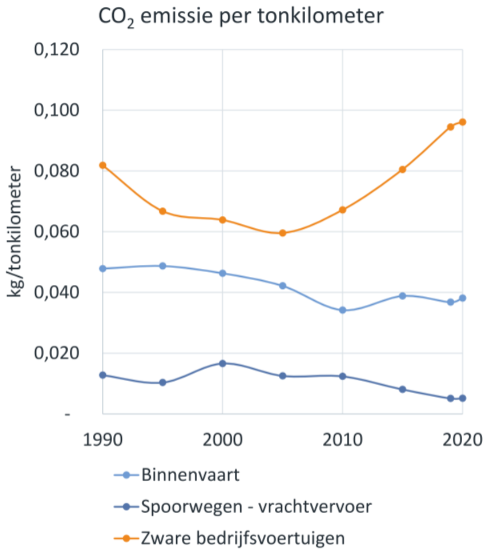


**Figure 1.1:** CO$_2$ emissions per tonne-kilometer (van der Geest, 2022)

Considering this, inland shipping is assigned a role in the model shift by the Dutch government and the European union with the intention to increase the share of cargo transported over water in order to meet the set 90% emission reduction in the transport sector by 2050 agreed on in the European Green Deal (European Commission, Secretariat-General, 2019; Rijksoverheid, 2021). A practical application is voiced by the Port of Rotterdam, which targets to increase the share of container transport via inland shipping from the Maasvlakte to the hinterland to 45% by 2030 at the decision to construct the Maasvlakte (Port of Rotterdam, n.d.). Overall, the inland shipping sector is expected to grow in the future, exemplified by an anticipated annual growth in transported weight between 0.65 and 1.12% until 2040 (Rijkswaterstaat WVL, 2021).

### 1.2.2. River Waal

Roughly 2/3 of the cargo in European inland shipping is transported over the River Rhine (CCNR, 2023a), being part of the 'Rhine-Alpine' corridor, one of the nine corridors of the Core Network, defined in the Trans-European Network for Transport (TEN-T) by the European Union (European Commision, 2017). The route connects the Port of Rotterdam to the German (and Swiss) hinterland with 100.000 vessel passages carrying 135 million tonnes of cargo passing the Dutch/German border via Lobith annually (Destatis, 2021). The core network links major cities and nodes with the highest infrastructure quality standards. By doing so, it is a "key instrument for the development of coherent, efficient, multimodal, and high-quality transport infrastructure across the EU" (European Commision, 2017).

The River Rhine, originating in Switzerland and ending in the North Sea, is a normalised free-flowing river and is fed from melting glacierized catchments in the Alpine drainage basins. These glacierized catchments store precipiation for a period of time, delaying the runoff. Winter precipitation is stored and released during the summer melting period. Furthermore, the river is also fed by rainfall, especially in the downstream regions where rain-fed river side-branches discharge in the River Rhine, which naturally results in a higher discharge during winter and lower discharge during the summer period (Junghans et al., 2011). Inland shipping is related to discharge levels by means of navigability, being '*the degree to which an area of water is deep, wide, or safe enough for a boat to go through*', as formulated by the Cambridge Dictionary (Cambridge University Press, n.d.). For free-flowing rivers as the River Rhine, the discharge determines the water depth and width of the river sailed by the vessels.

The River Rhine enters the Netherlands at Lobith, where after the bifurcation at the Pannerdensch Kanaal, the river goes by the name 'Waal' for 85 kilometers whereupon he ends at the former confluence point with the River Meuse. The River Waal is the most important transport axis of the Dutch waterway network (Rijkswaterstaat WVL, 2021)) and is managed by Rijkswaterstaat, the executive arm of the Dutch Ministry of Infrastructure and Water Management. Figure 1.2 indicates the River Rhine and Dutch section Waal.

**Figure 1.2:** Dutch waterway network highlighting the River Rhine and Waal (Rijkswaterstaat, 2013)

### 1.2.3. Climate change

The inland shipping sector on the River Rhine and Waal faces challenges due to the effects of climate change on navigability. This challenge is the reason for this research.

#### Global climate change

The most recent IPCC publication AR6 on climate change emphasises that the climate is irreversibly going to change as a result of human actions regarding emissions on greenhouse gasses (Calvin et al., 2023). The severity of this change is dependent on human actions and interventions. The IPCC adapts pathways to be used for modelling, which are scenario's based on future emission rates. These so-called ”RCP's” (Representative Concentration Pathway) range from RCP 1.9 to RCP 8.5 with intermediate levels, where RCP 1.9 represents the lowest emission scenario resulting in a global temperature increase below 1.5° Celsius, as described in the Paris Agreement in 2015. RCP 8.5 is considered the 'worst-case scenario' where emissions continue to rise all through the 21th century (Calvin et al., 2023). With the current state of emissions and implemented policy, the overall global temperature will increase and weather extremes, including periods of drought, are likely to become longer, more frequent and more severe in the future (Calvin et al., 2023).

#### Impact on discharge regime River Rhine

Climate change is expected to change the future discharge regime of the River Rhine, amongst others because the ratio of feeding source contribution is going to change (Junghans et al., 2011). The River Rhine is fed by ice melt, snow melt and rainfall. Climate change induced temperature increase in the alps is very likely to affect the melt of snow and ice in the Rhine catchment due to glacier retreat (Junghans et al., 2011).

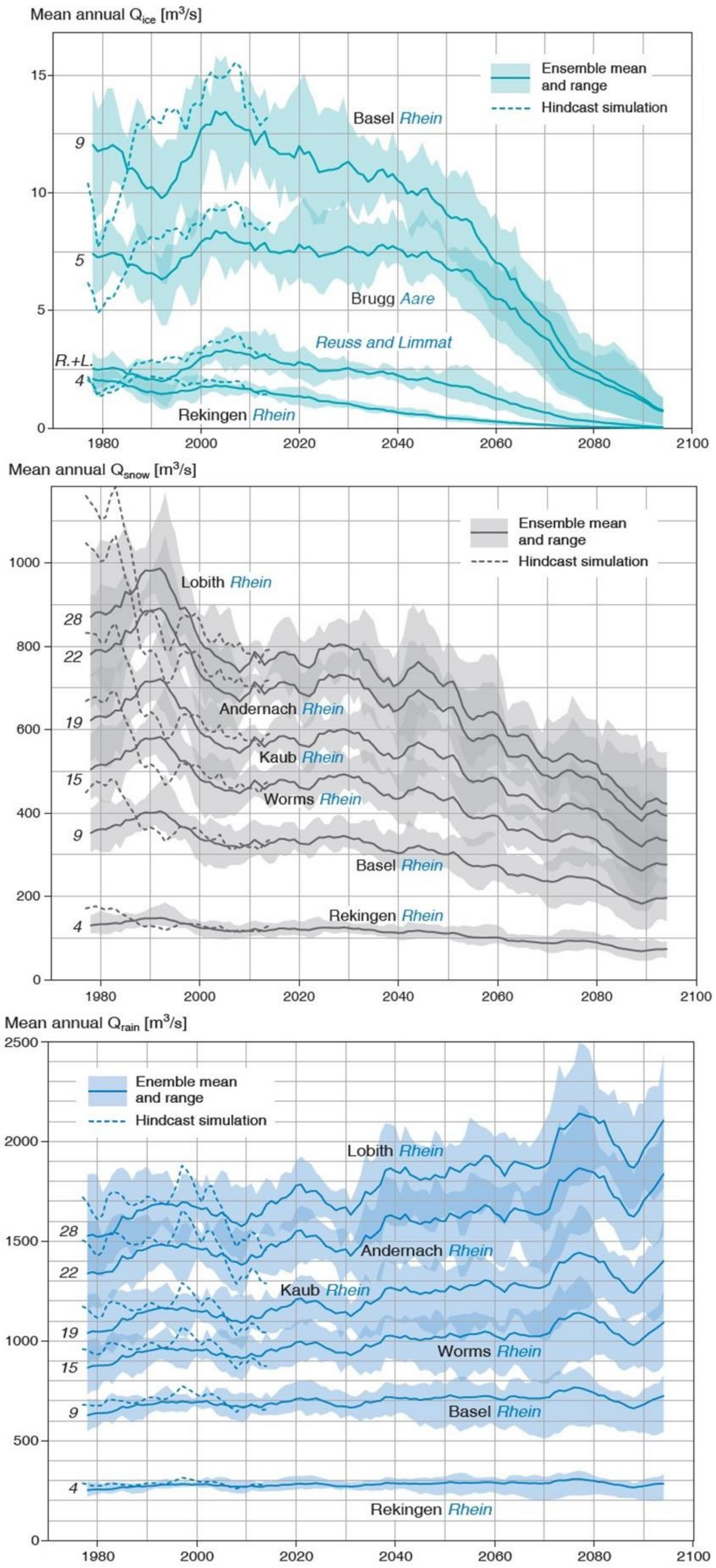


**Figure 1.3:** Overview of modelled future River Rhine discharge component contribution (Stahl et al., 2022)

Figure 1.3 shows the discharge component change predictions modelled by Stahl et al. (2022) based on the RCP 8.5 scenario. The main conclusions from this research are:

- Ice component ($Q_{ice}$):
    - Contribution of ice melt will decrease to almost $0\,\text{m}^3/\text{s}$ by the year 2100;
    - Half of the glacial volume will be lost by 2050;
    - The contribution of $Q_{ice}$ is already past it's peak, also known as the glacier peak water.
- Snow component ($Q_{snow}$):
    - Contribution of snow melt decreases in all tributaries and will be halved by the year 2100;
    - Limited variation until 2030, whereupon a steady decline starts;
    - Decrease mainly caused by warmer winters with a smaller snowpack, generating less (delayed) melt water after the winter.
- Rain component ($Q_{rain}$):
    - Contribution of rain increases in a warmer future;
    - Downstream of Basel the annual precipitation is set to increase, since the projected increase in winter precipitation is expected to be larger than the decrease in summer precipitation.

The amount of glacial feeding will decrease, which increases the share of rain feeding. The rain component will dominate the variability in discharge, giving it a more variable character, since the seasonal water storage capacity of snow diminishes (ICPR, 2018).

This means that the seasonal variation of the river discharge increases resulting in higher flows during the wet season and lower flows during the dry season. Furthermore the dry season shifts to earlier in the autumn. This is visualised in Figure 1.4.

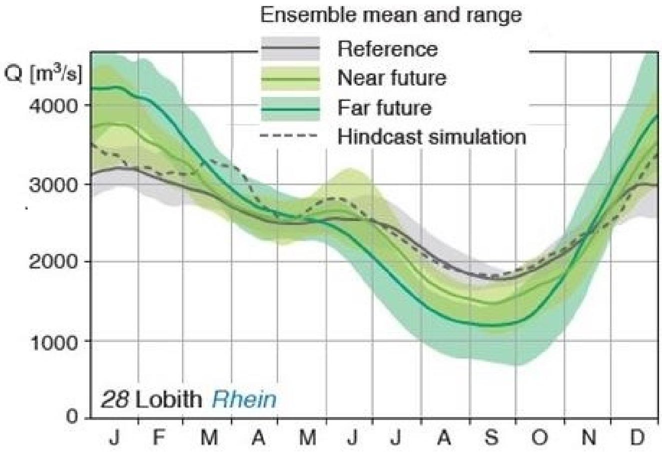


**Figure 1.4:** Changing discharge regime at Lobith represented as a 30-day moving average of mean daily discharge (Stahl et al., 2022)

Projecting these future component contributions to discharge on previous events of drought (1976, 2003 and 2018) for the downstream region of the River Rhine, which includes the Dutch River Waal, shows that in the RCP 8.5 scenario the discharge would be up to 30% lower during all these events, according to van Tiel et al. (2023). A similar conclusion is drawn by Stahl et al. (2016) showing that the 2003 drought event would've been less severe if the glacier retreat was less (implying that droughts are more severe in case of glacier retreat).

To conclude, it is very likely that in the (far) future the discharge regime of the River Rhine and Waal is going to change with more frequent and severe periods of drought during the summer. The severity of the change will depend on the amount of human induced greenhouse gas emissions (Buitink et al., 2023).

### 1.2.4. Inland navigation in periods of drought

During drought (<1800 $m^3/s$ at Lobith), the water level in the River Rhine is low compared to average discharge (2200 $m^3/s$). During low water levels vessels are not able to load to full capacity, since a reduced draught must be applied. For a constant transport demand, but lower loading capacity of the vessels, the number of vessels required to transport the cargo demand increases. More vessel trips are observed in periods of drought, where for example the number of monthly trips by dry bulk vessels during the 2018 drought increased from 600 to 1400 (de Jong, 2020a). Since there are more trips required, waterborne transport costs increases (see Figure 1.5), leading to a financial loss in the supply chain (Van Dorsser et al., 2020). Recent periods of drought in the River Rhine in 2018 and 2022 showed the dependence and vulnerability of the economy to a decrease in transport capacity by inland shipping (CCNR, 2023b). The economic loss of the 2018 draught period was estimated to be 2.7 billion euros of which 2.4 billion in Germany (Streng & van Saase, 2020). Other observed effects were an increase in traffic intensity, an increased level of filled stocks at sea ports, an increase of port calls, queue formation at locks and delays in hinterland supply chains (Reguly, 2020). Furthermore this lead to a disruption in the industrial supply chain (Reguly, 2020) and reduction of German and Swiss national strategic reserves (Kirschbaum, 2018).

**Figure 1.5:** Freight rates during drought (CCNR, 2020) based on statistics from Panteia

The River Rhine has historically been characterized by periods of drought, however the current negative perception is instigated by the relative long absence of severe droughts in the recent past and the increasing consequences these drought events have on the inland shipping sector (ICPR, 2018). These consequences are expected to further increase in the future. A simulation on navigation cost using BIVAS (Binnenland Analyse Systeem, Inland Shipping Analysis System) by de Jong (2020a) showed that the increase in annual inland waterway transport costs due to drought can increase between 10% and 30% depending on the severity of climate change and economical growth.

The increase in transport costs differ per type of cargo transported. The load factor of vessels decreases in periods of drought, which is especially visible for wet (70% to 30% in 2018) and dry (90% to 30% in 2018) bulk cargo and to a lesser extend for containers (30% to 15% in 2018), since container vessels are loaded on volume instead of weight (de Jong, 2020a). The projected financial impact in future drought events is however larger for containers, since the share of containertransport is set to increase towards 2050 (Streng & van Saase, 2020).

The number of trips in 2018 more than doubled, up until the point that waterborne transport became unfeasible and vessels could not fulfill the total cargo transport demand. This initiated a so called reverse modal shift, where contrary to the concept of modal shift, cargo is transported by rail and road instead of over water (CCNR, 2023b). During drought, up to 30% of cargo has the incentive to shift mode, predominantly to rail (Krekt et al., 2011). This is not in line with the agreements of the European Green Deal to shift transport to water. de Leeuw van Weenen et al. (2023) has shown that since the drought of 2018, the waterborne container transport lost up to 30% volume, which was partially due to a reverse modal shift. It is likely that a part of this loss is permanent, because of the image loss of inland shipping as a stable mode of transport.

Thus, in the long term low waters in the current river system have a negative effect on inland shipping due to a substantial increase in transport costs, an image loss as reliable transport mode and a risk for a reverse modal shift (CCNR, 2023b).

### 1.2.5. Adequacy of low water measures

To counteract the threat of drought on navigability of the River Rhine, four types of measures are recognized in literature (CCNR, 2023b; de Jong & van der Mark, 2021a; KBN, 2023; Krekt et al., 2011). These measures have a different impact on the problem and vary in applicability on different timescales. In the future, it is likely that all measures should be used to keep the river navigable (de Jong & van der Mark, 2021a).

#### Information

A measure regarding information focuses on using the capabilities of the current river system as good as possible. Real-time depth measurements, discharge predictions and communication contribute to a better fleet planning, decrease waiting time and optimise routing. These systems are already in use (CCNR, 2023b). These methods help to be prepared for periods of low water, but will not per definition reduce the impact of low water on navigation, therefore this solution is mainly short term, when the other solutions are not put into action yet (Krekt et al., 2011). It is in a sense more a mitigation measure than a solution.

#### Logistics

Flexibilisation of logistical processes is a solution on supply chain level, where robustness in the chain is built in at the client and the supplier side with the aim to make them less dependent of just-in-time delivery and reduce vulnerability to disruptions in the transport chain in order to reduce transport costs, prevent production loss and maintain strategic stock (CCNR, 2023b). Furthermore flexibility is an option for synchro- and/or multi-modal transport. This requires a shift in logistical processes especially for the transshipment companies. Flexibilisation does not solve the issue of reduced navigability of the river, it mitigates the effects it has on the supply chain.

#### Fleet

Fleet optimisation aims to adapt the fleet to low water conditions, in order to reduce the (relative) capacity loss during periods of drought and implies changes in the current composition of fleet and/or development of new low water fleet. Current fleet can switch to the use of additional push barges, smaller vessels or smaller propellers/different configuration. New barges can carry more cargo on low draft than the current fleet with an improved hull design. Krekt et al. (2011) states that draft could reduce up to 50cm. Chemical producer BASF already operates a newly designed low drought tanker vessel which is capable to carry more cargo than conventional vessels during drought. HGK Shipping has a similar vessel for gaseous cargo transport. Steel producer Thyssenkrupp is investigating the possibility to reduce the draught of the push barges they operate and container liner CONTARGO used a mix of vessel-push barge combinations to counteract the capacity loss during the 2018 drought (CCNR, 2023b). A problem, recognized by KBN (2023) is that it's not economically feasibly yet to invest in fleet optimisation. The capacity improvement doesn't outweigh the cost, especially since these vessels are optimised for low water, which most of the times it is not. Implementation is therefore only possible if the traditional market forces are bypassed, which requires either high industry commitment and/or regulatory incentives.

#### Infrastructure

The aim of infrastructure improvements is to change the (discharge) characteristics of the river and create permanent sufficient water depth to favour navigability. In order to keep waterways navigable in the future even at extremely low discharge, adaptation of infrastructure is considered inevitable (KBN, 2023). Infrastructure improvements are large scale and have effects on corridor level (KBN, 2023). Solutions are narrowing of the river, coarsening of the river bed, removal of solid layers, construction of longitudinal dams, water buffering and canalization. All of these solutions have pro's and cons. A recent pilot on longitudinal dams in the River Waal for example showed a maximum increase in water level of 15-20 cm, but also introduced new shallows and reduced the river width during drought (Mosselman et al., 2021). The common argument mentioned is that these solutions have an impact on all river functions, not only shipping. Solutions as these should be seen in integral context with eye for every stakeholders demands representing all river functions.

### 1.2.6. Introduction to canalization

It is very likely that a combination of measures should be made to keep the River Waal navigable (de Jong & van der Mark, 2021a). The infrastructure improvement with the largest impact and long term effectiveness is canalization of the river (KBN, 2023; Krekt et al., 2011). Canalization is a measure where hydraulic engineering works in the form of weirs are constructed to regulate the discharge of the river, giving the possibility to regulate water levels. Canalization can either be permanent or only during certain periods. When in use, vessels have to pass these hydraulic engineering works by locks.

Canalization is not a new concept in the Netherlands. In 1915 Rijkswaterstaat decided on canalization of the Dutch section of the River Meuse (Burgers, 2023). Canalization as a measure was chosen, since other normalisation options would have too little effect on navigability in periods of drought, since the River Meuse, being precipitation fed, was characterized by a highly seasonal discharge variation with extreme low water in the dry summer (Schlingemann, 1912). Furthermore, for the purpose of navigation and water distribution in the Lower-Rhine (Neder-Rijn) and IJssel, the construction of weir-lock complexes in the Lower-Rhine was initiated in 1954 (de Gaay & Blokland, 1970), leading to canalization of this side branch of the River Rhine (see Figure 1.6).

**Figure 1.6:** Overview of canalization works on the River Meuse (bottom) and Lower-Rhine (top) (Rijkswaterstaat, 2013)

Outside the Netherlands there is a plethora of rivers that have undergone canalization for the purpose of navigation. Nearby major examples are the Belgian upper River Scheldt, French River Seine, Mosel and Rhône and German upper River Rhine, Main, Neckar and Weser. Large global canalized river systems are the River Nile, Yangtze, Mississippi and Volga.

River regulation with weirs and locks is a possibility to permanently achieve sufficient water depth for inland navigation. Such a measure has large consequences for the river system and it's functions. It should however be considered as part of the long term strategy preservation of the Dutch navigation industry (Kosters, 2023). When other measures don't have the desired effect, canalization is seen as a last resort, as argued by the NPRC, one of the largest inland shipping companies in the Netherlands. (Brenninkmeijer & Wittig, 2022). If the drought related issues continue to persist, canalization could be inevitable in the second part of this century to maintain a navigable River Waal (KBN, 2023).

### 1.2.7. State of knowledge

Canalization of the River Waal is at the moment conceptual and research on this topic is very limited. Taekema (2017) studied the consequence of climate change and canalization from a financial point of view. In the study the relative costs of climate change are compared to the costs of canalization, seeking for a tipping point where the costs of construction of weirs and locks would outweigh the financial losses as a result of drought disrupted navigation. Two time horizons are considered, 2050 and 2085 with knowledge and predictions of fleet development and climate change available at time of research. The conclusion was that the feasibility of such a project fully depends on the cost of a canalization system. Cost estimation for such a project is deemed difficult, considering the long time horizon and uncertainty in predictions.

Ligtenberg (2022) studied the required lock capacity and configuration for the case of a canalized River Waal. This research did not consider the (financial) feasibility of such a project, as Taekema did. Ligtenberg came up with a configuration for two weir-lock complexes which should supply sufficient locking capacity to comply with the requirements on waiting times for vessels. The moment of closure (the point of canalization) was an importand decision for this research. This is the moment that the water depth was considered insufficient for navigation that impounding of the free-flowing river was necessary. Three definition methods are described: finding the optimum, allow all vessels at all times and an integral approach. The integral approach was chosen, which implies closure when vessels choose a route via the canalized River Meuse over continuing their route via the River Waal, due to the lack of available water depth.

Yossef et al. (2019) conducted an expert panel case study on the topic of the regulated Waal. It describes that the development of this plan is between signalling and exploration, thus there are much questions yet unanswered. The aim of the research was to identify the main research questions and initial steps to be taken in answering this questions. Commonly mentioned is the uncertainty of future developments in inland shipping and questionable necessity to investigate this problem.

Considering this uncertainty, Solar (2012) conducted a research with the aim to identify 'Adaptation Turning Points' for inland waterway transport due to climate change, which are points where the magnitude of change is such that the current state does not meet its objectives anymore. The definition of adaptation turning point is often used in climate change impact research (Smit et al., 1999). The tipping point was studied from a water level threshold as the minimum water level for normal propeller performance, based on experts opinions as representatives for Inland Waterway Transport companies. This threshold water level (1.7-2.1 meter) was projected on available future discharge projections at time of research to define the moment in time that the water level did not comply with the threshold anymore. This was considered the tipping point. In the three most severe climate scenario's the tipping point would be around 2085. Solar mentioned three threshold assessment methods: economic, policy related and technical. The technical assessment was chosen, since this was considered the most realistic assumption, having low uncertainty and being fixed in time, whereas and economic approach has high uncertainty and policy is subjected to change.

### 1.2.8. Problem statement

Recent periods of drought have shown that low water significantly impacts the navigability of the River Waal, causing it to lose it's transport function by inland waterway transport, contrary to the stated ambitions to increase transport over water. In the future, navigability is expected to decrease further, implying an increasing loss of function. It is not inconceivable that it eventually will be necessary to intervene in the system to counteract this loss of function. Canalization is a (last resort) measure with the potential to solve that problem. At this moment however, it is unclear how navigation and transport function will develop in the (far) future due to climate change. In addition, such a decision to intervene should be substantiated with valid arguments. Currently there is no clear guidance on how such a decision to canalization must be made and what considerations play a role. Because of this missing guidance, it is not possible to evaluate the necessity of canalization.

## 1.3. Research objective, scope and research questions

### Research objective

The research objective is to outline and evaluate considerations that guide the decision on canalization and determine the necessity of canalization based on these considerations.

### Research scope

This research focuses on the navigability during dry periods in the intensively navigated Dutch section of the River Rhine, the River Waal. The emphasis is on the navigation function of the river. Other river functions do have an influence on the decision for canalization and are also impacted by this decision. The focus in this research however is on the relevancy of canalization from the interests of inland navigation. Furthermore, the technical feasibility of the canalization concept is considered indisputable, therefore a technical elaboration on the practical design or location is not carried out. Navigation is studied by means of guidelines and agreements that prescribe what safe navigation is, in the past, current and future. The technical aspect of navigation is of lesser importance. Lastly, long-term macroeconomic developments affecting inland shipping have also been excluded from this research.

### Research questions

Following the research problem, objective and scope, the main research question for this study is:

*What considerations guide the decision to canalize the River Waal and will climate change induced drought necessitate canalization based on these considerations?*

This research question is supported by the following subquestions:

1. *What impact can climate change have on the navigation conditions of the River Waal?*
    (a) *How does discharge at the River Waal change due to climate change?*
    (b) *How does this discharge change affect the water depth?*
2. *What impact can climate change have on the transport function of the River Waal?*
    (a) *What is the relation between water depth and transport function?*
    (b) *What transport function change is expected based on water depth change?*
3. *What considerations lead to the decision on canalization?*
    (a) *What limits are prescribed by (inter)national regulations?*
    (b) *What limits of previous canalization practices can be applied to the River Waal?*
    (c) *What is the necessity of canalization based on navigational limits?*
    (d) *Which considerations should be taken into account in the decision on canalization?*

## 1.4. Research approach and reading guide

### Research setup

In this research six steps are set out that give answers to the subquestions and main research question. Step-by-step the impact of climate change on inland navigation investigated, forming the basis for the determination of necessity of canalization. The research approach is visualized in Figure 1.7

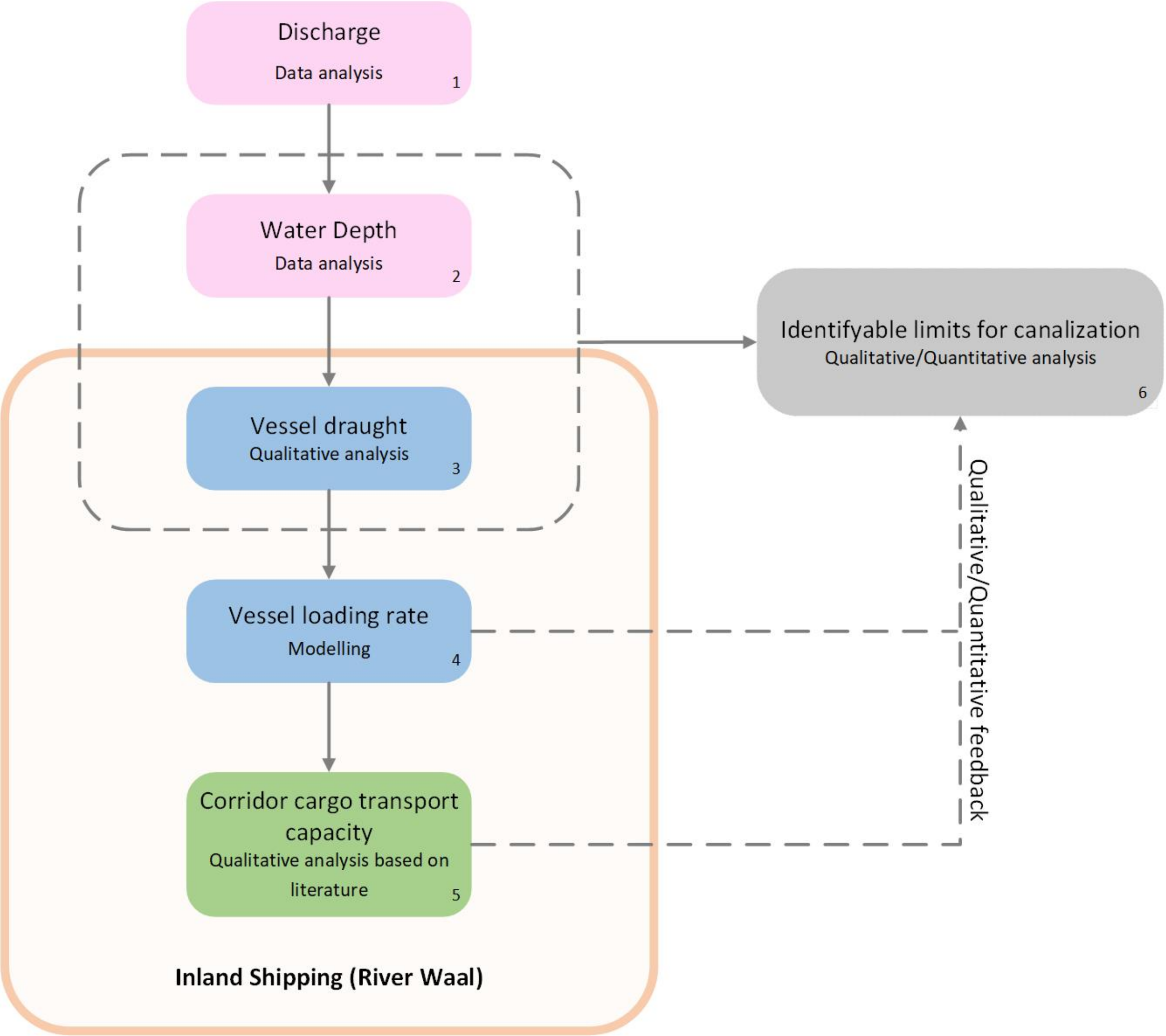


**Figure 1.7:** Research approach

- The pink blocks represent climate change, where research step 1 identifies the changing discharge at Lobith due to climate change through statistical analysis. Step 2 determines the occurrence of (critical) water depths at the bottleneck location in the River Waal, as a result of changing discharges.
- The blue blocks represent the individual vessel level, where step 3 and 4 cover the effects of changing water levels on draught and loading rate for individual vessels, using a model of Van Dorsser et al. (2020).
- The green block represents the entire corridor cargo transport capacity, where in step 5 a qualitative analysis on this capacity is made based on Vinke et al. (2024).
- In the grey block the main research question is answered. In step 6 limits on navigation are identified, which are projected onto the future climate scenarios sketched in steps 2 and 3. This is followed by feedback with the knowledge from steps 4 and 5 to put the necessity of canalization in broad perspective.

## Reading guide

Chapter 1 introduced the context of this research and explained the problem statement. The remainder of this research is divided in three core chapters, each corresponding and answering a research question:

- Chapter 2 describes the development of navigability in future climate change scenario's. This is expressed in occurrences of low discharges and low water depths and cover step 1 and 2 from the research approach.
- Chapter 3 describes the development of the transport function of the River Waal, with the impact of climate change on individual vessels as well as on the full corridor. This covers steps 3, 4 and 5 of the research approach.
- Chapter 4 describes limits on navigation based on prevailing regulations and previous canalization practice. This chapter concludes with considerations on canalization, creating a broad picture on the necessity of canalization. It covers step 6 in the research approach.

This research is ended with a discussion on the results obtained and methods applied in Chapter 5, followed with the conclusion and recommendations for further research in Chapter 6.

# 2

# Development of Navigability

The first research subquestion asks for a description of the hydrological development of the River Waal under future climate conditions to describe the development of navigability. The change in hydrological conditions and it's effect on the navigability of the River Waal is a consideration in the decision on canalization. This chapter aims to identify and characterize this hydrological development of the River Waal, based on projections for future discharge scenario's. The first step is to quantify the occurrence of future low discharge events. The second step is to determine the impact this has on the (critical) navigable water depth in the river. These are step 1 and 2 as described in the research approach in section 1.4. Additionally, a comparison with the 2018 drought is given to put future hydrological development in perspective.

## 2.1. Determining discharge development

The goal of this section is to process the future discharge projections as modelled by Deltares in response to the 2023 climate predictions by the KNMI, the Dutch Meteorological Institute. First the data used is more elaborated on. Secondly the processing is described and afterwards the results are presented.

### 2.1.1. Required data: modelled future discharge time series

The data required for this section are the future discharge time series developed by Deltares (Buitink et al., 2023), derived from the KNMI'23 climate predictions (KNMI, 2023). This data is publicly available and formatted to be used for future analysis and research.

The KNMI, Dutch Meteorological Institute, developed climate scenario's for the Netherlands based on simulations runs with a global and regional climate model (EC-EARTH and RACMO). The combination of these models is said to represent the spread in climate signals that these models produce, thereby producing a spectrum of future scenario's with equal probability of occurrence. Three emission scenario's are considered: High 'H' (SSP5, RCP8.5), Moderate 'M' (SSP2, RCP4.5) and Low 'L' (SSP1, RCP2.6). Different climate models don't give a distinctive view on how much wetter or drier it will get. Therefore for each scenario there are two conditions specified: Wet 'n' and Dry 'd'. In the wet scenario winters get much wetter and summers slightly dryer. In the dry scenario winters get slightly wetter and summers much dryer. Four representative time horizons are identified: 2033, 2050, 2100 and 2150, where 2033 represents the 1.5 degrees Celcius temperature increase according to the Paris agreement. Additionally there is a reference scenario, which retrospectively models the years 1991-2020 based on RACMO simulations. Table 2.1 gives an overview of the scenario's considered. The variation in the future scenario under low emission conditions between the chosen time horizons is negligible and therefore this is represented by the year 2100 (Buitink et al., 2023).

**Table 2.1:** Overview of modelled discharge scenario's (Buitink et al., 2023)

| Time horizon | Low | Moderate | High |
|---|---|---|---|
| Reference | - | - | - |
| 2033 | 2033L (Paris) | - | - |
| 2050 | 2100Ln<br>2100Ld | 2050Mn<br>2050Md | 2050Hn<br>2050Hd |
| 2100 | | 2100Mn<br>2100Md | 2100Hn<br>2100Hd |
| 2150 | | 2150Mn<br>2150Md | 2150Hn<br>2150Hd |

Per scenario an ensemble of 8 time-series is used to model a 30 year period around the representative year. The 8 time-series capture the internal variability that can occur in modelling those 30 years. Deltares uses these 8 ensembles and 30 years as a time-series of 240 years per scenario (Buitink et al., 2023). This method is also applied in this research. It is important to note that these 240 years are not consecutive years, but 'parallel' years (in a specific emission scenario + condition). The large set of data makes averaging per year a valid analysis method.

The climate scenario's form the basis for future discharge scenario's of the River Waal at Lobith, where the Rhine enters the Netherlands. These scenarios are simulated using the hydrological wflow sbm model, which is developed by Deltares and Rijkswaterstaat (Buitink et al., 2023). For working with threshold-based discharge analysis, which this research does, it is advised to use the bias-corrected version for the Rhine modelling projections, which compensates for overestimating the extremes.

### 2.1.2. Processing data

#### Discharge thresholds definition

To quantify the development of drought (low discharge) events, critical thresholds for discharge as Lobith are identified, which are used as markers. The majority of these thresholds are also considered in the 'Klimaatbestendige Netwerken', climate-proof networks project from Rijkswaterstaat which aims to make the Dutch water- and waterway network resilient to climate change (de Jong, 2020a). The following discharge thresholds are chosen:

- 600 $m^3/s$, $\sim$the lowest discharge value in the dataset;
- 700 $m^3/s$, the lowest discharge value for which a Qh relation is available (see section 2.2);
- 850 $m^3/s$, the lowest long period sustained discharge value during the 2018 drought;
- 1020 $m^3/s$, the current OLA discharge (Overeengekomen Lage Rivierafvoer, Agreed Low River Discharge);
- 1100 $m^3/s$, a low discharge value for which a Qh relation is available (see section 2.2);
- 1400 $m^3/s$, $\sim$the limit below which MGD announcements are initiated;
- 1800 $m^3/s$, $\sim$the limit when exceeded, no negative impact on navigation is expected.

#### Computation methodology description annual average discharge

For every scenario and precipitation condition combination the number of times a discharge value is undershot is counted. The data gives a discharge value per day, therefore averaging over 30 years and 8 ensembles gives the annual average undershot of the threshold values in the corresponding years. Afterwards, the average is rounded up, so that a half day of undershot will be counted as a full day of undershot. Last, the undershoot count is binned in bins that represent two consecutive discharge thresholds. Furthermore a bin is added which counts the overshoot of the highest considered discharge (1800 $m^3/s$), so that the sum of the bin counts represents a full year (365 days). In de Jong (2019) a similar methodology is adopted to describe low discharge levels under climate change.

### 2.1.3. Future annual average discharge at Lobith

Based on the calculation method described in section 2.1.2 the distribution of low discharge threshold values in all climate scenario's is visualised in Figure 2.1, which is a stacked histogram showing the cumulative count of discharge threshold undershoot. Appendix A shows the results in a table format.

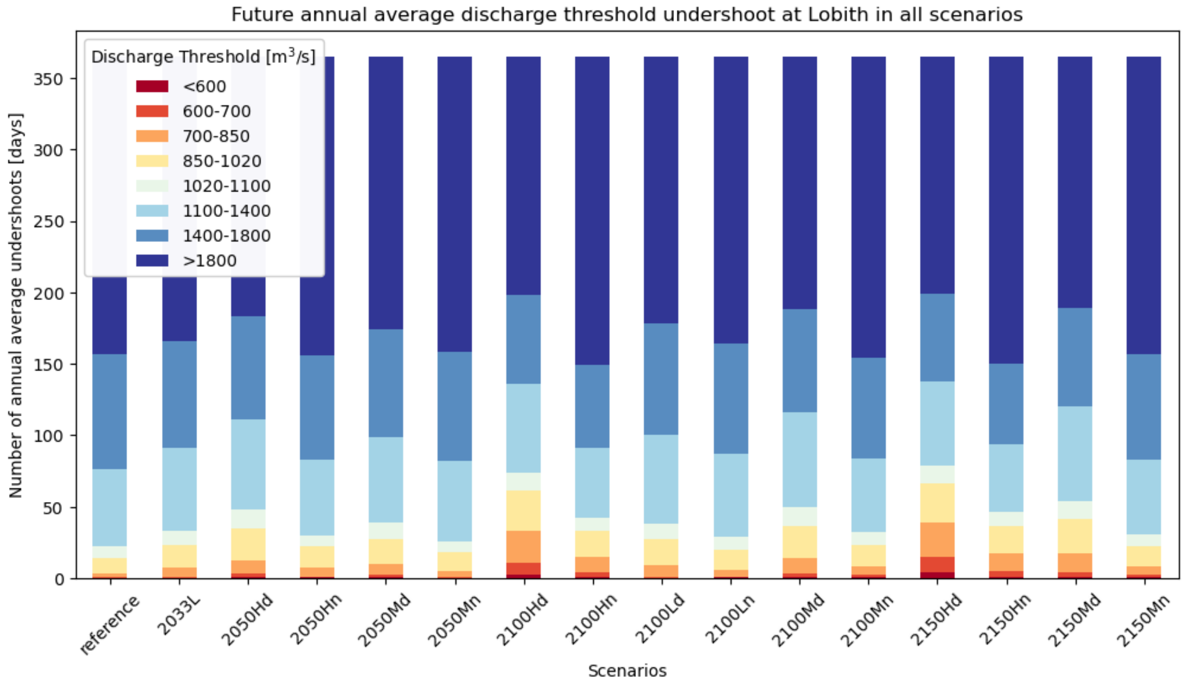


**Figure 2.1:** Average annual low discharge threshold undershoot

#### Forecast of low discharges

The annual average number of days with discharges below 1800 $m^3/s$ tend to increase in a future with a relative dry climate, but remain rather constant in a wet climate. This trend is independent of the anthropogenic emission developments. Furthermore, in all low emission scenario's (2100 is representative for 2050 and 2150), the occurrence of discharges is in line with the occurrence of discharges in the 2033L Paris climate agreement, which means the average undershoot stabilises after 2030 in case of low emissions. Generally speaking there is a trend visible that after 2100, there is only a light increase of threshold undershoots, for the high, as well as the low emission scenario. With that, it looks like a new equilibrium state of discharges has developed after 2100. This could be the due to the glacial retreat, where Stahl et al. (2022) expects the glaciers of the Alps to have disappeared by 2100.

#### Distribution of low discharges

When zooming in on the distribution of discharges it is clear that the lower discharges in the spectrum, below 1020 $m^3/s$, double and triple in occurrence in respectively the Moderate and High dry emission scenario's, but again remain stable in the wet scenario. This trend continuous until 2100. The number of days with discharges between 1100 and 1400 $m^3/s$ seems to be stable in general, independent of scenario, condition and year. In the 2100 and 2150 Hd scenario's discharges below 600 $m^3/s$ appear. To date, such extreme discharges are not or very limited observed. Lastly, discharges below 850 $m^3/s$ such as in 2018 tend to occur in every scenario, but the frequency varies with a factor 4-5 between Hd and Ln. It should be added that for everything, this is an average year. This says nothing about the distribution of low discharges over one year and over the years within a representative scenario year period.

### 2.1.4. Future daily average discharge at Lobith

Besides annual averages, the pattern of discharge during the year also changes. Figure 2.2 visualises the daily average discharge cycle over a full year. For the sake of clarity, per year 2 discharge scenario's where chosen that represent the bandwidth in climate variability. The upper extreme was determined the high emission and dry conditions combination, the lower extreme was the low emission and wet conditions combination. Continued is with the reference year, 2033 and representative years 2050, 2100 and 2150. The basis again is the fictive 240 years of parallel discharge series at Lobith per scenario. From this the average discharge per day of year is computed, so it represents the discharge value occurring in a scenario on a specific day in an average year.

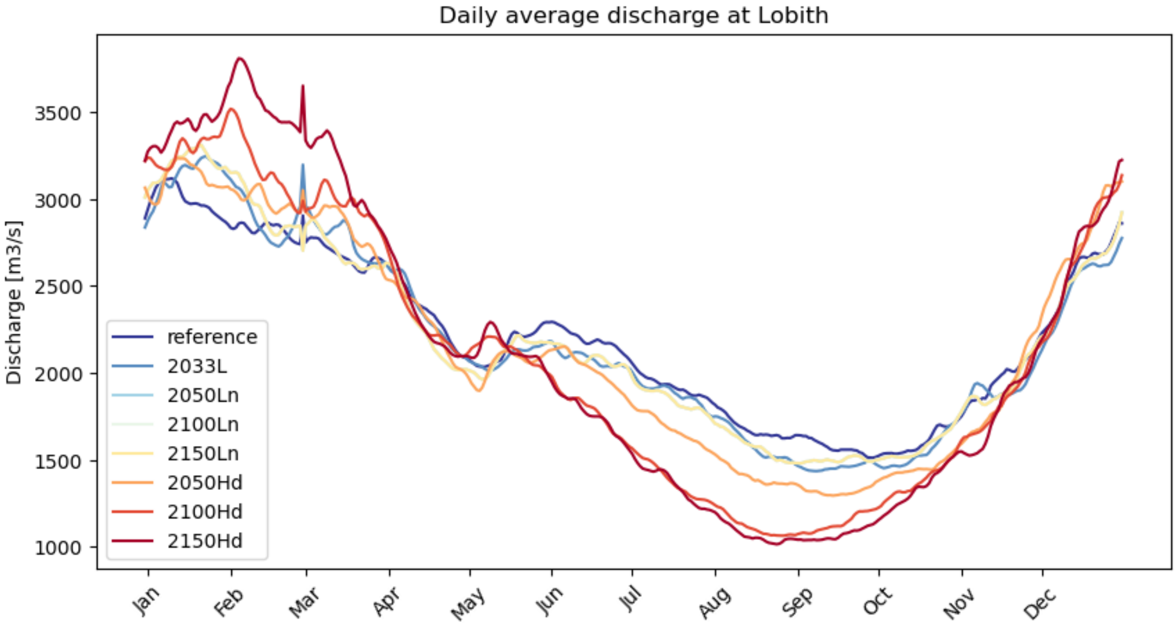


**Figure 2.2:** Daily average discharge at Lobith in Hd and Ln climate scenario's

In the Ln scenario, the annual discharge cycle follows the same sinusoidal pattern as in the reference scenario with only minor quantitative deviations. Winter period tends to be wet (2800 $m^3/s$), whereupon discharge declines after March to a minimum of roughly 1500 $m^3/s$. In a wet climate with low emissions, the long term annual average pattern thus does not seem to deviate from the recent past.

In a scenario with high emissions and dry conditions however, the deviation from the reference scenario tends to become increasingly larger in time. Although being marked 'dry', in the Hd scenario the winters get more wet, this is in line with the findings in section 2.1.2. Furthermore the dry season tends to shift to begin earlier in the year, by up to a month, from October to September.
The lowest average discharge in 2150 Hd is almost 750 $m^3/s$ lower than in the reference scenario, while the average daily discharge remains above 1000 $m^3/s$. This seems contradictory to the findings in Figure 2.1 where discharges below 1000 $m^3/s$ are observed in all climate scenario's, but this is due to the difference in computation. The discharge threshold undershoots are counted as a sum of the 240 year timeseries, which is then divided over the years, which makes it the *average per year*. Figure 2.2 is the average per day, making it an *average year*. The extremes are therefore less extreme.

Figure 2.2 thus gives a first indication that on annual average drought becomes more severe and tends to be longer. This is however highly depended on the climate scenario, where Hd is the most extreme, Ln the least extreme and other scenario's somewhere between that range.

## 2.2. Determining water depth development

The next step is to determine how often critical low water depths occur in the future climate scenario's. Based on this, in line with the research approach, in the next chapter the draught and loading rate of vessels can be determined.The following section describes the process of defining the rivers bottleneck location, identifying characteristic water depths and computing the average annual undershoot of these water depths in all climate scenario's.

### 2.2.1. Required data

In addition to the 2023 discharge projections at Lobith, two other datasets are used: Bed profile River Waal 2018 and Qh-relations River Waal 2018. Both datasets are provided by Rijkswaterstaat.

#### Bed profile River Waal 2018

The bed profile of the River Waal from 2018 is a set of data with the measured bed profile in m + NAP along the length of River Waal, with 2 to 5 measurements per kilometer (RKM, Rhine kilometer). These measurements are made using a multibeam sounding and are the highest points within a 150 meter wide fairway (which is required for the River Waal). Additionally, the water level in meter + NAP at these measuring locations is given (at Q=1020 $m^3/s$). From these two sets of information the water depth in meter is computed. A similar approach is used for determination of MGD (Minst Gepeilde Diepte, Lowest Measured Depth) values, which are communicated to users of the waterways by Rijkswaterstaat. Skippers use these depths to determine the maximum drought available for a trip (de Jong & van der Mark, 2021b).

To obtain the same spatial density as given in the Qh relations dataset, the information is upscaled to one bed profile measurement per kilometer. For every kilometer, the representative bed level was chosen which corresponded to the location of the lowest water depth (at 1020 $m^3/s$) within that kilometer. An example is given in table 2.2 where the representative bed profile for RKM 867 is at location 867.3. This method is considered valid, since the exact location of the bottleneck in the river (i.e. the location with the smallest waterdepth) is of minor importance for this research. The most interesting to know is the actual bed profile at this bottleneck. A spatial resolution per kilometer is sufficient for visualisation purposes.

**Table 2.2:** Example bed profile downscaling

| Location [RKM] | Waterdepth at Q=1020 $m^3/s$[m] | Measured bed level [m+NAP] |
|---:|---:|---:|
| 867.0 | 3.9 | 3.2 |
| **867.3** | **3.3** | **3.7** |
| 867.7 | 3.4 | 3.6 |

#### Qh relations River Waal 2018

The Qh relations for the River Waal in 2018 is a combination of measured and modelled waterlevels in m + NAP corresponding to certain discharge values at Lobith per kilometer of the river. For this research only low discharge values are of interest, therefore data above 1800 $m^3/s$ is omitted. The only measured/modelled discharge values left were 700, 1100 and 1800 $m^3/s$. As described in section 2.1.2, a list of critical discharge thresholds is defined. The Qh relation for the missing discharge thresholds is obtained using linear inter- and extrapolation, which is a simplified approach. For Q = 1020 $m^3/s$ this interpolation is validated, where the computed waterdepth in section 2.2.2 is compared to the given waterdepth in the dataset of the bed profile 2018. The results of this validation can be found in appendix B. For RKM (Rhine Kilometer) locations of interest (bottlenecks) in the upper section of the River Waal, the difference in water depth is at maximum 10 cm. This is considered acceptable, given the scarcity of measured data points and the purpose of computation, which is visualisation and bottleneck selection.

## 2.2.2. Processing data

### Determine general water depth

As a first step to identify the river bottleneck location, bed profile and measured/computed Qh relations are plotted together in a graph (see Figure 2.3). The graph shows the progression of the Dutch section of the River Rhine, where it enters the Netherlands in Lobith at RKM 863. The river is shown similar to it's geographical course (from East to West). Additionally, 6 locations are indicated which are known bottlenecks for water depth. At these locations (Haaften, St.Andries, Ophemert, Nijmegen, Erlecom and Hulhuizen) there is the most frequent occurrence of MGD's. For discharges below 1900 $m^3/s$, at least 92% of MGD points in the period 2015-2020 is at one of these locations (van Putten & Tönis, 2021). These locations are bottlenecks because there is either an (artificial) solid bed layer or infrastructure in/on the bed. Therefore dredging at these location is not possible and/or allowed. The River Waal is a natural system and subject to erosion, with the bed slowly eroding up to 2 cm per year (van Vuren, 2020). Solid or non-dredgeable sections don't subside and therefore create bottlenecks because of a reduced water depth.

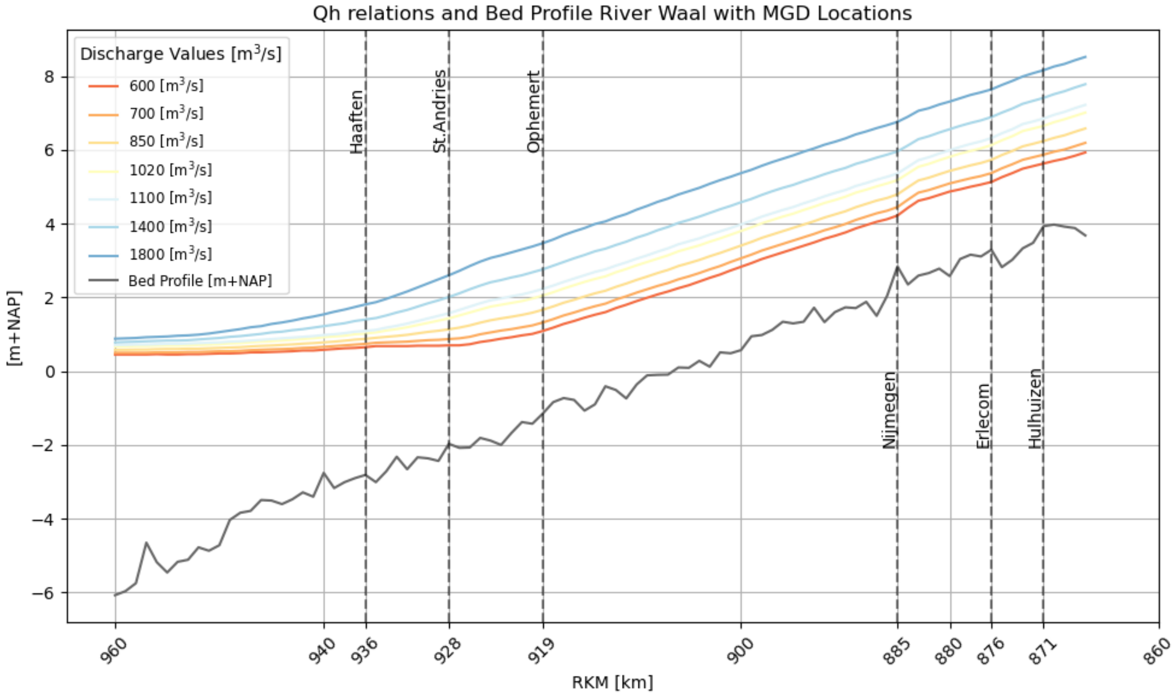


**Figure 2.3:** Qh relations and bed profile River Waal 2018

Substracting the relative Qh relations from the relative bed profile (with respect to NAP) leads to the absolute water depth in meters along the River Waal, as shown in Figure 2.4. For the MGD locations, the lowest waterdepth is highlighted, which obviously occurs when the lowest discharge of 600 $m^3/s$ prevails, however the pattern is similar for all discharge levels.

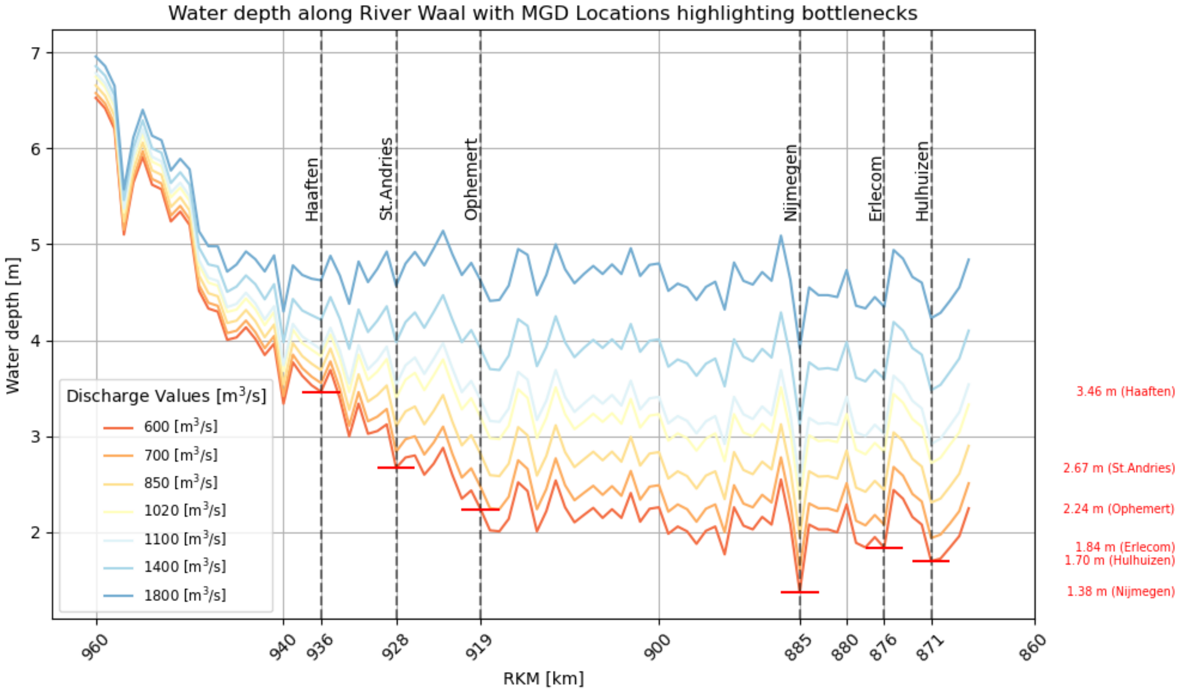


**Figure 2.4:** Water depth along River Waal with MGD locations

Based on this graph, it is concluded that RKM 885 at Nijmegen is the critical bottleneck for navigation along the River Waal at low discharges, therefore this location is chosen for further analysis as normative bed profile for the whole River Waal. This is a conservative assumption, however given the fact that most vessels on the River Waal pass Nijmegen to and from Germany (de Jong, 2020a), it is valid to say vessels sailing the River Waal have to determine their draught based on the water depth at this location. van Putten and Tönis (2021) concluded that for the lowest discharges (<900 $m^3/s$) 36% of MGD's were located at Nijmegen. As discharges increases, the MGD location tends to move downstream. For the sake of consistency however, Nijmegen is chosen as the critical bottleneck.

## Water depth at RKM 885

The next step is to quantify the occurrence of low water depths in the future scenario's at this critical location. This is done in a similar fashion as in section 2.1, where the undershoot of threshold discharge values is determined. The use of the defined discharge values to compute characteristic water depths is however not a useful method, since the generated water depths at these discharges are rather arbitrary and don't have a direct relation to navigability. Therefore a new set of characteristic water depth values is defined.

### Definition of characteristic water depths

The following characteristic water depths are identified, which are deemed relevant for further analysis in this research. Only low water depths here are of interest, so the median water depth of 4.5 meter is chosen as upper bound. As lower bound the lowest water depth 1.6 meter observed during the 2018 drought is considered. Intermediate depths represent current navigational requirements (discussed in Chapter 4) and depths important for vessels:

- 1.6 m, $\sim$ the lowest MGD during the 2018 drought;
- 2 m, a very low water depth;
- 2.5 m, TEN-T draught requirement + 0m UKC (see section 4.1.1);
- 2.8 m, the current CCNR depth requirement at OLR (see section 4.1.2);
- 3.5 m, the (future) required vessel draught at the canalized River Meuse;

- 4.5 m, median water depth where vessels should be able to load to 4 m draught, which is the maximum draught for the largest inland vessels.

The Qh relations only work for given discharges, not for demanded waterdepths. Therefore the relations have to be inverted to a hQ (dQ) relation. For RKM 885 a linear regression is formulated to compute water depth d as a function of Lobith discharge Q. When verifying this equation with the water depths at discharge thresholds, the function doesn't return the discharge thresholds accurately. A 2nd order polynomial fit was more accurate, therefore this equation is applied. This is contrary to the assumption of linear interpolation in section 2.2.1, however this was only used for visualisation purposes and bottleneck selection. The Qd relation for RKM 885 is equation 2.1:

$$Q = 21.493d^2 + 358.91d + 64.523 \tag{2.1}$$

With this equation the discharges corresponding to the critical water depths are computed (2.3):

**Table 2.3:** Critical discharge at Lobith corresponding to water depth thresholds RKM 885, following equation 2.1

| **Water depth at RKM 885 [m]** | 1.6 | 2 | 2.5 | 2.8 | 3.5 | 4.5 |
|---|---|---|---|---|---|---|
| **Discharge at Lobith [m$^3$/s]** | 693 | 868 | 1096 | 1237 | 1584 | 2114 |

Similar results are obtained by de Jong (2020b), which verifies the computation method. In Figure 2.5 the slightly nonlinear Qd relation is clearly visible:

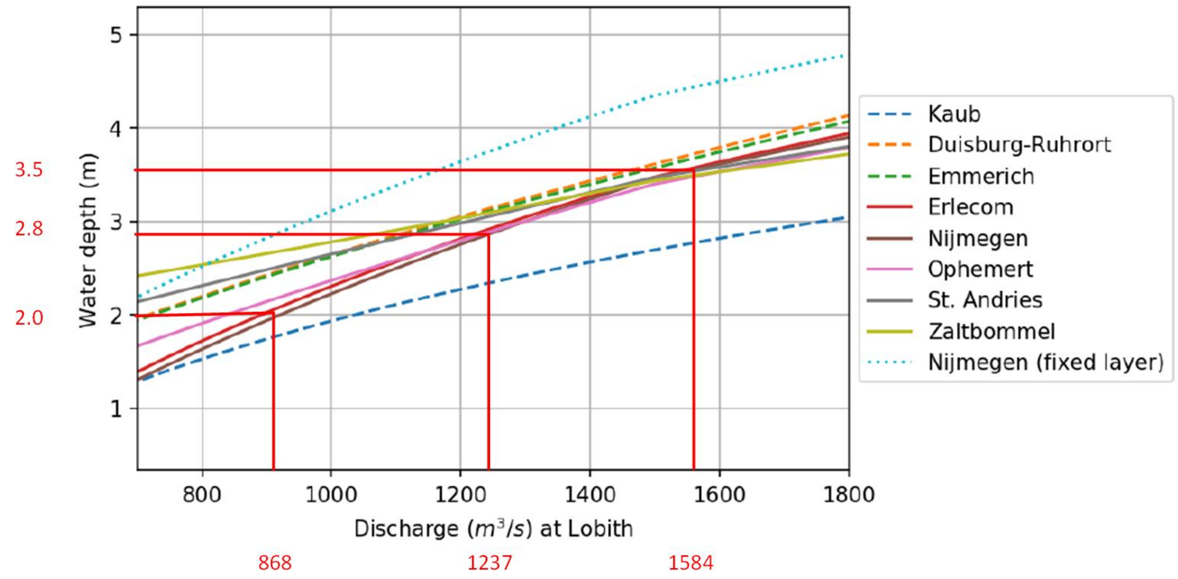


**Figure 2.5:** Comparison Qd relation with model results Deltares (de Jong, 2020b)

For these new obtained characteristic discharges the annual average undershoots are computed with a similar method as in section 2.1.2.

### 2.2.3. Future annual average water depth at RKM 885

The annual average undershoots of characteristic water depths is visualised in Figure 2.6, which is a stacked histogram showing the cumulative count of the undershoot. Appendix C shows the results in a table format. This distribution of water depths is valid under the assumption of a stable bed profile and discharge distribution over the Rhine branches until 2150 based on the 2018 bed profile and Qh relations.

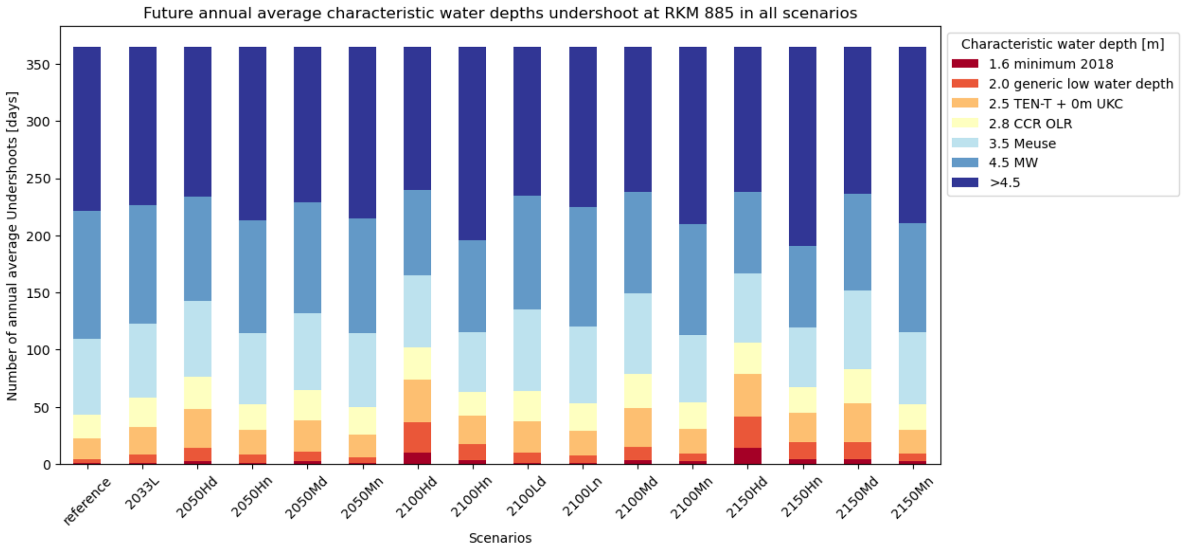


**Figure 2.6:** Average annual water depth undershoot at RKM 885

This plot shows great similarities to Figure 2.1 despite the non-linear Qd relation, but is more insightful for analysing the navigability of the river. RKM 885 is the critical bottleneck location and it is clear that the effects on water depths are larger than the discharge distribution suggests. The undershoot of what is currently considered median water depth is substantial (up to 70 % of the year) in almost all scenario's except Hn. Per definition the median water depth should be undershot 50% of the year, which means that in that in a future with increasing droughts the median water depth will decrease.

It is also noticeable that there tends to be an increase of water depths >4.5 meter in almost all scenario's except Hd, compared to the reference scenario. This indicates an increase in wet extremes. This effect was not visible in the discharges, but that was due to the selection of thresholds, where >1800 $m^3/s$ covered all values except the extreme low discharges. Furthermore, the lowest water depths as known from 2018 occur in every scenario except for low emissions. The number is minimal, except for the Hd years. More insight in the development is gained when future scenario's is plotted against the reference scenario in Figure 2.7.

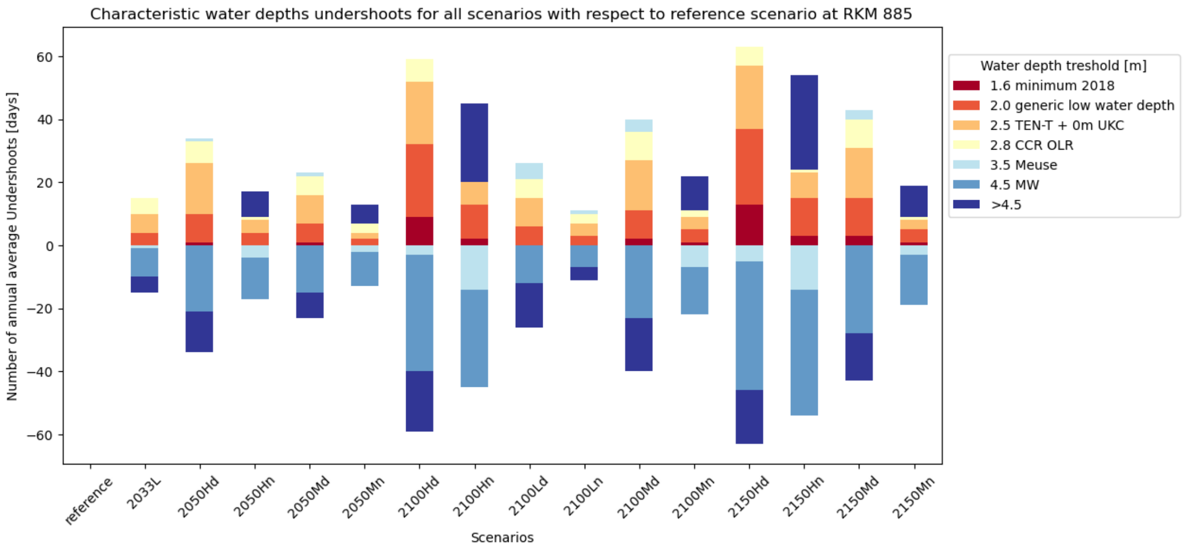


**Figure 2.7:** Relative characteristic water depth undershoot at RKM 885

The increase in low water depth undershoots (below 2.8 m) is limited to 20 days for all wet scenario's, whereas in dry scenario's this can double or triple to 60 days with respect to the reference scenario. In all scenario's there is an increase of water depths below 2.5 m and decrease of water depths between 3.5 and 4.5 m. Furthermore in all scenario's except the Hd and Ln there is an increase in water depths above 4.5 m. 2150 does again clearly show the same composition as 2100.

Based on this Figure 2.7, two scenario's are chosen per year which ought to display the spread in climate variability representing low discharge cases, so the most and least extreme drought case. For analysis steps further in this research it is more convenient to work with less scenario's. In every year the scenario Hd leads to the most extreme results. Scenario Ln isn't shown for 2050 and 2150, since they are similar to 2100, therefore only 2100 is shown. The Ln scenario however represents the least drought case, with the lowest deviation from the reference scenario, so scenario's Ln - Hd represent the spread in possible outcomes. Therefore from now on these two scenario's are considered, where Ln is more or less a static scenario that continues throughout the years. Note that the discharges and water depths in the Mn scenario are very similar to the Ln scenario and sometimes even slightly 'less worse'. For consistency however the Ln scenario is chosen as baseline, since this gives more often the 'least worst' case.

### 2.2.4. Future daily average water depth at RKM 885

To characterize the impact of climate change on water depth, the daily average water depth is computed in a similar fashion as in section 2.1.4. A description of the relation between discharge and water depth is required to compute the water depth for all discharges provided in the discharge projection dataset. The known Qh relationships (at 700, 800, 1020 $m^3/s$, etc.) were extended to a generic Qd relation for all discharges by a 2nd order polynomial fit to the existing data points. The dQ relation for RKM 885 (which in fact is the inverse of equation 2.1) is:

$$d = -8.35063 + 0.000232666\sqrt{1.232702489 \cdot 10^9 + 859600Q} \tag{2.2}$$

Applying equation 2.2 to the daily discharge from Figure 2.2, the daily average water depth is obtained:

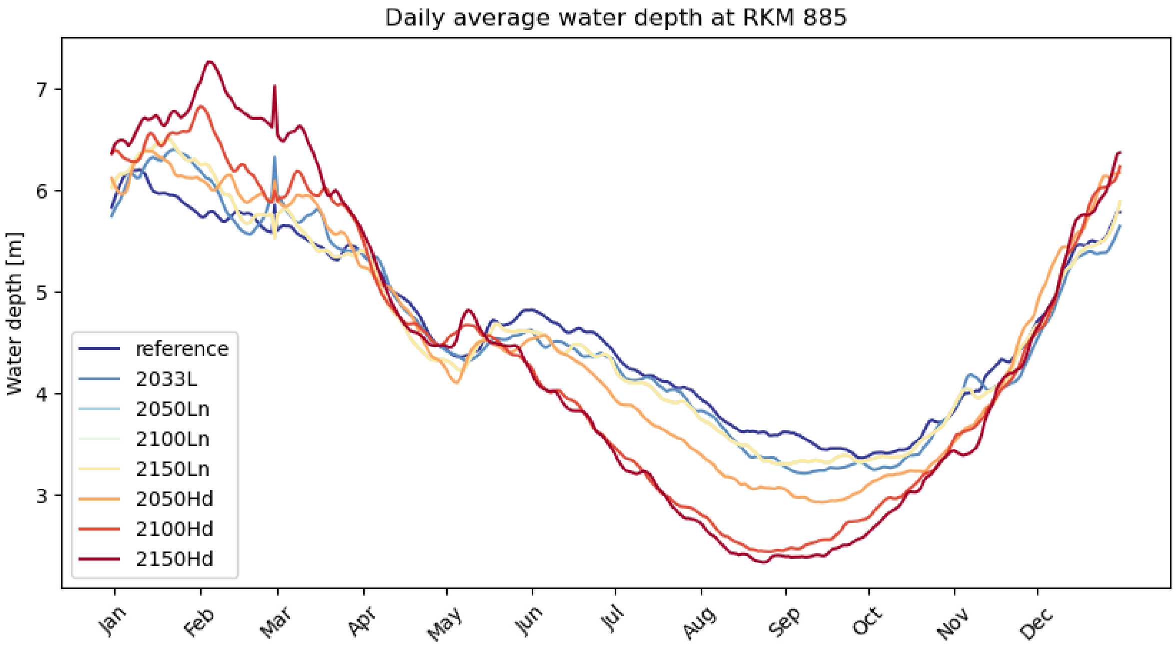


**Figure 2.8:** Daily average water depth at RKM 885

This Figure 2.8 shows the same pattern as the discharge, which is a logical expectation, since the dQ relationship is close to linear. At first glance, it is clear that there is almost a meter difference between the Hd and Ln scenario's during the period August-October when the lowest water levels prevail. The lowest annual average drought is expected in 2150 Hd with less than 2.5 meter water depth in august. This is very close to the situation in 2100. The leap between reference-2050 is in the same order as 2050-2100, indicating a steady decline. Obviously this is only the case for Hd scenario, since in Ln scenario the averages are similar to the reference scenario

## 2.3. Identifying trends in navigability and placing it in retro perspective

Based on previous sections it became clear that there are trends in the occurrence of low discharge and water depth in the future under climate change. This changing trend and it's effect on navigability are considerations for canalization. In this section these trends are more elaborated on. Furthermore the hydrological developments are put into perspective of the 2018 drought, to help interpret the severity of the future developments.

### 2.3.1. Trends in low discharge

A discharge of <1800 $m^3/s$ is recognized as a low discharge with hindrance for navigation. Zooming in on the occurrence of discharges <1800 $m^3/s$ gives an indication of the trends in low discharge.

#### Days of low discharge

If the trend in days of low discharge development is plotted in Figure 2.9, it is apparent that the number of days with hindrance for navigation increases for a high emission and dry climate scenario. For the low emission and wet scenario this remains rather stable. It is however the least extreme development, so it is likely that the real development ends up somewhere in between the bandwidth, thus implying an increase in days with low discharge. It is important to realise that already in the reference scenario almost half of the year there is no completely full unhindered navigation for (the largest, 6-barge push convoy, elaborated on in section 4.2) vessels possible.

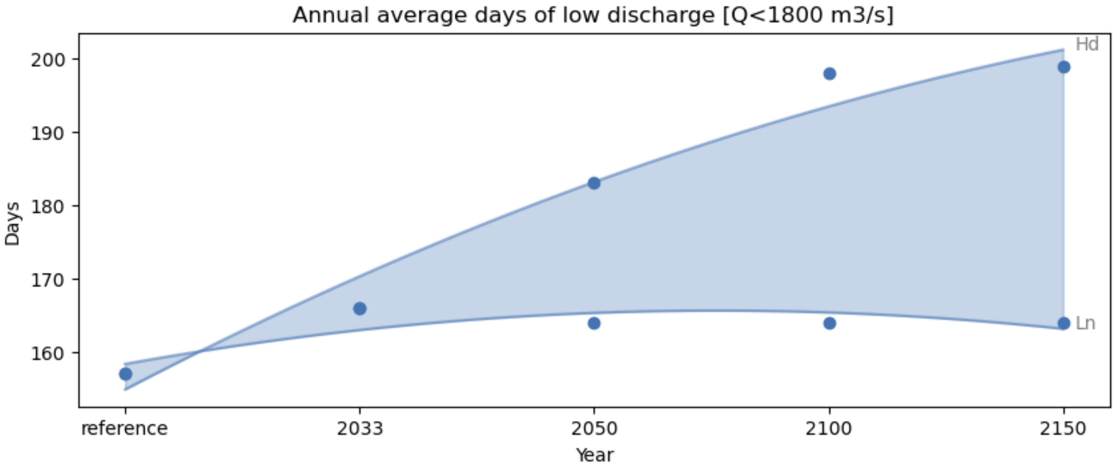


**Figure 2.9:** Development of days for Q<1800 $m^3/s$ at Lobith

### Water depth during low discharge

The water depth during these periods of discharge <1800 $m^3/s$, depicted in Figure 2.10, shows a mirrored trend of the days of low discharge. During the period of low discharge, the water level decreases on average in the high dry scenario. Again, under the low scenario, development remains fairly stable. In general this means that water depth during low discharge decreases.

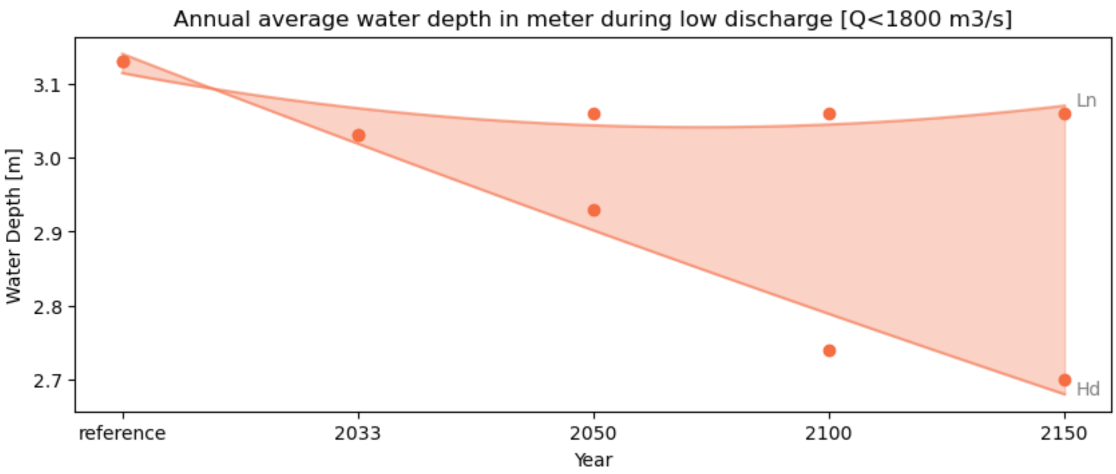
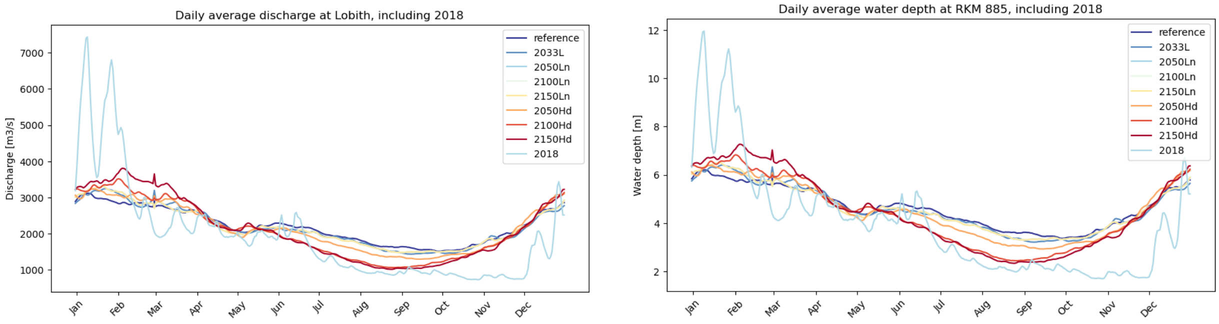


**Figure 2.10:** Development of water depth during Q<1800 $m^3/s$ at Lobith

## 2.3.2. Future navigability in light of the 2018 drought

As described in the introduction, 2018 is recognized as an extreme year with a long period of sustained low water levels, leading to tremendous financial losses due to transport costs increase. It is interesting to investigate how a year like 2018 compares to an average future year (under scenario's) in terms of discharge and water depth. When plotting similar graphs as in the previous sections the hydrological development looks as:



(a) Discharge Lobith

(b) Water depth RKM 885

**Figure 2.11:** Hydrological development including 2018

It is immediately clear from Figure 2.11 that 2018 has not had a standard discharge pattern. Whereas that an average year is characterised by a sinusoidal pattern, 2018 experienced 2 extreme high peaks during the wet season and a low discharge during the dry season that persisted for an unusually long time. The average, of course, does not tell the story of an individual future year where it is not at all inconceivable that a year like 2018 occurs again. de Jong (2019) determined that a year as 2018 has a return period of 10 years in the most extreme climate scenario. In the 2150 Hd scenario's, the minimum water depths reached during summer almost matches the 2018 case, which means that the severity of low water depth in 2018 is approached every year in these scenario's. The duration however is way shorter, only half of the time.

## 2.4. Concluding remarks

In this chapter the first research question is answered, which is described in terms of discharge and water depth:

**1. What impact can climate change have on the navigation conditions of the River Waal?**

### 1a. How does discharge at the River Waal change due to climate change?

As for discharge in the future, there is no single path that can be described. The development is highly dependent on the climate scenario that unfolds in the future. However, a spread can be distinguished between a low emission scenario with wet conditions ‘Ln’ on the one hand and a high emission scenario with dry conditions ‘Hd’ on the other. These two scenario’s represent the most extreme cases when discussing drought. As turns out, the difference between wet and dry conditions is more decisive than anthropogenic emissions.

The Ln scenario is in line with the 2033 Paris climate agreements. In this scenario there is little deviation from the reference scenario over time. The number of days with low discharges (<1800 $m^3/s$) remains similar as in the current situation with around 160 days. The lowest discharge in an average year is around 1500 $m^3/s$.
The Hd scenario however shows structurally lower discharges in a steady decline until 2100, after which the trend flattens. Extreme low discharges <600 $m^3/s$ appear and summers in an average year have minimum discharge of 1000 $m^3/s$ in 2150, which is 750$m^3/s$ lower than in the reference scenario. Furthermore the low discharge peak shifts as much as one month earlier where the peak also lasts longer. This is supported by the trend that there are more days with discharge <1800 $m^3/s$ further into the future.

### 1b. How does this discharge change affect the water depth?

Based on the analysis of annual, as well as daily discharge/water depth there will be no scenario with improved navigability (=less low water depth events). The worsening of navigability depends on the climate scenario where stabilisation in line with current navigability conditions is the ’best case’ scenario.

The location with the lowest water depth of the navigation route determines the maximum loaded draught of vessels. For the River Waal RKM 885 at Nijmegen is found the most critical location, based on known Qh relations and the bed profile of 2018. The water depth shows the same patterns as for the discharge, with a Ln scenario stable through time and a dry extreme Hd scenario.
Low water depth as 2.8 meter occur in the Hd scenario up to 3 times as much as in the reference scenario, including outliers to <1.6 meter, which matches the lowest recorded water depth in 2018. In the Hd scenario, the lowest observed average depth declines from 3.5 meter in the reference case tot 3 meter in 2050 and <2.5 meter after 2100. Again, Ln is fairly constant in time having a lowest average water depth of 3.5 meter. An average future year does not match the annual discharge pattern as observed in 2018, especially not the duration of drought in 2018. The lowest water depth in an average 2150Hd does however match sections of the 2018 drought. It should be mentioned that it is not inconceivable that individual years are as bad or worse than 2018. In general, the water depth during low discharge tends to decrease in the future. This is expected to cause problems for inland navigation.

This insight and the description of occurrence of specific water levels, serves as the input for the considerations on canalization in Chapter 4. The knowledge about occurring water depths on the future River Waal serves as a basis for the next step (3) in the research approach, in which a start is made on considering the impacts of climate change on the loading rate of vessels.

# 3

# Development of Transport Function

The second research question aims to find an answer on how the cargo transport function of the River Waal evolves in the future under climate change. The change in transport function of the river is a consideration in the decision on canalization. To answer this, first the relation between water depth and cargo transport is elaborated on followed by a methodology description which is used to determine the future vessel cargo loading capacity on a daily average and during low discharge. Lastly a first order investigation of future corridor cargo transport capacity is made. This chapter covers steps 3, 4, and 5 from the research approach, respectively in section 3.1, 3.2 and 3.3.

## 3.1. Determining the relation cargo transport and water depth

This research focuses on the River Waal as a corridor for transport from the Netherlands to the European hinterland via inland shipping as modality. The function of inland shipping is to transport cargo over the River Waal. From a navigation perspective, the function of the river is to accommodate vessels, allowing them to transport cargo, which gives the river a function for cargo transport. There is assumed to be three limiting factors to cargo transport via inland navigation. First one is the size and composition of the fleet, second is the capacity on the waterway for (safe) navigation. Both these are outside of the scope of this research. Last is the water depth, which is a physical restricting factor on the loading rate of vessels. This section aims to describe the relation between the cargo transport by inland navigation and water depth, used to investigate the effect of changing water depth on cargo transport later on.

### Tonnage certificate

For every vessel there is an official tonnage certificate (Dutch 'Meetbrief) which shows the relation of the draught of the vessel and the cargo loaded in the vessel in tonnes. Every vessel has different characteristics (dimensions, equipment, custom modifications, etc.), therefore an individual assessment is made per vessel. Captains use these relations to determine the amount of cargo they can transport, based on the (critical) water depth along their route from origin to destination. Van Dorsser et al. (2020) developed a method that determines a generic relationship between a vessel's draught and its loading rate based on a large set of certificates, distinguishing between the type of vessel and its dimensions. The next section elaborates on the methodology proposed by Van Dorsser.

### Method to relate vessel draught and loading rate

Van Dorsser aims to aggregate the detailed knowledge about relationships between draught and loading rate for individual vessels and upscale it to an overall corridor performance, which can be used for the design of supply chains, optimisation of the fairway and long term infrastructure development. Furthermore the model structure is well-suited for analyzing the effects of climate change on inland shipping, with which the judgement of low water effects on the loading rate of inland ships can be better estimated (Van Dorsser et al., 2020). This makes the model suitable for this research.

In principle, there is a general model with three supporting models with which the absolute and/or relative loading rate of a vessel is estimated with as input the empty draught of the vessel and the actual draught. It is important to note this method is made generic for different vessels by applying a baseline load factor, which is set to 100 and corresponds to the load factor of a vessel at a draught of 2.5 meter. By applying this methodology the computation becomes dimensionless, making it independent from vessel dimensions. The three supporting methods simplify the run-up to using the generic method. The first model estimates the empty draught as a function of the vessel's length, beam, type, hull type and design draught. The second model estimates the design draught and the third model estimates the design capacity (which is used if the absolute capacity in tonnes is asked for). For further details about the supporting models is referred to Van Dorsser et al. (2020).

The baseline capacity serves as a pivot point for the output modelling purposes. The baseline capacity is determined in two steps. First, the relative loading capacity factor at design draught is estimated, compared to the loading capacity at the baseline draught. Afterwards, the absolute design capacity is divided by this relative loading capacity factor. From the obtained baseline capacity, the capacity at any draught can be estimated by multiplication of the relative load capacity factor at a desired draught by the absolute capacity at the baseline draught.

The main input of the computation is thus the actual draught of a vessel. The (maximum) draught is the water depth minus the applied under keel clearance. Under keel clearance is used as a safety margin by captains to prevent hitting the bed. The application of UKC in practice is not very straightforward and depends on the vessel type, sailing conditions, type of waterway, personal preference of captain, etc. Van Dorsser elaborates on this discussion and mentions various application strategies. One argument mentioned is the UKC applied in the modelling approach in the BIVAS software (used for network analysis in inland shipping), which assumes a minimum of 30 cm UKC during low water events. This is in line with the other observations (de Jong, 2020a; Solar, 2012), therefore in this research a UKC of 30 cm is applied.

The model is build as an extensive regression to known draught-capacity relations. 157 vessel loading certificates, of which 124 are used for modelling and 33 for validation, served as input for a generic regression fit. The certificates spread around vessel types among others dry bulk single hull, dry bulk double hull, containers, tankers and dumb barges (excluding the pusher). These are said to represent the fleet at the Rhine. Figure 3.1 shows the model fit to the actual capacity index CI for the various vessel types. It is a visual representation of equation 3.1, where Te is the empty draught and Ta the actual draught.

$$CI = 2.0 \times 10^{1} - 7.9 \times 10^{1} \cdot Te - 7.1 \times 10^{0} \cdot Te^{2} + 2.8 \times 10^{1} \cdot Ta + 7.6 \times 10^{-1} \cdot Ta^{2} + 3.7 \times 10^{1} \cdot Te \cdot Ta \quad (3.1)$$

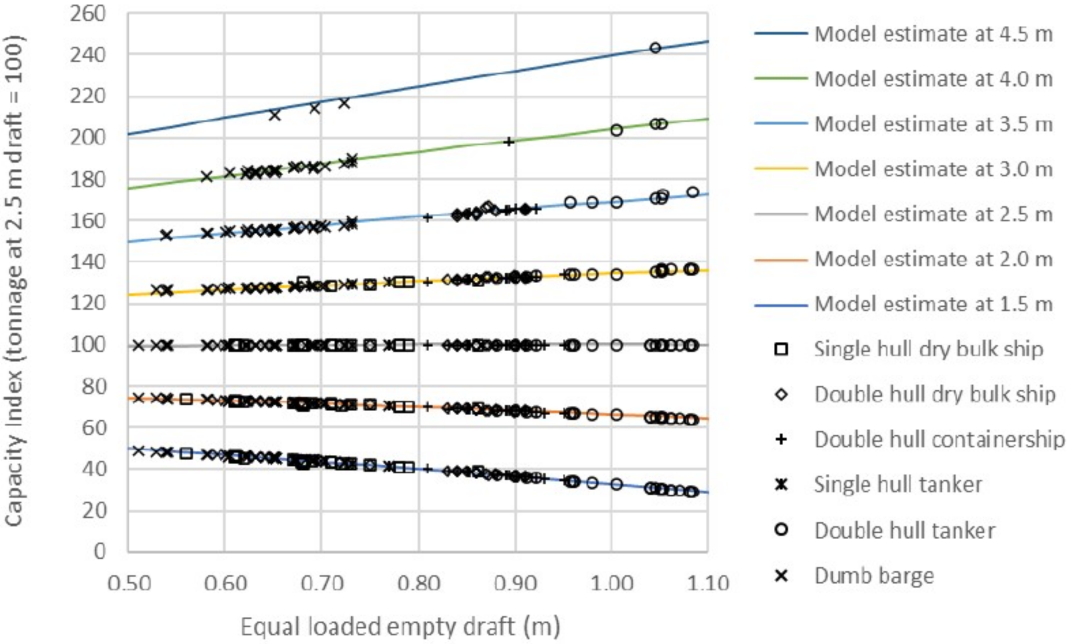


**Figure 3.1:** Fit of regression model for capacity index, adopted from Van Dorsser et al. (2020)

The method is best explained by means of an example calculation. For this a reference is made to chapter 8 of Van Dorsser et al. (2020). In appendix D, an overview is given of the calculated application of the methodology for determining the minimum and maximum capacity, applied to different vessel types and sizes. Overall, this method is a simple, yet useful and insightful way to determine loading rate of vessels solely in relation to water depth. The supporting models are of great added value, since they limit the amount of required additional input vessel data.

## 3.2. Calculating vessel loading rate under climate change

Climate change causes discharge patterns on the River Waal to alter. Section 2.2.4 described the daily average water depth under in the 'Hd' and 'Ln' climate scenario. In this section the method of Van Dorsser is applied on the description of future water depth. The results give insight in the loading rate of vessels on a daily basis, as well as during low discharge.

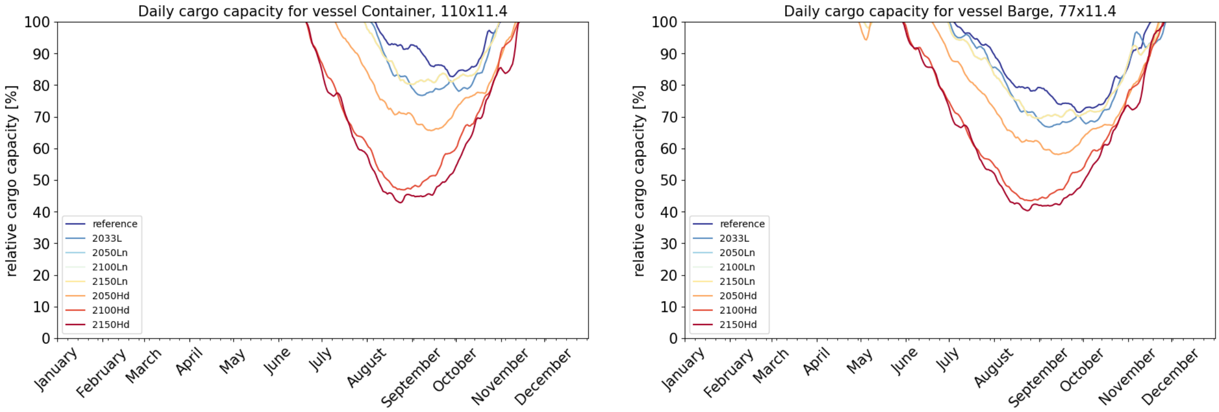
### 3.2.1. Daily average loading rate

The daily average water depth is the main input for the computation of vessel loading rate using the methodology as described in section 3.1. Furthermore it requires as input vessel type and dimensions. For the selection of vessels it is chosen the same as Van Dorsser considered, since this gives the opportunity to validate the output of the model. The computational script was tested to ensure that the results were consistent with the results of Van Dorsser et al. (2020) as in appendix D. Table 3.1 gives an overview of the considered vessel types. These are the most common vessels navigating the River Waal.

**Table 3.1:** Overview considered vessel types

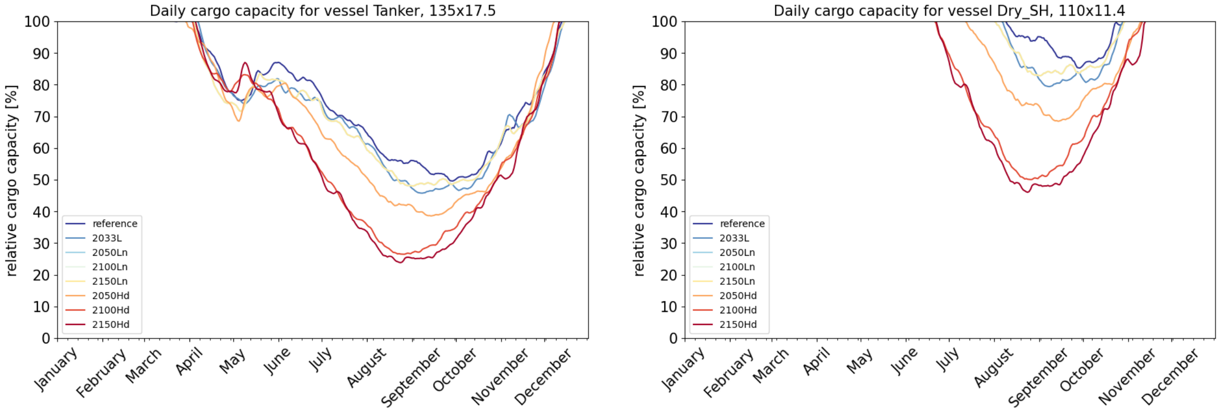
| CEMT Class | Dimensions | CEMT Class | Dimensions |
|---|---|---|---|
| **Tanker** | | **Containerships** | |
| Class IV | 85 x 9.5 m | Class III | 63 x 7.0 m |
| Class V | 110 x 11.4 m | Class IV | 85 x 9.5 m |
| Class VI+ | 135 x 17.5 m | Class V | 110 x 11.45 m |
| **Dry bulk (single hull)** | | Class VI | 135 x 14.25 m |
| Class II | 55 x 6.0 m | Class VI+ | 135 x 17.5 m |
| Class III | 80 x 8.2 m | **Dumb barges** | |
| Class IV | 85 x 9.5 m | Class IV | 70 x 9.5 m |
| Class V | 110 x 11.4 m | Class V | 77 x 11.4 m |
| **Dry bulk (double hull)** | | Class V | 90 x 11.4 m |
| Class IV | 85 x 9.5 m | | |
| Class V | 110 x 11.4 m | | |
| Class VI | 135 x 11.4 m | | |

The output of the model computation is the theoretical *maximum loading rate* (as a fraction of 100%) possible at the corresponding water depth for a specific vessel type with given dimensions when a UKC of 0.3 meter is applied. Figure 3.2 shows the output for a selection of vessels. The loading rate of all modelled vessels can be found in appendix E.



(a) Container, 110x11.4m, CEMT V

(b) Barge, 77x11.4m, CEMT V



(c) Tanker, 135x17.5m, CEMT VI+

(d) Dry bulk (single hull), 110x11.4m, CEMT V

**Figure 3.2:** Daily average loading rate for a selection of vessels

For each individual vessel it is clear that the annual pattern of loading rate is similar as the annual water depth pattern in Figure 2.8, however, the loading rate stops at a factor of 100%, which is reached when the maximum vessel draught is possible for navigating vessels. With increasing water depth the loading rate increases. These characteristics differ per vessel, which means that the duration of 100% loading rate differs. Larger vessels have a large maximum draught, thus experience depth restrictions for longer period of time than smaller vessels.

For every vessel type in Figure 3.2 there is a large difference in loading rate pattern between climate scenario's. Once again the Ln scenario closely matches the reference scenario, no matter how far a time horizon is considered. The most common vessel type 110x11.4 meter CEMT Class V in Figure 3.2a is unable to load full draught, with restrictions in August to November and a minimum loading rate of 80% in the reference case. In the Ln scenario this decreases in an average year to 75% in the worst case. The duration of hindered loading remains the same. For the largest size vessel on the River Waal, a 135x17.5 meter CEMT Class VI+ tanker, loading is already restricted for the largest share of the year. Full draught is only possible between December and April on average. An Ln scenario doesn't change much here. At the lowest point in September a loading rate of around 50% is possible.

The Hd scenario describes a different future. For a 110x11.4 meter CEMT Class V vessel the minimum loading rate in September decreases from 60% in 2050 to 45% in 2100 and 40% in 2150. The duration of restricted loading steadily increases from 2 months in the reference scenario to 5 months in 2150. For 135x17.5 CEMT Class VI+ tankers the minimum loading rate drastically decreases in September to only 25% in 2150 Hd. Clearly here is also the minimum peak shifts from October in reference to September in 2150. In 2100 already the pattern of loading rate closely matches 2150. What does stand out is that for this vessel type the duration of restricted loading does not substantially increase in the future, independent of climate scenario. This could be explained by the tipping point of 100% loading rate to <100% loading rate being around a time in year where the discharge pattern experiences little variation in the future under climate change.

It is important to mention that not every vessel type in the active Rhine fleet is modelled here. Coupled barges and coupled vessels for example are not taken into account, as well as vessels with non-standard dimensions. This is a limitation of the applied methodology.

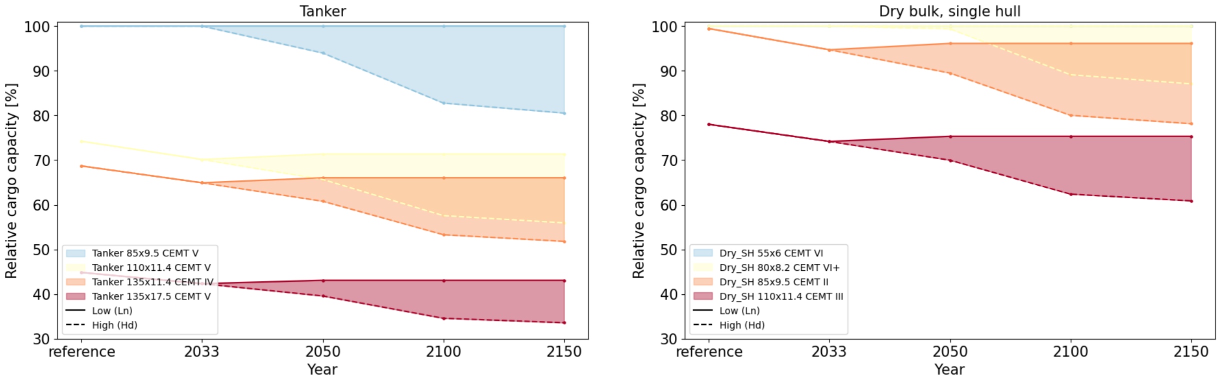
### 3.2.2. Vessel loading rate during low discharge

Financial losses in inland shipping such as in 2018 are a result of reduced loading rate during low water. In section 3.2 it was shown that reduced draught was only experienced for specific time period. It makes sense to zoom in on the time of year when lower water levels occur, so that the effect on loading rate during these extreme event between years/scenario's can be quantified. Within the 'klimaatbestendige netwerken' project (de Jong, 2020a), a discharge of 1800 $m^3/s$ at Lobith is recognized below which level navigation is experiencing restrictions. In section 2.3 this threshold is also considered, where it could be seen that the number of days lower than 1800 $m^3/s$ increases and the water level also decreases during this period. In this section the impact this has on average loading rate during discharges <1800 $m^3/s$ is studied.

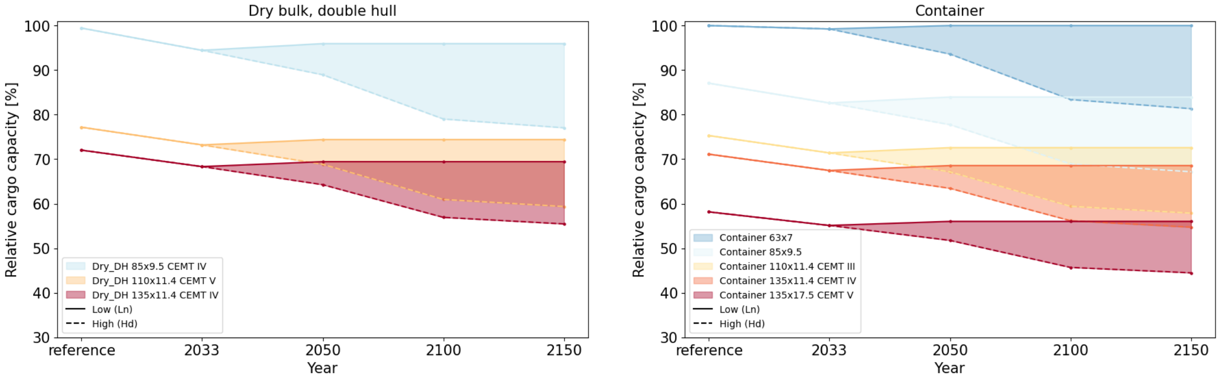
#### Implications low discharge on vessel loading rate

Starting point is the average water depth at RKM 885 in a Hd scenario and Ln scenario from Figure 2.10 during conditions of <1800 $m^3/s$ discharge at Lobith for every characteristic year in the climate modelling. Via the Van Dorsser method, per vessel type and dimension the relative loading rate corresponding to this average water depth is computed against the time in Figure 3.3 as a scatter. A solid line connects the data points from the Ln scenario and a dashed line connects the data points from the Hd scenario. The lines are however not per definition the computed development between years, but more a visual aid to understand the trends better. A hashed area represents the spread of climate scenario's that can occur. Every vessel type and it's CEMT classes are combined in a single graph.

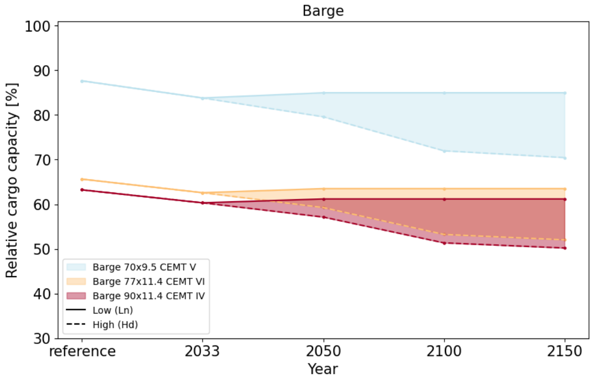
There is only one vessel type that can sail without draught restrictions over full year independent of the climate scenario, which is a dry bulk 55x6 meter CEMT Class II. This is also expected to be the case for smaller non-modelled vessels. A 80x8.2 meter CEMT Class III experiences unrestricted sailing all year round only in the Ln scenario, whereas it decreases tot 85% in the Hd scenario. Generally speaking for every vessel type and size there is roughly a difference of 15% point in loading rate between the Hd and Ln scenario. It can also be clearly seen that after 2100 the average loading rate stabilises, independent of climate scenario or vessel type. What is particularly striking is that based on this calculation method, there are already serious loading limitations in the reference scenario. To this, climate change in an average year does not add particularly much, only a decrease of up to 15%. For a 135x17.5 CEMT VI+ container the average is already slightly above 60% and same size tanker even below 50%. It is important to note however that this method determines theoretical maximum loading rate. In practice loading rates will be lower, predominantly due to external factors. Theoretical maximum is however a good method to compare between scenario's, conditions and vessel types.



(a) Tanker (b) Dry bulk (single hull)



(c) Dry bulk (double hull) (d) Container

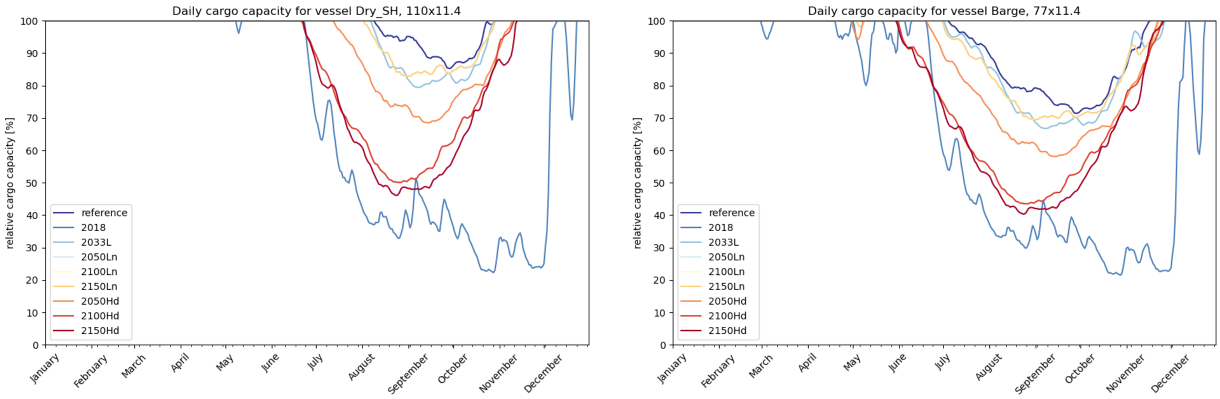


(e) Barge

**Figure 3.3:** Maximum (theoretical) average vessel loading rate during Q<1800 $m^3$ at Lobith

### 3.2.3. Future transport capacity in light of the 2018 drought

Section 2.3.2 showed the 2018 daily discharge and water depth compared to the future daily average under climate conditions. It became clear that 2018 was not standard, especially because of the long sustained low discharge. In this section the daily average water depth of 2018 is translated to daily average loading rate using the Van Dorsser method in order to put the development of future loading rate under climate change into perspective.



(a) Dry bulk (single hull), 110x11.4m, CEMT V

(b) Barge, 77x11.4m, CEMT V

**Figure 3.4:** Daily average loading rate for a selection of vessels including 2018

Figure 3.4a shows the daily average loading rate for the most common vessel 110x11.4 meter dry bulk CEMT class V. The lowest average loading rate in the most severe scenario 2150 Hd is around 50%, whereas at the same moment the loading rate in 2018 was <40%. The most notable fact is that after September in an average future year the loading rate steadily increases tot 100% in November, while in 2018 the loading rate initially decreases further to 25%, after which a very steep correction occurs to 100% in November. Besides, the peaks are more profound in 2018, because the other years are an average. These peaks can cause the theoretical loading rate to increase more than 10% for only a single week.

In Figure 3.4b the volatility of loading rate in an individual 2018 year is more profound, since in the period from March to July, multiple times a week or more occurs with a loading rate lower than 100%, whereas in an average future year this period is steady at 100%. Also the steep increase and decline in 2018 stands out. That is different from an average sinusoidal pattern, thereby making the predictability of loading rate in 2018 a lot lower than for an average year.

Generally speaking, loading rates as observed in 2018 will not be matched on average even in the most severe 2150 Hd scenario. It is however not inconceivable that individual years may match or surpass 2018. This chance seems to be much higher in a Hd scenario however than an Ln scenario.

## 3.3. Determining the corridor cargo transport capacity

Due to climate change the loading rate of vessels changes according to the previous section. It was shown that there where large differences between climate scenario's and types/sizes of vessels. To get a good idea of the overall transport function development of the River Waal under climate change the corridor cargo transport capacity must be determined, which is step 5 in the research approach. To be able to give an in depth view on corridor capacity raises the demand for new variables, including fleet composition, fairway intensity/capacity, fractions of empty sailing and overall market developments. Considering the time available for this research such a computation is deemed too large and complex. To still have a perspective on future development of total cargo transport, an alternative method is applied based on historic data. For more detailed and accurate results a simulation method should be applied. A suggestion for this method is briefly elaborated on later in this section.

### 3.3.1. Method description corridor cargo transport capacity

With the simplified method the aim is to project the response of inland shipping to discharge extremes from the recent past on the future, in which daily average discharge is the linking variable. The historic behaviour is studied by Vinke et al., 2024. This section elaborates on the research conducted by Vinke and the applied methodology to determine the future behaviour.

The goal of this method is to project the performance indicators of the recent past to future daily average discharge to get a first order estimate of performance in the future under climate change. With this simple methodology results are not expected to be dead accurate, but they do show a trend of the performance. The application of this method involves assumptions, mainly the idea that the 2010-2020 period behaviour is leading and characteristics of IWT do not change in the future. This includes amongst others: composition and size of fleet, performance of individual vessels in a fleet, distribution of various cargo types, stationary demand of transport over water and repetitive/similar reactions to drought events.

#### Historic response inland shipping to discharge extremes

Vinke et al. (2024) conducted a research on the response of inland shipping to varying discharges on the River Waal for the period 2010-2020, by means of various performance indicators. This is based on 10 years of discharge data and detailed IVS data ('Informatie Systeem voor de Scheepvaart', Information System of Inland Shipping). This data includes vessel information, amount of trips made and type of cargo transported. This insight in shipping behaviour is said to be useful for estimating the risks of climate change and corresponding alterations in discharge regime. It matches the aim of this research, so this information is suitable to use here.

Two datasets are used, the daily average discharge at Lobith in the timeframe 2010-2020, as well as the data from the IVS data system at measuring traject Germany - Maas-Waalkanaal, which also cover Lobith. The studied performance indicators from IVS are transported volume [tonnes], transported containers [TEU], number of trips and vessel loading rate. Within the transported cargo a distinction is made between cargo types dry bulk, liquid bulk and containers.
The discharge is sorted out in bins, within a range of 700 $m^3/s$ and 8500 $m^3/s$. For low discharges <1200 $m^3/s$ a bin size of 50 $m^3/s$ is applied. For high discharges >4500 $m^3/s$ a bin size of 250 $m^3/s$ is applied. Intermediate bins have a width of 500 $m^3/s$. An average discharge over a day at Lobith adds a single count towards the corresponding discharge bin
For each daily discharge event, the corresponding value from the performance indicator is added to the bin and summed. Afterwards the total value from the performance indicator is divided by the number of days in that bin, which gives the daily performance in a discharge event. Figure 3.5 is an example of the performance for daily cargo transport at Lobith, sorted per discharge bin.

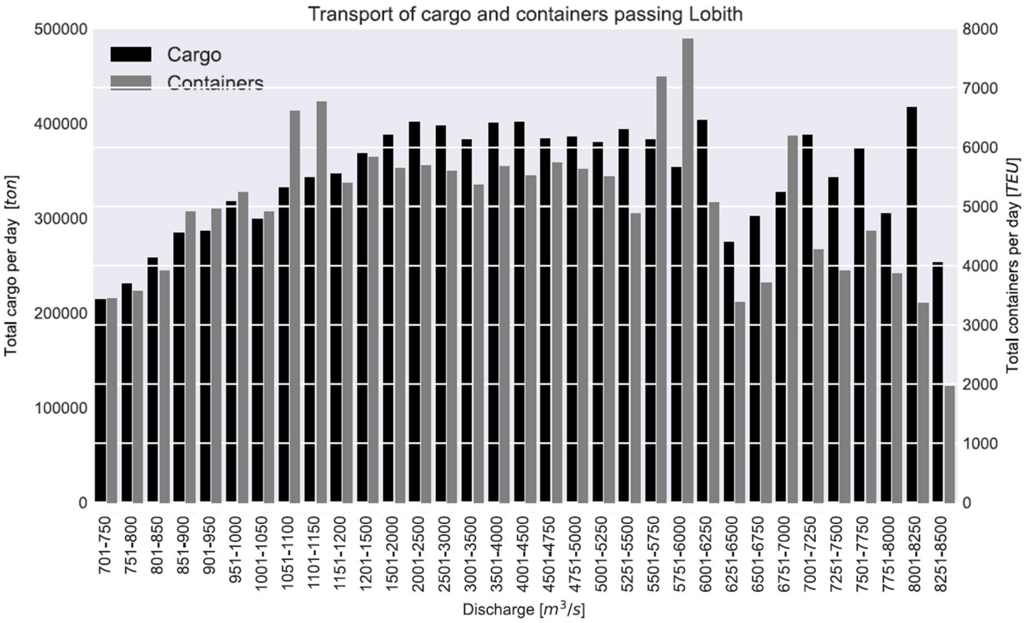


**Figure 3.5:** Observation of cargo transport in relation to discharge 2010-2020 (Vinke et al., 2024)

#### Projecting historic response inland shipping to future discharge

In section 2.1.3 a description of future annual average discharge at Lobith was given, based on the daily undershoot of characteristic discharge values. In the calculation method also discharge bins where used, based on the characteristic discharge values. When altering the bin sizes to match those of Vinke, the number of future days within those bins can be determined, with which a comparison is made to 2010-2020. For discharges >3000 $m^3/s$ a standard value is chosen for the performance indicators, since this research focuses on the effects of low discharge. Measurements of past high discharges are scarce which makes the data unreliable, while the impact of high discharge on the performance indicators is high. The effects would unfairly count too much in the computation of annual total.

### 3.3.2. First order assessment of future corridor cargo transport capacity

The future corridor cargo transport capacity under climate change is explained by means of performance indicators, which are used as a consideration for canalization. Two performance indicators are considered, the annual transported cargo via Lobith, as well as the number of annual trips via Lobith. Both parameters are computed for the total transport, but also a distinction is made between dry and liquid bulk, since in the past they showed different behaviour during low discharge which is expected to remain in the future. A view on the future is given with the known representative years in climate modelling. The most extreme climate scenario's form the bandwidth between which the development is likely to unfold. The Ln scenario is a dotted line representing the 'stationary' scenario, which matches the reference scenario closest. Unlike previous sections in this research, Ln is not per definition the 'least worst' scenario, which is due to the behaviour of the performance indicators during high discharge. There are scenario's other than Ln where more high discharges are observed, which have a positive effect on the performance indicators. This is however outside the scope of this research and will not be elaborated on.

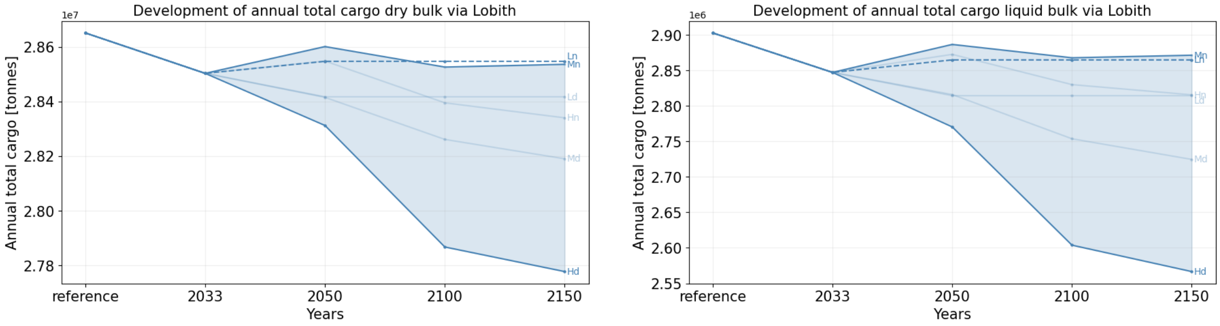
### Total annual transported cargo

The total annual transported cargo via Lobith is split between dry bulk and liquid bulk. Despite the simplicity of the method, the modelled performance of total annual cargo transport in the reference scenario only have a deviation of a few percent, compared to measured annual cargo performance in 2020, 2021 and 2022 in Figure 3.6. The order of magnitude is correct.

| Rhine stretch or affluent | Measurement point | Name | Volume of transport (in million tonnes) | | |
|---|---|---|---|---|---|
| | | | 2020 | 2021 | 2022 |
| Lower Rhine * | Border DE/NL | Emmerich | 130.0 | 134.5 | 124.9 |

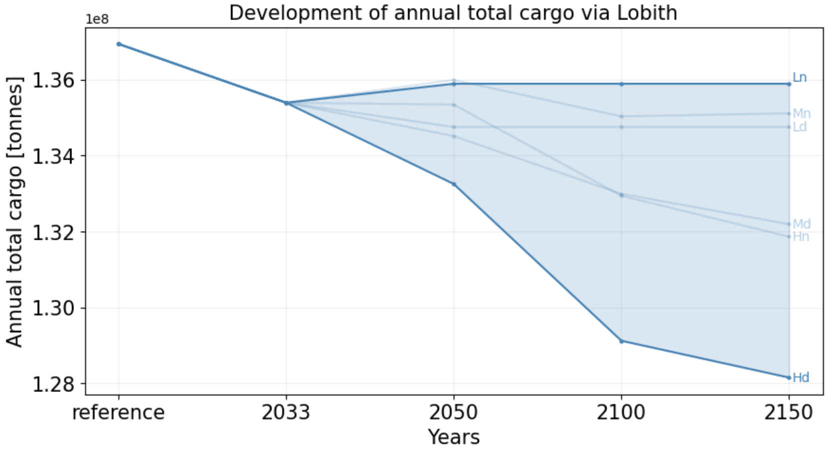
**Figure 3.6:** Recent annual cargo volume Lobith in million tonnes (CCNR, 2023a)

In Figure 3.7 the development of future annual average cargo in all climate scenario's is plotted for the total, dry bulk and liquid bulk transport (note: for the dry and liquid cargo only outbound data was available, the total cargo covers inbound and outbound cargo, both do however still cover the trend development) .



(a) Dry cargo

(b) Liquid cargo



(c) Total cargo

**Figure 3.7:** Future annual average cargo transport in climate scenarios via Lobith

In all scenario's, the total annual cargo transport decreases, although with varying rates, in a line that continues until 2150. Immediately the Hd scenario stands out, where performance decrease is up to twice as much as the second worst Hn scenario. Starting from a reference performance of 137 million tonnes, a <1% decrease is observed in the Ln scenario, independent of year, whereas -5% is estimated in an average 2150 Hd scenario. The strongest decrease initiates after 2050, in which the performance loss is -1.5%.

Zooming in on dry bulk shows the same pattern as total cargo. Starting with a reference performance of 28.7 million tonnes, a decrease of <1% is expected in the furthest Ln scenario. For a 2150 Hd scenario year this is -3% with again the strongest decrease after 2050. For liquid bulk, starting with a reference performance of 2.9 million tonnes, an annual decrease in Ln scenario of 1.5% is modelled. A Hd scenario implies a strong decline from -4.5% in 2050 to -10% in 2100 to -12% in 2150, a clear difference with dry bulk. It is important to mention that the total volume of liquid bulk (2.9 million tonnes) is small compared to dry bulk (28.7 million tonnes), making the contribution of liquid bulk decrease in total cargo decrease small.

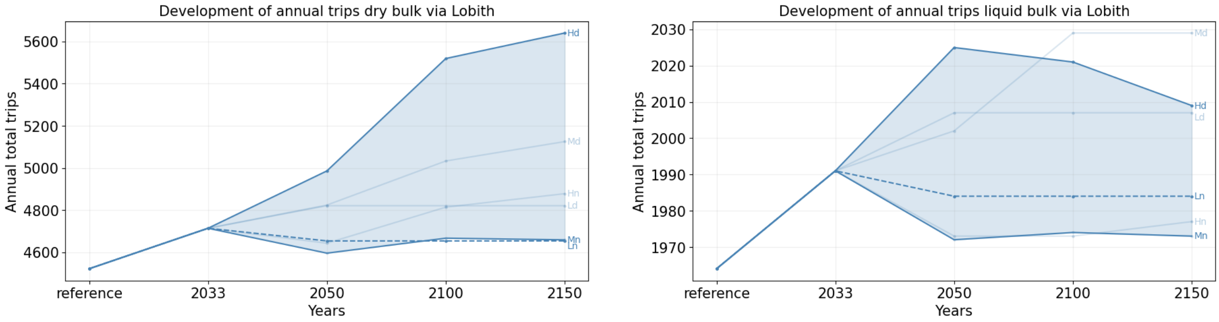
### Total trips

The difference in cargo transport for dry and liquid bulk can partially be explained with the number of trips. The total number of trips are determined as well as the number of dry and liquid bulk trips. The modelled reference number of trips do match the performance of recent measured trips in Figure 3.8. This supports the assumption that via this calculation method a reliable perspective of future trends can be made, even with the assumption of constant shipping characteristics during Q>3000 $m^3/s$.

| Rhine stretch or affluent | Measurement point | Name | Number of cargo vessels passing | | |
|---|---|---|---|---|---|
| | | | 2020 | 2021 | 2022 |
| Lower Rhine * | Border DE/NL | Emmerich | 102,555 | 106,497 | 105,886 |

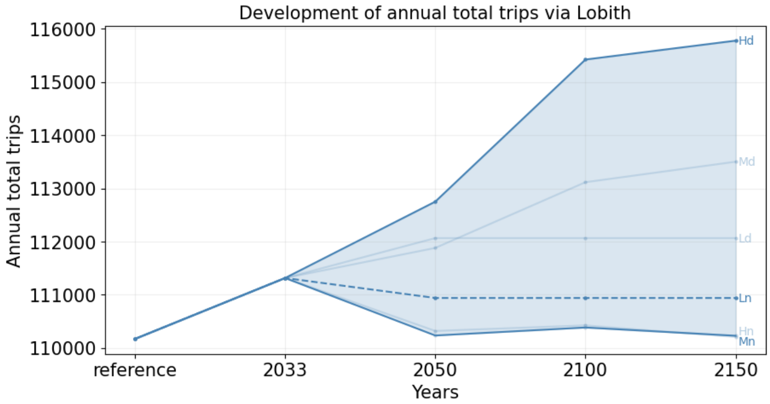
**Figure 3.8:** Recent trips Lobith (CCNR, 2023a)

In Figure 3.9 the development of future annual trips in all climate scenario's is plotted for the total, dry bulk and liquid bulk transport. (note: for the dry and liquid cargo only outbound data was available, the total cargo trips covers inbound and outbound cargo, as well as trips made by container vessels, which are not considered here. The graphs still support the trend development.)



(a) Dry cargo

(b) Liquid cargo



(c) Total

**Figure 3.9:** Future annual average trips in climate scenarios via Lobith

In the figures above a clear distinction is seen between a wet and dry climate scenario. Especially for total cargo it stands out that in a general wet climate the number of trips stays constant, whereas in a dry climate the number of trips steadily increases towards 2150. The 110.000 trips in the reference scenario remain stable in an Ln scenario, while in a Hd scenario the number increases with >5% in 2150. So despite an increase in trips of 5% in 2150 Hd (with which in theory more cargo can be transported), the total number of transported volume decreases with 5%. This says something about the resilience of the fleet. The extend to which the (current) fleet can counteract the effect of climate change on cargo transport. This is more evident when zooming in on the cargo types.

Starting from a dry bulk reference year with a number of trips of 4500, there is a light increase to 3% in every representative Ln year, but a stable increase in a Hd scenario of +11% in 2050 tot +22% in 2100 and +25% in 2150. The decline in cargo transport performance for dry bulk is minor, which is explained by the resilience of the fleet. The fleet can be deployed different, with different operation characteristics, so that the transported cargo performance does drop less as a result of climate change. The dry bulk fleet is large, diverse and flexible. In addition, vessels not normally carrying dry cargo can be used to carry dry cargo in extreme situations. This is not possible for liquid cargo. Since when zooming in on liquid bulk trips with a reference scenario number of trips of 1965, in the best scenario Mn there is an increase of <1% and worst case Md an increase of only +3% in 2150.

The loss of transported liquid bulk volume cannot be compensated with the resilience in the liquid bulk fleet by making extra trips. Vinke et al. (2024) states that a large dry bulk fleet can cover the effects of climate change better. Furthermore the market of liquid bulk works different, where a client is less willing to pay for additional transport costs than for liquid bulk. Vinke et al. (2024) also shows that the largest share of liquid bulk is transported with a 110x11.4 meter CEMT Class Va vessel (RWS M8) and barely any with smaller vessels. Dry bulk transport on the other hand is spread out over a larger selection of vessels, including coupled barges and push convoys, which can be employed more flexible. The liquid bulk fleet does not have substitution options that the dry bulk fleet has.

### 3.3.3. Description of a method for simulating impact of climate change on inland waterway transport

The applied methodology to describe performance of inland waterway transport (IWT) in the future in section 3.3.1 is a simplified first effort method. A more detailed result can be obtained via simulation of the IWT fleet using models. A qualitative description of future cargo transport is the basis on which requirements can be assessed who can substantiate the necessity of canalization. Models give the opportunity to simulate future cargo transport in which, by changing input variables, quick and clear different scenario's can be perused. Furthermore simulations serve well in threshold oriented research, where threshold performances are sought after (Wienk, 2021). For simulating IWT the OpenCLSim model can be used. The 'Open Source Complex Logistics Simulation' software uses Agent Based Simulation (ABS) and Discrete Event Simulation (DES) and finds its application in a wide spectrum of purposes, including quantifying IWT performance (de Boer et al., 2023). Discrete Event Simulation implies a model structure with discrete events that run in consecutive order, where for every event the model status updates. The execution of events is done by Agents. The behaviour of Agents is determined by input characteristics and interaction with other agents, which is Agent Based Simulation. IWT is well captured in a structure of events and agents. Kievits (2019) proposed a model, developed in OpenCLSim, with which the performance of IWT can be determined. In this section this method is explained, which should serve as a basis for a follow-up of this research. Hence, resulting in a better description of future corridor cargo transport capacity on the basis of which a decision for canalization can be better substantiated.

#### Model concept

The model is based on a combination of DES and ABS. It is assumed that in IWT, vessels interact with each other. The processes one vessel goes through affect the way other vessel go through processes. OpenCLSim uses 'work methods' which describe how discrete events work via equipment, sites and activities (see Figure 3.10). Equipment execute events that take place on sites where activities describe the processes of the event. All work methods require a set of input values. With consecutive events step by step the chain is modelled of activities between an origin and destination site. Using this framework the performance of the network can be expressed by transported cargo in time or time required to transport a set amount of cargo. Afterwards this can be post-processed to obtain transport costs (Kievits, 2019).

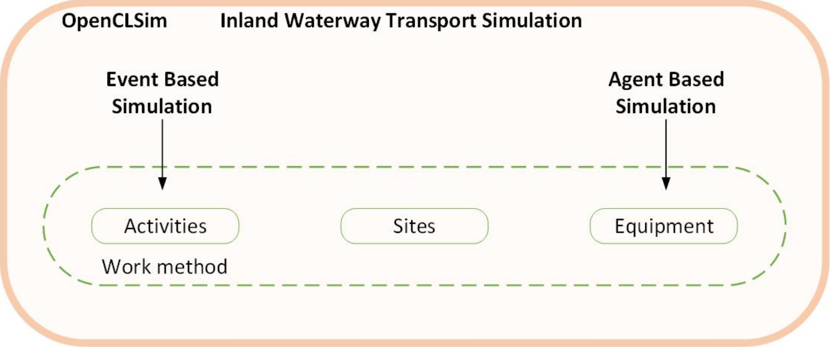


**Figure 3.10:** Simulation model concept, adopted from Kievits (2019)

#### Model structure

A number of steps precede the simulation part in the model structure. These steps do match the steps the approach of this research. Kievits states water depth as starting point, which is step 2 in the current research approach, preceded by a description of discharge. Kievits suggest modelling of hydrodynamics (discharge and water depth) via SOBEK software. Here, the relations are determined based on measurements. The model describes a negative relation between water depth and active vessels in the fleet, assuming the number of active vessels increase when water depth decreases, due to higher demand for cargo transport capacity. Furthermore water depth determines the loading rate of vessel. Kievits used a rule of thumb computation interpolating between minimum and maximum loading rate. This research applied a methodology proposed by Van Dorsser et al. (2020) (research step 3) where

a function fit is applied to real life vessel loading rate statistics to obtain an general equation that determines loading rate based on given water depth with low input variable demand.
The combination of loading rate and number of active vessels determine the number of trips required to fulfill a set cargo transport demand. The number of trips and loading rate determine the corridor cargo transport capacity performance in tonnes. This is an iterative process in which at insufficient cargo transport performance the number of vessels increase until a (predefined) maximum is reached.
Subsequently a step to costs can be made, which follow from two steps in the system. It is assumed that there is a negative relation between loading rate and price of cargo transport. Total cargo transport costs are obtained by multiplying the number of trips by the cost of transport. When the corridor cargo transport capacity is insufficient to fulfill the cargo transport demand, additional costs are added on the basis of delayed time. The full simulation model structure is depicted in Figure 3.11. Based on this model structure, it is easy to provide a quantitative outline for the development of corridor cargo transport capacity and associated transport costs in the future. This is important in determining the necessity of canalization. Namely, requirements for transport capacity and/or costs can be tested against quantitative development. Failure to meet requirements could indicate the necessity of canalization.

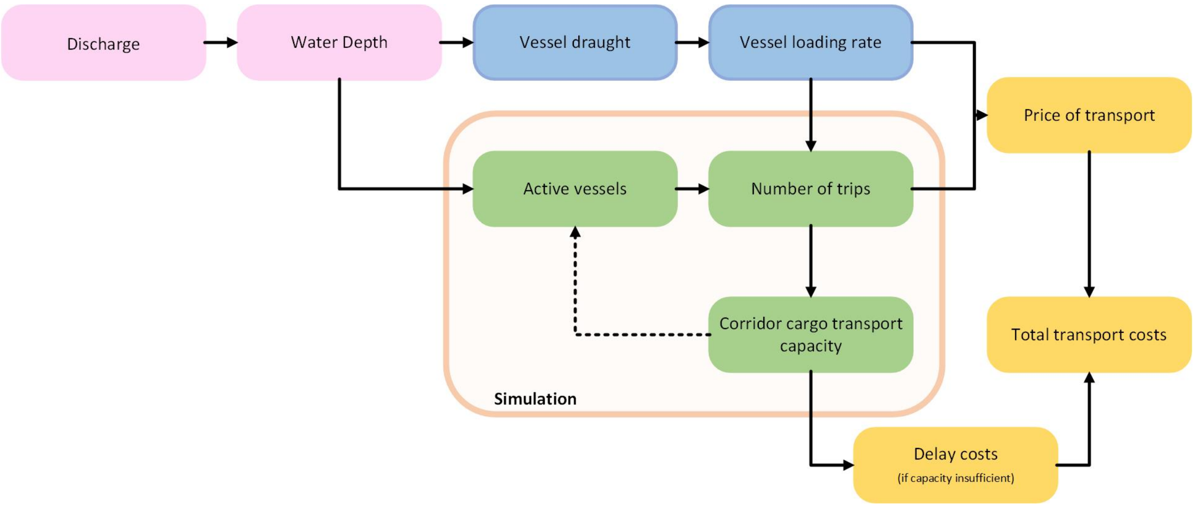


**Figure 3.11:** Simulation model structure, adopted from Kievits (2019)

### Simulation model input and output

Data input is subdivided into the previously mentioned equipment, sites and activities, shown in Table 3.2. Equipment describes the vessels that follow the IWT cycle and the infrastructure at a location that execute events. Sites are the borders in which the cycle operates with an origin and destination. Between origin an destination a path describes the route of vessels. Activities are the events in the IWT cycle. They link sites with each other and describe the activities of equipment. As said, activities are discrete where a new operation starts after the previous has finished. The activities in the IWT cycle are simple: (un)loading and sailing, with waiting time in between (see Figure 3.12)

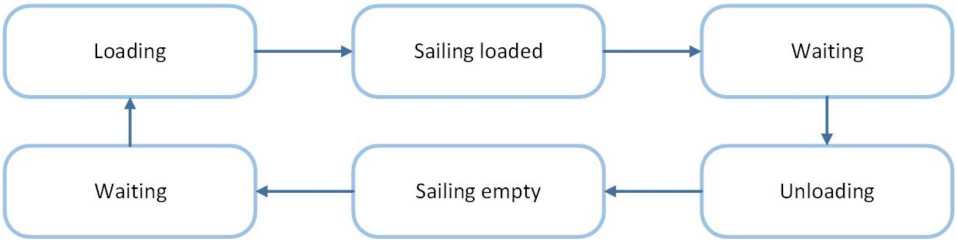


**Figure 3.12:** Simplified IWT cycle, adopted from Kievits (2019)

**Table 3.2:** Overview of IWT model simulation input and output variables, adopted from Kievits (2019)

| **Input** | | | | **Output** |
|---|---|---|---|---|
| *Equipment - Fleet* | *Equipment - Berths* | *Sites* | *Activities* | Number of trips |
| Vessel name | Berth name | Site name | Activity name | Transported cargo |
| Vessel capacity | Number of resources | Location | Origin | Vessel costs |
| Vessel empty draught | Loading rate | Capacity | Destination | Delay costs |
| Vessel full draught | Unloading rate | Initial volume | Loader agent | Transport costs |
| Under keel clearance | | | Mover agent | |
| Fleet size | | | Unloader agent | |
| Loaded sailing speed | | | Start event | |
| Empty sailing speed | | | Stop event | |
| Daily transport costs | | | | |

The simulation starts with a stockpile at the origin site. At every time step an activity is executed by an agent, so loading, sailing, waiting, etc. Agents interact with each other, how they do it is determined by the configuration of the equipment. The simulation runs until the end of a specified simulation time or until all cargo is moved from origin to destination. The output is the number of required trips, the cargo transported, the costs of transport and optionally added transport costs of delays. These factors are key performance indicators of the IWT, with whom the system effectively can be quantified. For more details about the model is referred to Kievits (2019). Quantification of the system is the first step in identifying tipping point moments for canalization. The second step should be to identify thresholds which, if under or overshot, necessitate canalization. The last step would be to project these thresholds on the development of performance indicators, to identify a canalization tipping point in time.

## 3.4. Concluding remarks

In this chapter the second research question is answered:

**2. What impact can climate change have on the transport function of the River Waal?**

### 2a. What is the relation between water depth and transport function?

The River Waal is suited for navigation by means of inland shipping. The function of these vessels is the transport of cargo from point a to point b. The transport of cargo via vessels imply that the river has a transport function. The minimum available water depth in the river determines the loading rate and thus amount of cargo vessels can transport. Every vessel has a different relation between water depth and loading rate. This depends among others on it's dimensions and cargo type. Using these characteristics as input the loading rate of a vessel relates linearly to the water depth. Note that this is a theoretical relation based on physics. There are factors outside the scope of this research that also have an influence on the actual loading rate.

The loading rate of an individual vessel, fleet composition and number of trips can be used to determine the total cargo transport capacity on a corridor such as the River Waal. This is a complex process which requires various variables to be determined. Corridor transport performance is often carried out using simulation models. OpenCLSim is an example of such a model which is often applied, because of it's capabilities to simulate complex (real-life) processes in a simplified form.

### 2b. What transport function change is expected based on water depth change

The transport function change is explained in terms of individual vessel loading rate and corridor cargo transport capacity. The daily average loading rate in a representative future year under climate change shows the same patterns as the daily average water depth. The quantitative effects on loading rate differ per vessel. The considered climate scenario has major implications on future loading rate. In an Ln scenario the daily average loading rate does not differ significantly from the reference period 1990-2020. Nonetheless for the largest vessels such as as 135x17.5 meter CEMT class VI+ this implies a restriction to loading rate with a minimum of 50% up to 7 months. In a Hd scenario this is worse where for a most common 110x11.4 meter CEMT class Va vessel the average minimum loading rate declines from 60% in 2050 to 40% in 2150. The duration of loading restriction doubles. The strongest decline is observed between 2050 and 2100.

During low discharge (<1800 $m^3/s$) there is a rather constant spread in loading rate of 15% between an Ln and Hd scenario, starting from 2050. After 2100 development remains fairly constant. For large vessels above CEMT V however this is a stable low level with roughly 60% loading rate on average. This applies amongst others for tankers and barges.

For this research a full computation of corridor cargo transport capacity was a step too far. Projection of historic transport characteristics on future a future under climate change showed that annual average transported volume in tonnes decreases, independent of climate scenario. The severity does depend on climate scenario where in the most severe Hd scenario the average decrease is twice as much as the 'second worst' Hn scenario. A breakdown in dry and liquid bulk however shows two different paths. In the most severe 2150 Hd scenario the annual average transport volume in dry bulk only decrease to -3% with respect to the reference scenario, whereas for liquid bulk this steadily declines to -12% in 2150.

The difference is explained by the number of trips. For decreasing navigability the theoretical number of trips with dry bulk vessels strongly increases to +25% in 2150 Hd. The resilience in the fleet compensates for decreasing loading rate, allowing a small total cargo transport loss. For liquid bulk this is not the case, since the loss of transported volume is not compensated by only +3% of additional trips in 2150 Hd. Insufficient resilience in the fleet implies loss of cargo. However, it must be stated that there are factors outside the scope of this study, such as congestion and lack of capacity in the fleet that complicate this resilience.

Due to climate change the transport function of the River Waal deteriorates, but no clear answer can be given on how severe it worsens, which is mainly explained by the difference in climate scenarios. Additionally the effects differ per vessel and cargo type, adding to the complexity of grasping the effects of climate change. This unpredictability will not make it straightforward to consider canalization based on the changing transport function.

# 4

# Determining the Limits on Navigation and the Necessity of Canalization

Previous chapters have step-by-step outlined the effects of climate change on navigation function and transport function of the River Waal. These changes may be considerations in the discussion on the necessity of canalization. This chapter identifies what the considerations are and how they play a role. First, limits to navigability are described based on prevailing international regulations and previous canalization practice. Afterwards a reflection is posed on the relevancy of the found limits and its implications, where navigational limits are put in perspective of the cargo transport function development, seeking to take a broad view on the question of the necessity of canalization. This chapter covers step 6 of the research approach.

## 4.1. Determining limits based on navigational regulations

Two associations prescribe requirements for navigability of River Rhine. On the one hand the European Union and on the other hand the Central Commission for Navigation of the Rhine (CCNR), which represents the five main countries in the River Rhine basin. This section describes the requirements set by these organisations and the actual future compliance of the River Waal, based on the hydrological development determined in Chapter 2.

### 4.1.1. TEN-T

#### Introduction to TEN-T

TEN-T is a European transport network policy, initiated in 1996 by the European Parliament, which comprises of inland waterways, railways, short sea shipping and roads which links urban nodes, ports, airports and terminals within the European Union to strengthen the economic, social and territorial cohesion within the EU and advance in jobs creation, services and allowing for trade and economic growth (European Communities, 2005). At the moment 9 main corridors are recognized which undergo continuous expansions. The Rhine-Alpine corridor is one of these 9 corridors which connects Rotterdam to Genoa over 1300 kilometer through the so-called ’Blue Banana’ (Figure 4.1). It is a mature corridor (without missing links) of multimodal nature, in which the River Rhine (and thus Dutch River Waal) are adopted as the key inland waterway in Europe (European Commision, 2017). Transport of cargo is the main objective for this corridor, but throughout the core network also a military objective is recognized. The initiative Military Mobility was launched in 2017 with the aim to move military personnel, material and assets quick, on short notice an on large scale within and beyond the borders of the EU. This decision was made since the military and TEN-T network already had an overlap of 93% (European Union External Action, 2024). Recent tensions on the European mainland made this theme important again, whereupon since 2021 also the Rhine-Alpine corridor is involved (Wojciechowski, 2022).

**Figure 4.1:** Rhine-Alpine corridor (Bal & Vleugel, 2023)

### Navigation Criteria

TEN-T sets requirements for the quality of its network. Since the start in 1996, the following requirement is applicable for the River Waal, as described in Article 11.2 in the 'Community guidelines for the development of the trans-European transport network', Decision No 1692/96/EC from 1996:

> *"The minimum technical characteristics for waterways forming part of the network shall be those laid down for a class IV waterway, which allows the passage of a vessel or a pushed train of craft 80 to 85 m long and 9,50 m wide. Where a waterway forming part of the network is modernized or constructed, the technical specifications should correspond at least to class IV, should enable class Va/Vb to be achieved at a later date and should make satisfactory provision for the passage of vessels used for combined transport. Class Va allows the passage of a vessel or a pushed train of craft 110 m long and 11,40 m wide and class Vb allows the passage of a pushed train of craft 172 to 185 m long and 11,40 m wide."*

In the latest revision of this requirement, dating from 13-06-2024, article 23.3a from Regulations (EU) No 2024/1679 states:

> *"Member States shall by 31 December 2030 in particular ensure that: rivers, canals, lakes, lagoons, inland ports and their access routes provide a navigable channel depth of at least 2,5 m..."*

Thus the waterway should accommodate class IV vessels at all times, with a vision to accommodate for Va/Vb at a later date. The minimum vessel draught required is 2.5 meter. The requirement has been adopted so that the waterway manager can design the waterway accordingly and shall be fulfilled by 31 December 2030. The CEMT classification approach on vessel size was chosen because generic requirements for waterways are almost impossible to formulate because of the different geography in the EU member states.

The waterway manager in the Netherlands, Rijkswaterstaat, should thus guarantee a minimum vessel draught of 2.5 meter along the entire River Waal for 365 days a year. This research determines navigation based on a bottleneck. In the most extreme case dry bulk vessels are observed that have a loaded draught that matches 0 meter ukc for the water depth at the bottleneck location (= MGD location) (de Jong, 2020a). This is possible because experienced captains know the position of the MGD location and sail around the shoal. For the utmost case of drought, a 2.5 meter water depth can be a 2.5 meter draught. This case is set out against future climate scenario's.

### Future compliance with TEN-T

Figure 4.2 shows the future annual average undershoot of 2.5 meter draught + 0 meter ukc at Nijmegen RKM885 for all climate scenario's. The requirement of 365 days compliance (0 days undershoot) is highlighted.

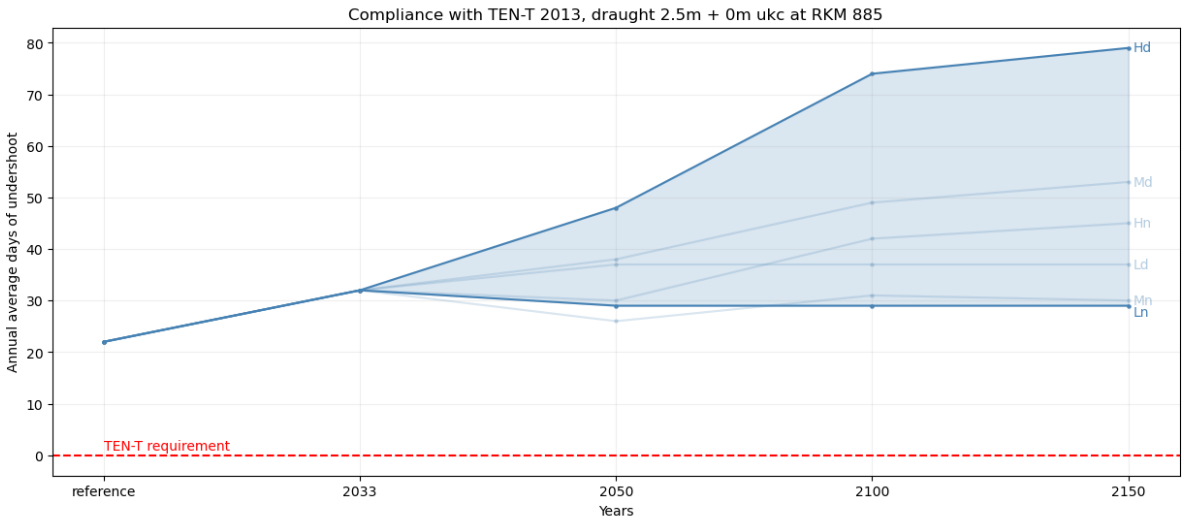


**Figure 4.2:** Compliance with TEN-T requirement

Already in the reference scenario a water depth of 2.5 meter is undershot more than 20 days, which is not in line with the current requirement. In the Ln scenario this increases with 50% to 30 days in 2150, whereas in the Hd scenario it increases with 400% up to 80 days of undershoot in 2150. The compliance with TEN-T is insufficient and will not get better, independent of the climate scenario.

### The necessity of River Waal canalization based on compliance with TEN-T requirements

The River Waal currently does not meet the navigational requirement set by the TEN-T and will not do so in any future climate scenario. Canalization of the River Waal would guarantee year-round sufficient water depth to comply with the navigational requirements set by the TEN-T

## 4.1.2. CCNR

### Introduction to CCNR

In 1815, the Central Commision for Navigation on the Rhine (Dutch CCR, English CCNR) was established at the congress of Vienna by five member states involved in navigation on the River Rhine: Belgium, Germany, France, The Netherlands and Switzerland. The organisation ensures freedom and safety of navigation on the River Rhine by issuing rules and regulations. With this said, the main objectives of the CCNR are (CCR, 2001):

- Prosperity of Rhine and European inland navigation
- Ensuring a high safety standard for navigation and its environment

In addition, the organisation is also committed to the competitiveness of inland shipping compared to other modes of transport. The main product of the CCNR, which is applicable to date (in modified version), the Mannheim Act dating to 1868. This describes, among other things, the free transport of persons and goods with an equal treatment for all vessels and exemption from toll and taxes.

### OLA and OLR

One of the tasks of the CCNR is the management of the river during periods of low discharge, where characteristic values play an important role. Periodically the CCNR determines the so-called OLA and OLR (English ALD, Agreed Low river discharge and ALR, Agreed Low Riverlevel). The OLA (Overeengekomen Lage Rivierafvoer) is a characteristic discharge level which is 20 ice-free days per year below the long term average, based on timeseries of the most recent 100 years. Every 10 years this value is revised to include the impact of climate change and other discharge variations, for various gauging stations along the River Rhine. For the River Waal, gauging station Lobith is the most important, since here the River Rhine enters the Netherlands. The current OLA from 2022 is 1020 $m^3/s$ (CCR, 2022). In appendix G the current OLA is set against the hydrological development of the River Waal under changing climate scenarios. This shows that for low emissions in a wet climate, a discharge of 1020 $m^3/s$ is also undershot by about 20 days, steadily in time. However, in a drier scenario, this number increases, to more than 60 days in 2150 Hd. In that case, it is very likely that the OLA value is adjusted downwards.

Based on this OLA value, the corresponding water level on the river is determined through the waterdepth-discharge relations (Qh), which is the OLR (Overeengekomen Lage Rivierstand), which in a similar fashion is a characteristic water level of 20 ice-free days per year below the long term average. For the current OLA, the OLR at Lobith is 733 cm + NAP. Via the 10 year update on OLA and OLR, the subsidence of the river bed level is taken into account. Discharges and water levels are however fluctuating and therefore in practice the OLA value deviates from it's definition (100 years average value). In Figure 4.3 it can be clearly seen that after 2002 a major adjustment to the official OLA was applied in order to match the actual OLA.

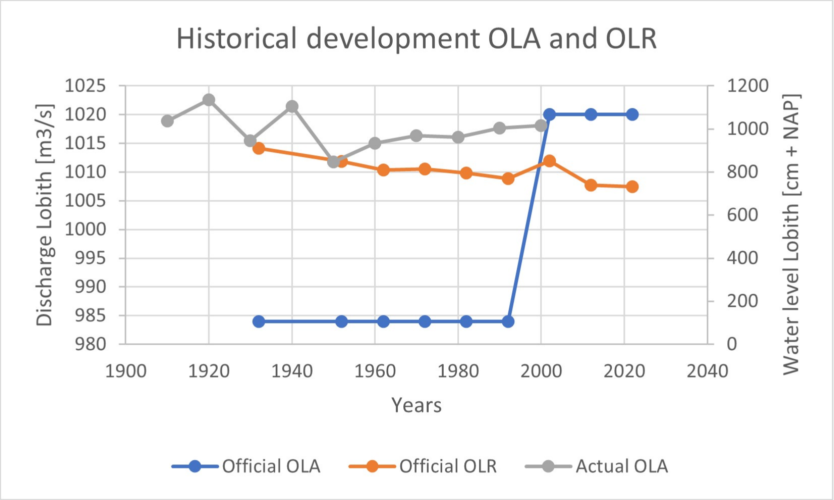


**Figure 4.3:** Historical development of official and actual OLA/OLR, adopted from Schuurman and Koolwijk (2002)

### Navigation Criteria

In the Mannheim Act, the obligation of effort to manage navigability of the River Rhine for participating member states is stated in article 28:

> *"The Contracting Parties undertake, as before, each for its area, to restore and maintain the existing towpaths as well as the waterways of the River Rhine in a proper condition..."*(translated)

The CCNR regulations are leading for river management in the Netherlands, which is carried out by Rijkswaterstaat. For the whole River Rhine an intended river profile is described (see appendix H), where for the Dutch section Waal a guaranteed water depth of 2.8 meter at OLR conditions is required. The Netherlands thus have an obligation of effort to guarantee a water depth of 2.8 meters at OLR conditions (Schulz, 2018).

### Future compliance with CCNR

Figure 4.4 shows the future annual average undershoot of 2.8 meter water depth at Nijmegen RKM885 for all climate scenario's. The CCNR requirement of maximum 20 days undershot (OLR conditions) of 2.8 meter is highlighted.

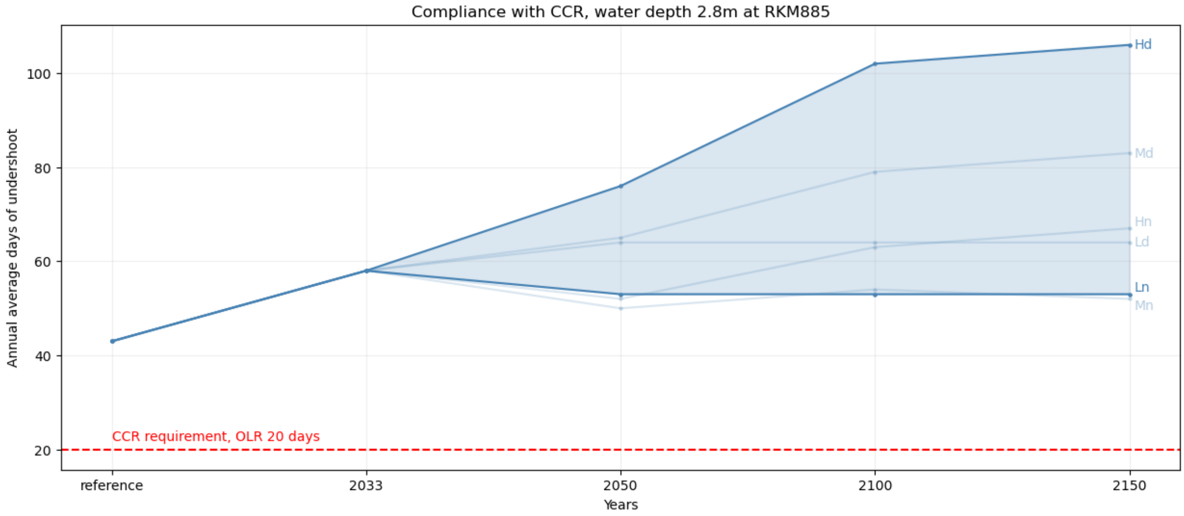


**Figure 4.4:** Compliance with CCNR 2022 requirement

The requirement of maximum 20 days 2.8 meter water depth undershoot is not met in the reference scenario, as well as all future climate scenario's. There is a wide spread between scenario's of up to 50 days difference, but even in the least severe Ln scenario, the undershoot is more than 2.5 times the allowed amount, starting from 2033 onward. In the current status, the River Waal does not match the requirements set by the CCNR and without intervention this will continue and worsen in the future.

### The necessity of River Waal canalization based on compliance with CCNR requirements

The River Waal currently does not meet the navigational requirement set by the CCNR and will not do so in any future climate scenario. Canalization of the River Waal would guarantee year-round sufficient water depth to comply with the navigational requirements set by the CCNR

## 4.2. Determining limits based on previous canalization practices

This section discusses two major canalization projects in the Dutch history, canalization of the River Meuse and Lower-Rhine. A parallel is drawn between the condition of rivers before canalization and the current River Waal, in order to gather arguments that can contribute to the discussion of the necessity of canalization of the River Waal.

### 4.2.1. Limits that necessitated canalization of the River Meuse

The River Meuse is a rain-fed river rising from the Plateau of Langres in France. Via France and Belgium the river enters the Netherlands in Eijsden, where after 200 kilometers he discharges into the Hollandsch Diep (see Figure 1.6, lower marked river). In 1919 the River Meuse is canalized for the purpose of navigation.

#### History of navigation on the River Meuse

Given the rain-feeding, the river Meuse is naturally characterized by a strong difference in summer and winter discharge. This could be as much as a factor 100 difference, whereas for the River Rhine this difference was only a factor 10-20 (Burgers, 2023). During winter discharges of 2600 $m^3/s$ could be observed at Venlo, while in summer this could be as low as 30-40 $m^3/s$ (Schlingemann, 1912). During a period of 5 months annually, upstream sections with a large bed slope gradient virtually dried up. All water available from upstream was absorbed by the river bed, which supplied groundwater sources (Bongaerts, 1912). Further downstream the water depth in summer was around 1.1 meter (Schlingemann, 1912). Since the discharge varied drastically throughout the year, the river was unsuitable for inland navigation. It was only sailed by small (sailing or steam) vessels <100 tonnes for local purposes. There were also limited businesses of any significance. The main function of the river was a source of water for (predominantly) Belgian shipping channels. This changed in 1834 when Petrus Regout started an industry for ceramics production in the 'Bassin' harbour in Maastricht, creating structural transport demand across the River Meuse for the first time (van Os, 1996). The company would later grow to ceramics producer at an international level.

Simultaneously, around 1850 the Belgian government decided to increase the draining of water from the River Meuse to supply the newly dredged Kempische Kanalen. As a consequence, the water level in the River Meuse downstream of the intake structurally decreased with up to 50 centimeters (see Figure 4.5). Later, inland navigation structurally decreased (see Figure 4.6). During this time around 1875, the Dutch government was putting much effort in normalising it's rivers, especially the River Rhine and it's side branches (van Heezik, 2007). In reaction to the decreasing navigability of the River Meuse, the first protests sparked, addressed to the House of Representatives of the Dutch government with a call for action to increase the navigability (Schaepkens, 1908). Stakeholders involved were local government bodies, individual politicians, industrialists and representatives from trade and shipping. In 1898 this even lead to a call from J. Schaepkens van Riemst (advocate of the interests of the province of Limburg) at the address of the French Minister of Foreign affairs at the International Navigation Conference in Brussels that the Dutch government structurally neglected the River Meuse and that is was not up to standards according to international agreements, resulting in an economic harm to all nations involved in the river (van Riemst, 1933).

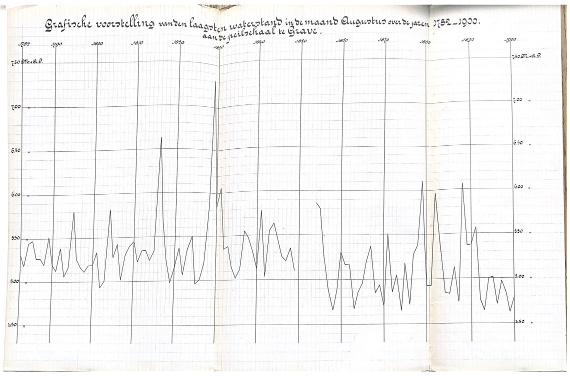


**Figure 4.5:** Graphic representation of the lowest water level in August in 1782-1900 at gauge Grave (adopted from Keurenaer (1902)

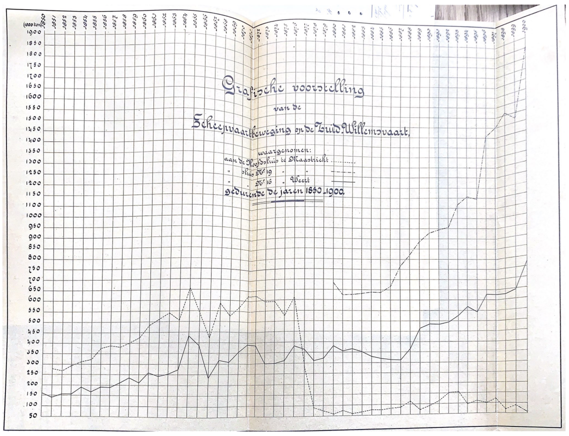


**Figure 4.6:** Graphic representation of vessel movements on the Zuid-Willemsvaart 1850-1900 (adopted from Keurenaer (1902))

Contrary, the normalisation works in the River Rhine made way for developments in inland shipping. Coal transport from the German Ruhr area to the Rotterdam port increased, which sparked a scale-up in the number and size of vessels. For these vessels it was impossible to navigate the River Meuse, which meant that destinations in Limburg were shunned and industry did not develop further, therefore the advancements in inland shipping had no positive effects on the River Meuse with which navigability fell behind that of the River Rhine. (van Os, 1996). The river was still poorly navigable, with 7 months accessibility with at best a navigable depth of 1.7 meter during L.R. (Lage Rivierstand, low river discharge) (Keurenaer, 1902).

### Staatsmijnen

Since 1850, the Dutch government spent little to no effort in the navigability of the River Meuse and inherently the economic development of the Limburg region. This changed around 1900 when large areas of coal-bearing soil where discovered in the southern part of Limburg. The extraction of this coal was by law in 1901 to be executed by the Dutch government and operated under the name 'staatsmijnen' (state mines). Inherently, the government did commit themselves to the establishment of an effective operating 'supply chain', with sufficient transport capacity to transport the coal. This was necessary in the view of the interests for the internal market, but also for the export and for military strategic purposes. Political tensions rose in Western Europe, which would later unfold into the First World War. The Netherlands relied on German supply of coal as main source of energy. With an own supply of coal the Dutch dependence on other countries would decrease (Regout, 1915) . The available possibilities at that time were transport by rail and via the Zuid-Willemsvaart canal between Maastricht and 's-Hertogenbosch. The first estimates of the coal production rates where conservative, but there was clear indication that the demand for transport capacity would significantly increase (Regout, 1915). The capacity of the Zuid-Willemsvaart was not sufficient, since around 1900 the average vessel sailing the canal had a capacity of 170 tonnes (van Os, 1996). For the Staatsmijnen, the vision was that vessels with at least 600 to 700 tonnes capacity where required on an 'almost regularly navigable river' (Lely, 1915). The other waterborne connection, via the River Meuse, was absolutely not suitable for this transport. This would imply a shift from waterborne to rail transport, which would give rail a monopolistic position in coal cargo transport. The 'Nederlandse Spoorwegen' (Dutch national railway company) where fine by this future, however the expectation was that freight rates would be too high, resulting in a lower profitability of the state owned mining operation. This would prevent the Netherlands form competing with coal imported from the German Ruhr area. To prevent this, there was a direct reason for the government to set up (rapid) waterborne transport options. Minister of water, trade and industry, Cornelis Lely (1915) expected a lowering of freight rate costs between 30% and 50%.

In call for advice, the House of Representatives of the Dutch government decide to ask Rijkswaterstaat, in the person of A. Keurenaer, what the possibilities where for improvement of navigation of the Dutch section of the River Meuse (Disco, 1998b). The Belgian government already canalized sections of the River Meuse up to Visé, just upstream of Maastricht, for the purpose of navigation. This resulted in a convenient navigable depth of 2.1 meter (Keurenaer, 1902). Keurenaer concluded that 2.5 meter water depth at M.R. (Middelbare Rivierstand, average river discharge) would be a preferred waterdepth, because the canal connection Liege - Antwerp was expected to soon be upgraded to a 2.4 meter depth channel. 2.5 meter in the River Meuse would guarantee a safe trespassing of vessels and connection to the canal, including a margin of 0.1 meter to account for rough weather conditions.

#### Canalization process

Keurenaer concluded that normalization works such as groyne construction and straightening of river sections, something that had been the common way of doing things up to that point, would not lead to the required navigable depth of 2.5 meter. Consequently, he suggested an initial plan for canalization by means of weir-lock complexes of the River Meuse. Since the river spans over Dutch and Belgian territory, decisions had to made in agreement (preferably). In 1906 the 'Commission Mixte' was established with representatives from Dutch and Belgian infrastructure responsible authorities. The aim of the commission was to decide what canalization of the River Meuse would look like. In 1912, they published their results.

The starting point of this design was an at all times available water depth of 2.6 metres, with the potential to extend this further to 3.0 metres (which eventually happened in the 1970s). This was based on the current trend in shipping of economies of scale (mainly in Rhine shipping), with the number of small vessels rapidly decreasing. The starting point was a large Rhine vessel, which at that time was a vessel with the size 100 x 12 x 2.8 meter and a loading capacity of 2000 tonnes. This vessel was assumed to sail the River Meuse in the near future, due to it's financial benefits (Schlingemann, 1912). The Netherlands had pushed for a larger draught, but Belgium stopped it in order to maintain Antwerp's competitive position with respect to Rotterdam regarding the transport of coal and industry in Liège. Belgium agreed to 2.6 meter fairway depth under the condition that a connection would be constructed between the River Rhine and Antwerp. The outbreak of the First World War eventually put an end to cooperation between the nations. After the war, attempts were made to restart cooperation, but relations between the Netherlands and Belgium had seriously deteriorated, so the Netherlands finally decided to continue the process alone (Disco, 1998b). The decision was made to canalize the Dutch section of the River Meuse beteen Maasbracht and Grave. The initial plans from the 'Commission Mixte' to extend the canalization to Maastricht turned out to be too expensive, because of the large bed slope around Maastricht (0.47 m per km). This would require too many weirs to make a small stretch navigable. It was decided to build a lateral canal (Julianakanaal) to bypass the steep section of the Meuse. In total 7 weir-lock complexes were constructed in the period between 1918 and 1929 (Burgers, 2023). The locks where build to accommodate a tugged vessel 'train' of 4000 tonnes, with 2 times 2000 tonnes vessels and a 42 meter tugboat. Locking dimensions where universally set on 260 x 14 meter with the lock sill on 3.8 meter below canalized water level (Schlingemann, 1912).

**Figure 4.7:** Weir-Lock complex Borgharen (KLM Aerocarto, n.d.)

### Navigation criteria

The River Meuse has been canalized with a view to fully load a then large Rhine vessel as normative vessel. These vessels had a draught of 2.80 meters, which would require a water depth of 3 meters, year-round. As a result of political negotiations, it was eventually decided to canalize to obtain a water depth of 2.6 meters, with the vision to raise it later to 3 meters. Before canalization, navigation on the River Meuse for this type of vessel was impossible at least half of the year.

### Projection Meuse canalization on River Waal

Towards canalization of the River Meuse, the requirement was expressed to facilitate a normative vessel of 2000 tonnes (100x12x2.8) year-round. A modern day normative vessel on the River Waal is a 6-barge push convoy either in 2x3 or 3x2 formation, CEMT class VIc, with dimensions either 22.8x270 meter or 34.2x195 meter and a loaded draught of up to 4 meter. Figure 4.8 shows the undershoot of a water depth of 4.3 meter at Nijmegen RKM885. At this water depth a VIc class can fully load, assuming an applied ukc of 30 centimeters.

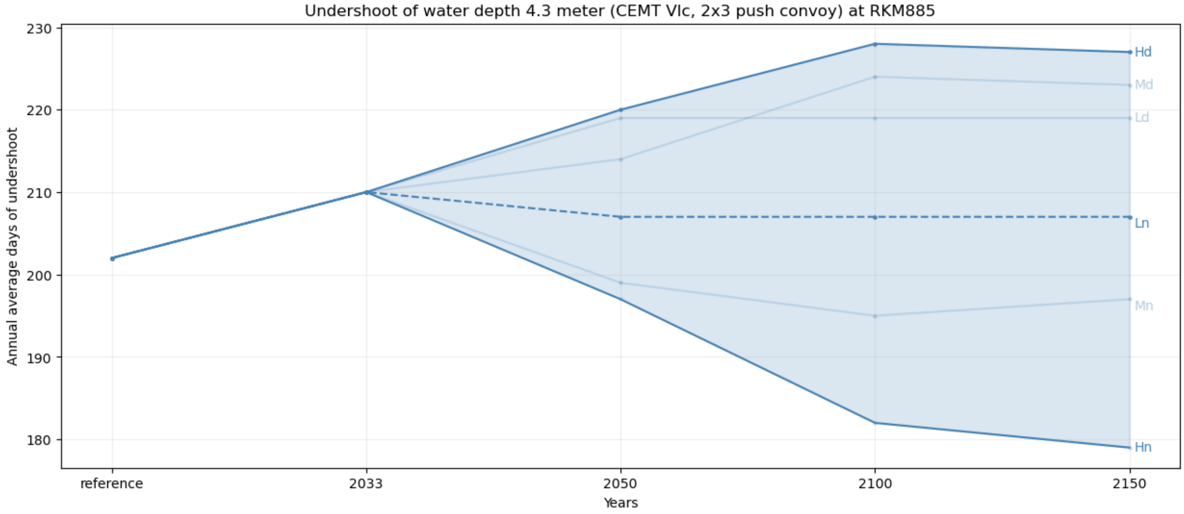


**Figure 4.8:** Availability of water depth for normative vessel River Waal

Already in the reference scenario the River Waal cannot guarantee a water depth of 4.3 meter, required to full draught load a CEMT VIc class vessel on average for more than 200 days. In a best case Hn scenario, this number decreases with -5% in 2050 to -10% towards 2150 with 180 days of undershoot. In a worst case Hd scenario, the number of days increases with +10% in 2050 to +13% in 2150 with 225 days. Independent of the climate scenario, a full draught guarantee for the normative River Waal vessel is not met for at least half of the year.
If a whole year round water depth of 4.3 meter is required to serve a fully loaded CEMT VIc class normative River Waal vessel, in the same line as the demands for a then normative vessel on the River Meuse, than it is clear that this requirement is not met by far at present as well as in all future scenario's.

It should be noted however that navigation on the River Waal is not only limited by physical low waters, but also by law. During low waters, 6-barge push convoys are not allowed to sail if the water level at Lobith reaches below 8.5m + NAP, as described in the 'Rijnvaartpolitieregelement' (Rhine Police Regulations), Article 11.02 (1995, updated 01-12-2023):

> *"On the river section Spijksche Veer (km 857.40) to Gorinchem (km 952.50), unless the competent authority has expressly authorised navigation at other water levels, a pushed convoy may only navigate if the water level on the gauge at Lobith is between 8.50 m and 13.50 m ..." (translated)*

A water level of 8.5m + NAP corresponds to a discharge of roughly 1600 $m^3/s$ and a water depth <4 meter. Appendix F shows the future development of undershoot of 1600 $m^3/s$ at Lobith in all climate scenario's. In the reference scenario a discharge of 1600$m^3/s$ is undershot for 120 days, which towards the future remains rather constant in a best case Mn scenario, whereas in a worst case Hd scenario this increases steadily towards >180 days in 2100 and beyond, which means that this normative vessel, with continuation of current regulations, could be banned up to half to the year. These numbers are lower than the days of undershoot of required full load draught water depth, which means that on a yearly average there is a time where 6-barge push convoys are not be able to fully load draught, while being allowed to sail.

### The necessity of River Waal canalization based on River Meuse canalization

- A water depth of 4.3 meter to accommodate a normative vessel on the River Waal is not met at bottleneck location RKM 885 for 200 days in the reference scenario and develops to 180-230 days in 2150. Canalization of the River Meuse caused year-round sufficient water depth for a then normative vessel. Canalization of the River Waal would make this possible for the current normative vessel
- In addition, a current normative vessel is not allowed to sail for 120 days in the reference scenario and >180 days in 2100, due to traffic safety concerns in a smaller and congested fairway. Canalization would guarantee normative vessels be allowed to sail year-round

### 4.2.2. Limits that necessitated canalization of the Lower-Rhine

The Lower-Rhine (Dutch Neder-Rijn) is a sidebranch in the Dutch section of the River Rhine (see Figure 1.6, upper marked river). A few kilometers downstream the border crossing of the Rhine with the Netherlands, the bifurcation at the Pannerdensche Kop splits the Rhine into the River Waal and Pannerdens kanaal. The River Waal continuous to the west, while the Pannerdens kanaal changes direction to the north. After a few kilometers, the river bifurcates another time at the IJsselkop. Here it splits into the River Lower-Rhine, which runs parallel to the River Waal and the River IJssel, which continues north up towards Lake IJssel (Dutch IJsselmeer).

#### History

The natural discharge distribution over these branches is fairly stable in nominal discharge of 2200 $m^3/s$: Waal 2/3, Lower-Rhine 2/9, IJssel 1/9. The River IJssel is of great importance for the connectivity of the Northern and Eastern part of the Netherlands, it is the only waterborne north-south connection in this area. It enables a connection with Amsterdam, Rotterdam, Europoort, Northern Belgium and the industry in Germany (van Til, 1960). Furthermore, the River IJssel plays an important role in water management in the northern part of the Netherlands. It is the only supply of fresh water to Lake IJssel.

Under normal conditions, the natural distribution of water over the branches is fine, but during dry periods, it is desirable to adjust the discharge for the purpose of water management and navigability. In these situations the discharge from the upstream River Rhine is sufficient to supply two branches, but not three (de Gaay & Blokland, 1970).

Navigation on the Rivers Lower-Rhine and IJssel has always been challenging. Already in 1878 plans where made to construct a parallel channel to the Lower-Rhine for the sole purpose of navigation (Dirks, 1878). At OLR (Overeengekomen Lage Rivierstand, Agreed Low River Level), the navigable depth of the Lower-Rhine was only 1.5 meter, which could last up to 4 months (van Til, 1960). The desired water depth was 2.7 meter, which could only be achieved with a discharge of 425 $m^3/s$ at the Lower-Rhine, but this was undershot for more than 220 days annually. The same was true for the River IJssel, where a navigable depth at OLR of 1.6 meter undershot the desired water depth for 190 days (Rijkswaterstaat, directie bovenrivieren, 1941).

The initial requests to enhance the navigability of both rivers, later combined with a demand for better water management sparked the idea and urgency for regulatory works (Tops et al., 1961). Initially a lateral channel was proposed along the river IJssel to guarantee a navigable connection with the Twentekanaal (Twente Channel). This would however not favour the navigability of the Lower-Rhine. Later, canalization of the IJssel was proposed. This would favour the navigability of the Lower-Rhine, as well as the River IJssel. Furthermore this would help prevent salt intrusion from the Nieuwe Maas (at the downstream side of the Lower-Rhine). This was however not a sufficient solution for fresh water supply in the norther part of the Netherlands, therefore canalization of the Lower-Rhine was proposed (Tops et al., 1961).

#### Canalization process

Canalization of the Lower-Rhine would guarantee rather stable navigation of the River IJssel and Lower-Rhine and could supply fresh water to the northern Netherlands. Due to the construction of the Deltaworks, in response to the North Sea Flood in 1953, major arms in open connection to sea were closed off. The Haringvliet, turned to fresh water by the Haringvliet barrier, supplied sufficient fresh water to counteract the salt intrusion via the Nieuwe Waterweg and therefore a continuous discharge over the Lower-Rhine was not necessary anymore (Disco, 1998a) opening the possibility for canalization.

The desired discharge on the River IJssel was between 250 and 350 $m^3/s$, which determined the weir operations in the Lower-Rhine. A 250 $m^3/s$ discharge would guarantee 2.7 meter water depth in the IJssel, sufficent to pass the sill at lock Eefde, at the entrance of the Twentekanaal (Rijkswaterstaat, directie bovenrivieren, 1941). 350 $m^3/s$ Is the upper limit to prevent flooding and not to disturb the sediment management where the IJssel would erode with higher discharges, causing subsidence of the bed level, limiting the connectivity to the Twentakanaal, which was the aim of the operation from navigation view in the first place. Above these levels, the Lower-Rhine would act as an open uncanalized river (de Gaay & Blokland, 1970).

The minimum water level at the Lower-Rhine would also be kept on 2.7 meter, to guarantee an almost all year round access for vessel of 2000 tonnes (Rijkswaterstaat, directie bovenrivieren, 1941). To satisfy the need of water users, the discharge in canalized situation was maintained at 50 $m^3/s$ (de Gaay & Blokland, 1970). During the period 1961 - 1970 three weir-lock complexes where constructed (see Figure 1.6 for lock locations). The upper weir at Driel regulates the discharge distribution, the others downstream at Amerongen and Hagestijn maintain navigable depth in the Lower-Rhine (de Gaay & Blokland, 1970). Improvement of the navigation is visualized in Figure 4.9. It shows that the navigability of both the IJssel and the Lower-Rhine was greatly improved after canalization. Undershoot of water levels required for the most common vessel during the days (1000 tonnes) was reduced to an acceptable 20 days, which increased the largest vessel that could sail during OLA conditions from 100 tonnes to 1000 tonnes. Furthermore the connection IJssel-Twentekanaal was also stabilised with only 20 days of inaccessibility for those 1000 tonnes vessels.

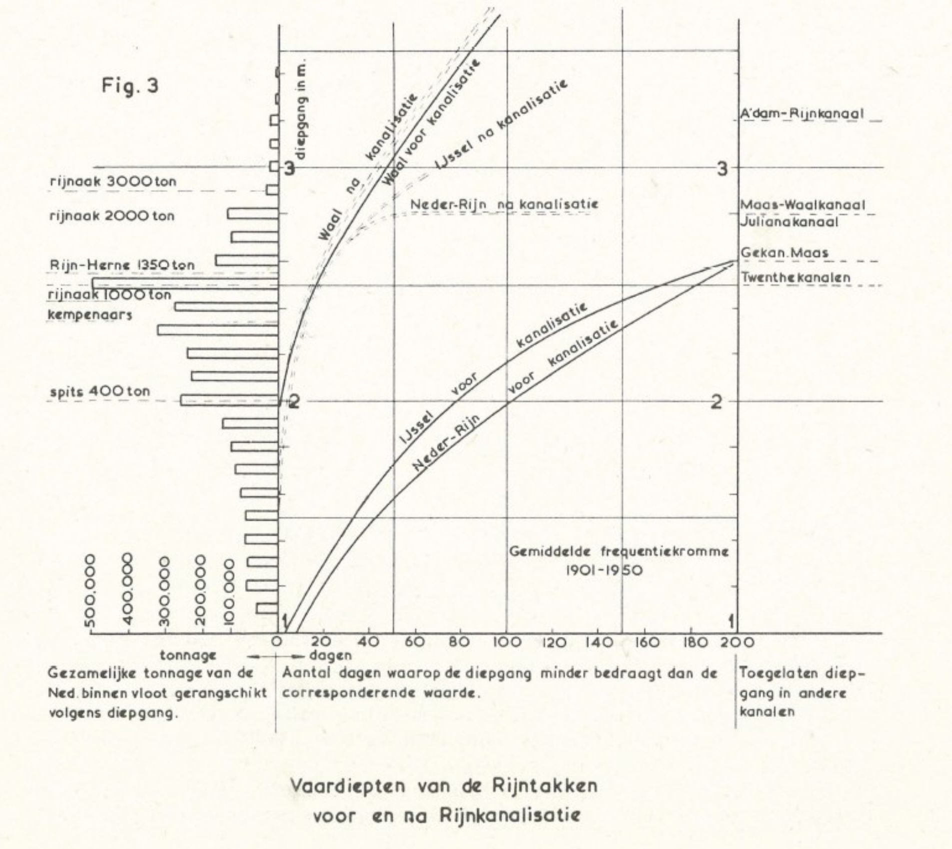


**Figure 4.9:** Navigable depth in the Rhine branches before and after canalization of the Lower-Rhine (adopted from van Til (1960)

### Navigation criteria

For the Lower-Rhine, as well as the IJssel, a draught of 2.7 meter during OLA (1066 $m^3/s$) conditions was requested (Rijkswaterstaat, directie bovenrivieren, 1941) when canalization was considered. With this draught, the most common 1000-tonnes vessels could load to full capacity when sailing the river sections, with on annual average 20 days of restrictions in loaded draught, complying with OLA definitions. In addition, the rivers, albeit with slightly fewer days, would also become navigable for the largest vessels of the time, up to 3000 tonnes. Besides, this water depth guaranteed adequate connection to adjacent infrastructure, the Twentekanaal.

### Projection Lower-Rhine canalization on River Waal

Before canalization of the Lower-Rhine, a navigational requirement of 2.7 meter at OLR conditions was required at the IJssel and Lower-Rhine. Currently for the River Waal there is a navigational requirement of 2.8 meter at OLR (elaborated on in section 4.1.2). Figure 4.10 shows the water depth of River Waal which complies with the current navigational requirement. Highlighted are the number of days the historical navigation requirements for Lower-Rhine and IJssel where undershot before canalization of these systems.

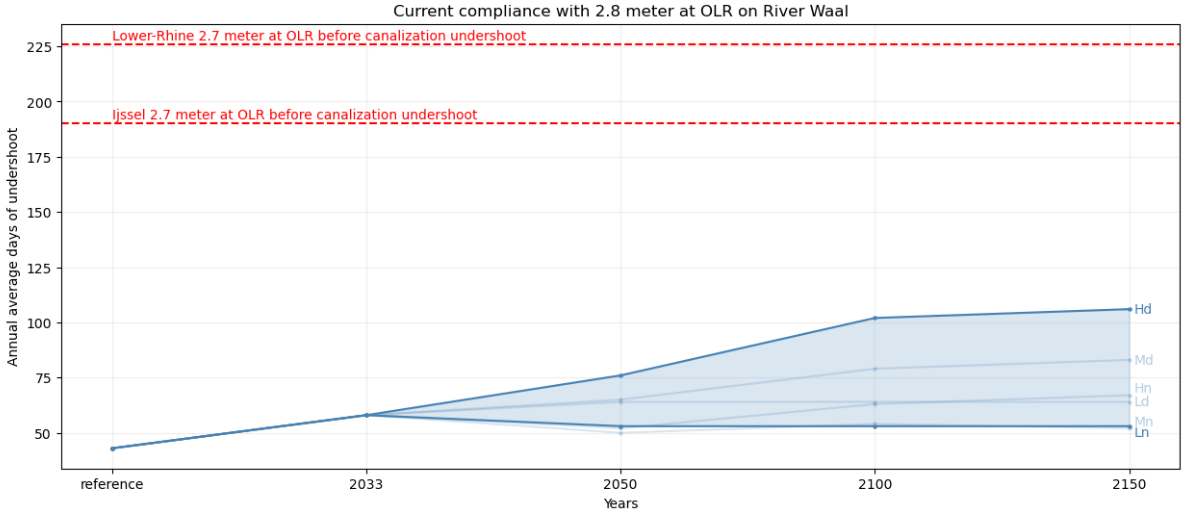


**Figure 4.10:** Comparison of historic Lower-Rhine/IJssel navigational requirements to current Waal compliance, both with respect to OLR

When posing a direct comparison to historic and current compliance with set navigational requirements, it is clear that now and in all future scenario's the undershoot of requirements will on average never be as severe as how it was during pre-canalization Lower-Rhine. For the Lower-Rhine, the compliance with requirements was twice as worse as in the most severe climate scenario 2150 Hd, with roughly 225 days of insufficient water depth. The same holds for the River IJssel, where undershoot of depth requirements was a minimum of 80 days more than in the worst 2150 Hd scenario. Considering navigational requirements, the current and future River Waal does not seem as bad as on the pre-canalization Lower-Rhine and IJssel.

However this perspective changes when we zoom in on the fleet, especially the most common vessel. With that, it is tried to make a comparison of the day-to-day situation on the rivers. Before canalization, the most common vessel around 1950 at the period of canalization of the Lower-Rhine sailing the Lower-Rhine/IJssel had a capacity of 1000 tonnes. A fully loaded vessel of this type had a draught of 2.7 meter. van Til (1960) describes that before canalization the water depth at the Lower-Rhine and IJssel was insufficient for this vessel, for respectively 180 and 160 days.
The most common vessel nowadays at the River Waal is a CEMT Va vessel, 110x11.4x3.5 with a cargo capacity of roughly 3000 tonnes (RWS class M8).

Figure 4.11 displays the undershoot of a water depth of 3.8 meter at Nijmegen RKM885. With this water depth a Va class vessel can fully load, assuming an applied ukc of 30 centimeters. The annual average days of undershoot for the most common vessel around 1950 at the Lower-Rhine and IJssel before canalization is highlighted.

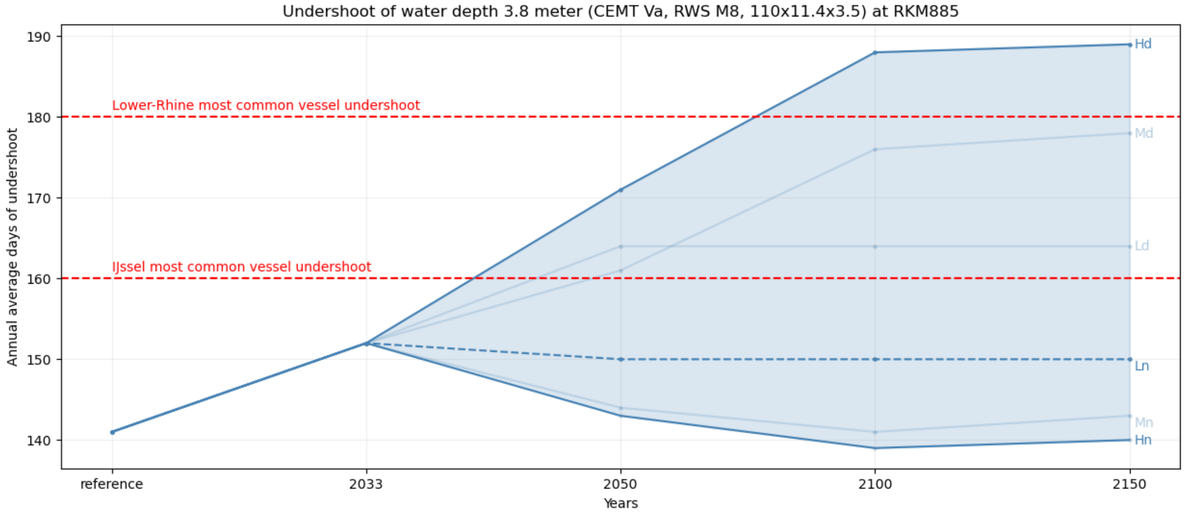


**Figure 4.11:** Comparison hindered navigation for current and historic most common vessel on respectively River Waal and Lower-Rhine/IJssel

There is a clear distinction in navigability conditions between a 'wet' and 'dry' climate scenario. In all wet scenario's the undershoot of a water depth of 3.8 meter is around 150 days in all years. This is lower than the undershoot of water depth required for a Lower-Rhine and IJssel most common vessel pre-canalization. For a dry climate scenario however an exceeding of the historic numbers is observed. In the period 2033-2050 for the most common vessel the River Waal becomes worse navigable than the River IJssel was in the past. Furthermore, in the Hd scenario in the period 2050-2100, the navigation is worse on the River Waal than it was on the Lower-Rhine. This is a different conclusion compared to solely judging navigability based on it's official requirements.

### The necessity of River Waal canalization based on River Lower-Rhine canalization

- The compliance with the current navigational requirements at OLR conditions for the River Waal is not half as bad as the River Lower-Rhine and IJssel complied with then navigational requirements at OLR conditions before canalization of the Lower-Rhine. Comparison between compliance with then and current navigational requirements does not necessitate canalization of the River Waal
- Between 2033 and 2050 in any dry climate scenario, the days with sufficient water depth to accommodate a most common vessel on the River Waal will be less than for a then most common vessel on the River IJssel before canalization of the Lower-Rhine. Canalization of the River Waal would guarantee sufficient water depth for the most common vessels to sail year-round
- Between 2050 and 2100 in a Hd scenario, the days with sufficient water depth to accommodate a most common vessel on the River Waal will be less than for a then most common vessel on the River Lower-Rhine before canalization. Canalization of the River Waal would guarantee sufficient water depth for the most common vessels to sail year-round

## 4.3. Discussing considerations that guide the decision on canalization of the River Waal

### 4.3.1. Considerations based on navigability

Sections 4.2 and 4.1 show identifiable limits on navigability of the River Waal, by projecting regulations and translating concepts from previous canalization practices on the current and future River Waal. Whether or not these limits/requirements are met is a consideration that supports the question of necessity of canalization of the River Waal. This section discusses considerations based on navigability.

#### River Meuse

A direct comparison between past River Meuse and current River Waal was made to identify similarities in navigability to serve as input consideration for the debate on necessity of canalization. It is debatable whether a direct comparison is fair. The main difference is the navigation function of the rivers. The River Meuse was known for it's inferior navigational conditions before canalization. It therefore had no structural transport function through inland shipping. After canalization of the River Meuse, it had obtained a transport function, since vessels could structurally use it to transport cargo. This is contradictory to the current River Waal where there is a transport function by means of inland shipping. Due to climate change this function is however under pressure. Canalization of the River Meuse created a navigation function, whereas canalization of the River Waal would stop deterioration of a function, as well as optimising navigation. This makes it difficult to compare the cases.

Furthermore there are large hydrological differences, mainly in the discharge regime. The high variability of discharge of the River Meuse, being rain-fed, explains the poor navigability before canalization, especially during summer when low discharges prevail. The River Rhine is a mixed rain and snow-melt fed river which gives it a more stable discharge throughout the year. Climate change does change the discharge pattern to a more rain fed regime with lower discharges in summer, but Ligtenberg and Vinke (2024) have demonstrated that at least until 2085 the mixed rain and snow-melt character of the River Waal will not match that of the rain-fed River Meuse. Therefore the River Waal up to 2085 will not have the characteristics of a rain-fed river to the extend of what was the case of the River Meuse before canalization. In section 2.1.3 it was found that after 2100 the discharge statistics of the River Waal tend to stabilise and don't decrease further to lower values. This also makes it plausible that up to 2150 a discharge regime (with relative high variability) of the River Meuse will not be matched.

When canalization of the River Meuse was considered, the requirement was to accommodate a then normative vessel, based on the scale-up trend in vessel size on the River Rhine and the expectation that these vessels would sail the River Meuse. With that, the River Meuse wanted to join the development in inland shipping. This is contrary to the current River Rhine, where in the western European waterway system already the largest vessels sail.

When a normative vessel perspective is considered than it is clear that there are restrictions on the River Waal. Even a normative vessel from 1900 would face draught restrictions on the modern river (2.8 meter loaded draught)! If unrestricted sailing for a normative vessel is requested, then at best in the future 180 days this is not achieved. Canalization of the River Waal would guarantee sufficient water depth for normative vessels to sail year-round.

#### Lower-Rhine

Canalization of the Lower-Rhine is more recent than canalization of the River Meuse. Navigational requirements where with respect to OLR, which makes comparison to the River Waal easier. If very straightforward the navigational requirements at that time are compared to current navigational requirements, then it is clear that the conditions on a pre-canalized Lower-Rhine and IJssel were much worse with a factor two more requirement threshold undershoots. No future climate scenario will bring the River Waal in comparable state.

However, there is a difference between the requirements of then and now. The past requirements did closer match the day-to-day profile of inland shipping, where the most common 1000 tonnes vessel had a draught of 2.5 meter with the navigational requirement 2.7 meter at OLR conditions (10 cm difference with 30cm ukc). The current most common vessel is 110x11.4 meter CEMT Va with a draught of 3.5 meter, whereas the navigational requirement is 2.8 meter at OLR conditions (1m difference with 30cm ukc). A direct comparison between requirements might not be fair. Zooming in on the most common vessel instead learns that between 2030-2050 and 2050-2100, depending on climate change scenario, the days of draught restrictions for the most common vessel on the River Waal with match that of the Lower-Rhine and IJssel. It can be argued that at that point the navigability of the River Waal becomes worse than the Lower-Rhine/IJssel from a most common vessel perspective. On the Lower-Rhine this was a consideration in the decision on canalization, therefore following this line of reasoning it is also a consideration for canalization of the River Waal.

### CCNR and TEN-T

The requirements are clear, as well as the implications. The River Waal did not comply with the requirements in the recent past and in no climate scenario it will do so in the future. Regarding the CCNR requirements, this has also been proven by van Dorsser and Buitendijk (2018). To date, this however has not prompted action. This is due to the lack of ability or willingness of decision makers to comply these regulations. The reason this is the case is unknown. An explanation could be in the underlying goals that should be achieved by complying with these regulations. The past also shows that compliance with navigational requirements alone was not enough of an argument to make a decision to canalize. There were actually always other and/or greater interests at play as well.
The call for canalization of the River Meuse raised way earlier than the actual execution of canalization. Only when a larger objective emerged after establishment of the Staatsmijnen canalization became relevant. Similar is said about the Lower-Rhine, which was canalized for multiple purposes, on the one hand preservation of a functional inland waterway network where the River IJssel served as a link between East-West and North-South, and on the other hand as a mean to control discharge distribution and supply fresh water to the Lake IJssel. This raises the question of what the greater goal is on the basis of which a decision for canalization of the River Waal should be substantiated.

Literature does not prescribe a unified goal that should be achieved. Schulz (2018) calls for measures to counteract navigability deterioration because of a legal obligation of effort set by international agreements and Dutch shipping law. van Dorsser and Buitendijk (2018) mentions measures because the quality of the Dutch section of the network is out of sync with the quality of the German section. Ligtenberg and Vinke (2024) states a disruption of the supply chain between seaports and the hinterland. Vinke et al. (2022) argues the use of inland shipping as economically feasible transport mode compared to road transport, as well as CCNR (2023b) who concretes this and refers to the European Green Deal, which states the ambition to shift cargo transport to waterborne. A risk of reverse model shift is argued by Ligtenberg (2022), as a result of reliability decline posed by Taekema (2017).

Thus, a range of goals can be imagined, all implying somewhat the same thing, but not formulated the same way, making it difficult to quantify them and determine whether or not these goals are met in a future changing climate.

Furthermore, this brings up an important point, about the different perspectives and interests at stake and who is responsible in the end. Goals may differ per stakeholder. Rijkswaterstaat as Dutch waterway manager is responsible for the infrastructure and ensure efficient and safe waterborne navigation. From this perspective it is possible to set requirements, since efficiency and safety are quantifiable. These requirements are assessed in this research and proven not achieved. Following this line of argument, there is enough reason to opt for canalization and thus provide a structural solution to the shortcoming in requirements. That does not necessarily directly mean that achieving other goals (from other stakeholders/perspectives) will also necessitate canalization. The sector itself is also commenting on the case. When other measures don't have the desired effect, canalization is seen as a last resort, as argued by the NPRC (Nederlandse Particuliere Rijnvaart Centrale) , one of the largest inland shipping companies in the Netherlands. (Brenninkmeijer & Wittig, 2022). If the drought related issues continue to persist, canalization could be inevitable in the second part of this century to maintain a navigable River Waal (KBN, 2023), as argued by the sector's representatives KBN (Koninklijke Binnenvaart Nederland).

### 4.3.2. Considerations based on transport function

Transporting cargo by means of navigating vessels on the River Waal define the transport function of the river. No clear transport function goals are found in this research, therefore no quantifiable limits that could necessitate canalization of the River Waal are identified. This section aims to discuss considerations on canalization based on the transport function of the River Waal, which should be taken into account to determine the necessity of canalization.

In the research approach is described that the transport function is obtained in steps, starting with the loading rate of individual vessel. Vessels having a lower maximum loading rate is a direct consequence of lower water levels, which are expected due to climate change. It should be clear that climate change can have a substantial impact on the operation of vessels. When following the line of reasoning on the River Meuse where sufficient water depth is required for a normative vessel, there is currently on the River Waal during low discharge (<1800 $m^3/s$) only an average loading rate of maximum 65% for normative dumb barges, which could decrease to 50% in 2150. That is half of it's full capacity for a section of the year on a long term average, which means it is structural. A description as in Figure 3.2 does show the differences in climate scenario's that have to be mentioned. An Ln scenario is close to the reference scenario at all times. To date, that has not led to action, so it is debatable whether an intervention would be necessary in an Ln scenario. A Hd scenario does imply a shift where loading rates structurally decrease, such that there are resemblances to an extreme dry 2018 year, which though everyone thought was a problem, attested by how often it is mentioned in literature. A repetition of the year 2018 is not desirable. Canalization would be a structural solution to prevent incidental extreme droughts in the future from happening.

And yes, the transport performance will decline, as demonstrated in Chapter 3.3. For the representative timeframes a steady loss in the order of percentages, under the assumption that in the future the fleet does not change much compared to the reference scenario. And if it's argued that a decline or standstill in total transport function is not accepted, then interventions do make sense. However, already zooming in one step and differentiate per cargo type shows as various cargo development. The performance of dry bulk transport does not seem to be much affected by climate change, due to redundancy in the fleet, which, in turn, is not the case for liquid bulk that does expect lower transport volumes due to climate change.
This difference raises the question if it is relevant to seek for a one-size-fits-all solution and improve the navigability for all vessels, while this may not be necessary for all vessel types and/or cargo types. Experts do not expect a large mutation in the future fleet composition and characteristics, since for example sizes of locks and waterways limit increase in vessel size. How this works out in practice is subject to market forces.

The market as a 'stakeholder' in the canalization discussion has a different objective than a waterway manager as Rijkswaterstaat, their goal is to run a profitable business model. Whether or not navigational requirements are met does not directly imply sufficiency of the overall transport performance of the river.

Figure 4.12 for example shows the loading rate of a 110x11.4m CEMT Class Va single hull dry bulk vessel, including it's loading rate at OLR conditions.

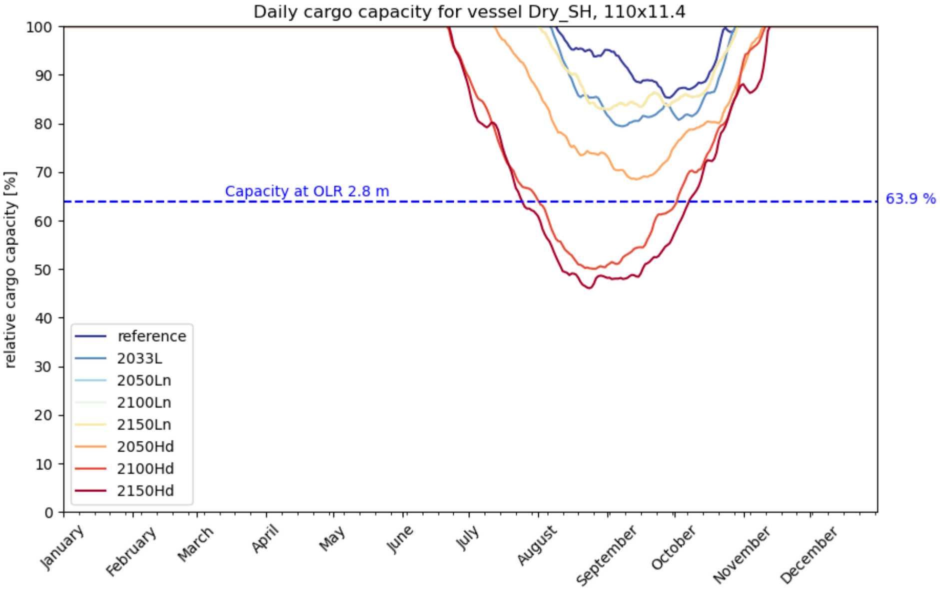


**Figure 4.12:** Loading rate of a dry bulk single hull 110x11.4m vessel, including loading rate at OLR

It sets the loading rate into perspective. The loading rate for this specific vessel at OLR conditions is 64%, which means there is a threshold moment where long term daily average undershoots the loading rate at OLR conditions. Between 2050 and 2100 in a Hd climate scenario this is observed, structurally. In an Ln climate scenario this is not the case. The total amount of cargo that can be transported between 2050 and 2100 drops with -4.5%. If these observations pose a real threshold for the transport function of the river is unknown, since for loading rate and total cargo transport are no clear limits or targets.

The transport function of the River Waal should be taken into account in the considerations on canalization. This research shows that you can look at the problem at different levels that are impacted by climate change. On one hand the loading rate of individual vessels. Due to climate change the loading rate of individual vessels could structurally decrease (periodically). At what point this becomes a problem which substantiates the necessity of canalization is unknown. It may well be that at on the individual vessel level, the market moves with the conditions outlined by climate change. Experts explain that inland shipping works with a horizon of 10 years, which is significantly shorter than the time scale at which climate change takes place. On this basis, it can be said that the transport capacity of an individual vessel is not a consideration in the decision on canalization. On the other hand is the corridor cargo transport capacity, which could structurally decrease due to climate change. This seems a problem at first, but that changes if you differentiate by cargo types, where redundancy in the fleet can partially counteract the effects of low waters. Canalization would be a one-size-fits-all solution, while this may not be necessary for all vessel types and/or cargo types. So it cannot unequivocally be said that climate change induced corridor cargo transport capacity change necessitates canalization. This requires a deeper understanding of the redundancy in the fleet and overall goals to be achieved.

### 4.3.3. Other considerations

And furthermore, in terms of the river's navigation function, there are a whole host of things that go into the consideration when talking about navigability. They are somewhat mentioned in the previous section, but are well summarized by M. Harbers, Dutch Minister of Infrastructure and Water Management in a letter to the House of Representatives where he elaborates on the relevance of inland waterway transport (Harbers, 2022). In no particular order he mentions:

- The added value to the Dutch society (GDP);
- The important role in other sectors (agriculture, construction, (Rotterdam) port industry), etc.);
- Contribution to economic growth, generation of wealth and employment in the Netherlands and Europe;
- Modal shift - decrease in road transport;
- Modal shift - sustainability of the transport sector;
- Supply of (strategic) resources within European territory.

This multiplicity of interests is not new. That was exactly the same on the River Meuse, where among other things canalization arguments mentioned were:

- Opportunity to develop (industry) region of Limburg;
- Profitability of the Staatsmijnen project;
- Competitive position on coal market versus the German Ruhr;
- Competitive position Rotterdam-hinterland versus Antwerp-hinterland;
- (Military) strategic, reducing dependence on other countries for the supply of resources.

Virtually all these interests are not quantified well, making it difficult to set limits on them, but these considerations must factor into any decision-making. Economically driven interests could be brought to the same level by converting investments and benefits to a monetary value. Necessity of canalization could then be explained as an economic optimum. The question is how to include interests that cannot easily be expressed in monetary value, such as strategic interests and indirect benefits as less road congestion and reduction of total transport emissions. Besides, outside the scope of this research, there are a lot of other functions of the river, including water distribution and nature. This is also difficult to capture in a monetary value, but must be included in the consideration for canalization.

## 4.4. Concluding remarks

In this chapter the third research question is answered:

**3. What considerations lead to the decision on canalization?**

### 3a. What limits are prescribed by (inter)national regulations?

In order to comply with TEN-T requirements, the River Waal should at least be suitable as a CEMT IV waterway and guarantee a year-round draught of 2.5 metres. The 2.5 meter requirement is not met in the present (annual average 20 days undershoot) and it will not do so in the future (up to 80 days in 2150 Hd).

The CCNR prescribes for the entire River Rhine a minimum river profile, where the Dutch section River Waal should guarantee a water depth of 2.8 meter at OLR conditions. A water depth that on long term average is undershot for 20 days. The 2.8 meter requirement is not met in the present (annual average 40 days undershoot) and it will not do so in the future in the future (>100 days in 2150 Hd).

### 3b. What limits of previous canalization practices can be applied to the River Waal?

The River Meuse and Lower-Rhine are two examples of rivers in the Netherlands that have been canalized in the past. After canalization of the River Meuse, sufficient water depth was created for a then normative vessel year-round. The current normative vessel CEMT VIc 6-barge push convoy is experiencing at least 180 days with limited draught now and in all future scenarios. At best, deployment of these vessels is allowed for maximum 250 days as described in the Rhine Police Regulations. If a whole year round water depth of 4.3 meter is required to serve a fully loaded CEMT VIc class normative River Waal vessel, in the same line as the demands for a then normative vessel on the River Meuse, than it is clear that this requirement is not met by far at present as well as in all future scenario's.

The future River Waal will not undershoot its set navigational requirements to the extend as was the case on the Lower-Rhine and IJssel before canalization. There are however scenario's where the (un)availability of water depth for a most common vessel on the future River Waal will match that of a then most common vessel on the Lower-Rhine and IJssel before canalization.

### 3c. What is the necessity of canalization based on navigational limits?

- The River Waal currently does not meet the navigational requirement set by the TEN-T and will not do so in any future climate scenario. Canalization of the River Waal would guarantee year-round sufficient water depth to comply with the navigational requirements set by the TEN-T;
- The River Waal currently does not meet the navigational requirement set by the CCNR and will not do so in any future climate scenario. Canalization of the River Waal would guarantee year-round sufficient water depth to comply with the navigational requirements set by the CCNR;
- A water depth of 4.3 meter to accommodate a normative vessel on the River Waal is not met at bottleneck location RKM 885 for 200 days in the reference scenario and develops to 180-230 days in 2150. Canalization of the River Meuse caused year-round sufficient water depth for a then normative vessel. Canalization of the River Waal would make this possible for the current normative vessel, a CEMT VIc 6 barge push combination;
- In addition, a current normative vessel is not allowed to sail for 120 days in the reference scenario and >180 days in 2100, due to traffic safety concerns in a smaller and congested fairway. Canalization would guarantee normative vessels be allowed to sail year-round;
- The compliance with the current navigational requirements at OLR conditions for the River Waal is not half as bad as the River Lower-Rhine and IJssel complied with then navigational requirements at OLR conditions before canalization of the Lower-Rhine. Comparison between compliance with then and current navigational requirements does not necessitate canalization of the River Waal;
- Between 2033 and 2050 in any dry climate scenario, the days with sufficient water depth to accommodate a most common vessel CEMT Va, 110x11.4x3.5m on the River Waal will be less than for a then most common vessel on the River IJssel before canalization of the Lower-Rhine. Canalization of the River Waal would guarantee sufficient water depth for the most common vessels to sail year-round;
- Between 2050 and 2100 in a Hd scenario, the days with sufficient water depth to accommodate a most common vessel on the River Waal will be less than for a then most common vessel on the

River Lower-Rhine before canalization. Canalization of the River Waal would guarantee sufficient water depth for the most common vessels to sail year-round.

### 3d. Which considerations should be taken into account in the decision on canalization?

This research step-by-step outlined the effects on climate change on the navigation and transport function of the River Waal. Within each step, considerations can be identified that contribute to the discussion on the necessity of canalization. There is no clear answer to give as to which considerations are ultimately leading. It's the clearest to evaluate per topic.

*Navigability*

Rijkswaterstaat as waterway manager is responsible for the infrastructure and ensure efficient and safe waterborne navigation. From this perspective the (declining) efficiency and safety of the waterway is a consideration to opt for canalization. These objectives are well formulated in quantifiable requirements (CCNR 2.8m at OLR conditions and TEN-T 2.5m 365 days/year), making it possible to identify limits in time where the requirements are not met and action is required. Since the requirements are not met and will not be met in the future, canalization can be considered a necessary step in order to fulfill the requirements.

*Transport Function*

Navigability requirements do not explicitly cover the transport function of the River Waal, which also changes due to climate change. It is seen that the declining loading rate of an individual vessel does not directly necessitate canalization. The considerations that play here should be sought on at large scale, including modal shift, (military) strategic positioning, contribution to GDP and role in other sectors. They don't serve a uniform goal and the interests are not well quantified. To actually prove that these are considerations substantiate the necessity of canalization, the goals will first have to be specified, after which it can be assessed whether these goals are met on a future River Waal. Only then can the necessity of canalization be stated for the river's transport function. The only tangible connotation is the sector's own vision, where the KBN (Koninklijke Binnenvaart Nederland) and NPRC (Nederlandse Particuliere Rijnvaart Centrale) state that canalization is a last resort measure and could be inevitable in the second part of this century to maintain a navigable River Waal.

# 5

# Discussion

In this chapter, the methods used, assumptions made and results obtained are discussed. This highlights the limitations in this study and describes how to interpret the results on this basis. The discussion points are structured similarly as the chapters of the core of this research: navigation, transport and canalization.

### Navigation

- For this research, the calculation of discharges at Lobith by Buitink et al. (2023) was used in future climate scenarios with representative years, based on KNMI (2023) climate modelling. In the statistical analysis of discharge values in Chapter 2, only averages were considered: average per year and an average year. An extreme value analysis went too far for this research. With an extreme year analysis, a better comparison could be made with past extremes such as 2018, as well as a better insight in the occurrence and severity of future dry years. One could think of descriptions of return periods of characteristic dry years/low discharges in a T10 or T100 style (1/10 year or 1/100 year). Such methods are used in climate modelling research, like in de Jong (2019).
- In Chapter 2, a selection of characteristic discharges was made and used to identify the occurrence of low discharges in the future. The selection of these discharges do have an effect on the results that are presented (de Jong, 2020a). The limit of 1800 $m^3/s$ for which it has been stated that above this discharge shipping is not hindered does not always seem to be correct in practice. Vinke et al. (2024) shows that at discharges <2000 $m^3/s$, changes are already visible in transported weight and number of trips made based on IVS data. This actually changes the definition of low water adopted in this study. This would be a bigger problem if, as in Vinke et al. (2024), you were to look in even more detail at the specific behaviour of individual vessels during drought, whereas this study focuses on capturing the long-term trend for the entire corridor.
- The basis of the calculation of occurring water depths in section 2.2.2 due to changing discharge in climate scenario’s is the 2018 bed profile of the River Waal. For simplification considerations, it is assumed that this bed profile is stationary in the future. This assumption is based on the intentions shared by Rijkswaterstaat to stabilise the bed profile of (potentially) 2018 to counteract subsidence and corresponding problems. Currently, however, this is not yet the case, making bed erosion an ongoing process. Erosion determines the bed profile shape and therefore influences the bottleneck location, as well as the water depth based on Qh relations. Thus, 2018 as a base year is a simplified assumption and morphological changes would come into play with detailed investigation.

### Transport

- To determine the loading rate of individual vessels in section 3.2, the method developed by Van Dorsser et al. (2020) was used. This is a simple method that allows an assessment of the effect of climate change on vessel loading with few input values. However, this method has two limitations. First, the outcome of this method is the theoretical maximum loading rate of vessels, where in practice, based on Vinke et al. (2024), it turns out that vessel by not always sail with maximum loading rate. So there is a mismatch here between model output and practice, which can lead to misinterpretation of modeled outputs and wrong conclusions. However, this study deals with drought extremes, for which it is precisely of interest what is still theoretically possible. Second, not all vessels are considered in this model, including push barge combinations and coupled barges. These have a contribution to the total weight transported as shown in Vinke et al. (2024), with more than 50% for dry bulk. However, for this research, no calculation step was made from individual vessel loading rate to total fleet cargo transport, thus no unreliable quantitative results where obtained.
- The research step from individual vessel loading rate to corridor cargo transport capacity was not made through a quantitative, but a qualitative analysis based on historical data for simplification reasons. The use of historical data to base the future transport character on is primed by a set of assumptions. In summary, it means that the composition and performance of the fleet navigating the River Waal over the past 10 years is assumed to be and function the same in all future years considered. For an initial indication this is sufficient, but in more detailed research the assumption of stationary fleet would be too simplistic and would not give reliable results.
- During periods of drought not only the water depth decreases, but also the navigable width of the fairway, resulting in an increase in intensity. Combined with the observed increase in number of trips, congestion occurs (Verschuren, 2020). Delays in cargo transport result in a lower total cargo transport. This effect is not explicitly studied in this research as a consequence of low discharges, and could on itself be an consideration in the discussion on canalization. Implicitly however this effect is incorporated in this study, since for the determination of future corridor cargo transport capacity, inland shipping performance of the past 10 years is used.

### Canalization

- Section 4 describes limits that can be imposed on navigation based on two canalization projects in Dutch history. Two events from the Dutch past give a limited view of the considerations involved in canalization projects in general, especially since they were long ago where past considerations may not be valid in the present. However, these two Dutch projects are easier to compare with the River Waal, because for example canalization projects abroad have different boundary conditions that are difficult to translate to a Dutch situation.
- International requirements were found for navigation in this research. Clear thresholds on the performance of cargo transport on the River Waal have not emerged. Because these were not quantifiable, it was not possible to set hard limits on cargo performance. With that it was not possible to put cargo performance on the same dimension as navigational limits (canalization year/scenario), making it impossible to compare these two aspects 1 on 1. Only feedback on the limits from transport function development was possible. That this is the case is a limitation in directly answering the research question as formulated at the beginning of this research. However, it does lead to an interesting conclusion and reason for additional research.
- This research has been limited to considerations of canalization only from the standpoint of inland shipping interests. In reality, there are many other river functions on the River Waal that are all impacted by climate change. All have to be considered when discussing the necessity of canalization. In fact, inland shipping has been assigned a marginal role in this according to the ’Verdringingsreeks’ (order of importance), after safety, water supply and small-scale high-value uses. All together would make the subject many times more complex with the risk that no unanimous outcome could be found. In this, politics and lobbying will have to provide an outcome, something this research does not engage in. Considering only inland shipping is thus a first order assessment as simplification of the real life problem.

# 6

# Conclusion and Recommendations

This chapter concludes the research by answering the main research question:

*What considerations guide the decision to canalize the River Waal and will climate change induced drought necessitate canalization based on these considerations?*

The main research question is answered by sub questions in section 6.1, following the same structure as the core chapters of this research. Section 6.2 gives recommendations for further research based on the knowledge and shortcomings that emerged in this research.

## 6.1. Conclusion

This section covers the most important conclusions drawn in the previous sections where answers to the sub questions where given.

1. ***What impact can climate change have on the navigation conditions of the River Waal?***

On the basis of the analysis of annual, as well as daily discharge/water depth development under climate change it is concluded that in all climate scenario's the navigability will decrease. This follows from the starting point that navigation conditions of the River Waal are described by the occurrence of certain (low) discharges at Lobith and water depths at bottleneck location RKM 885 at Nijmegen. There is not a clear answer to give how exactly the navigability will change, since it highly depends on the climate scenario that unfolds. The 'best case' scenario is a stabilisation in time in line with the current navigability conditions.

### 1a. How does discharge at the River Waal change due to climate change?

As for discharge in the future, there is no single path that can be described. The development is highly dependent on the climate scenario that unfolds in the future. However, a spread can be distinguished between a low emission scenario with wet conditions 'Ln' on the one hand and a high emission scenario with dry conditions 'Hd' on the other. These two scenario's represent the most extreme cases when discussing drought. As turns out, the difference between wet and dry conditions is more decisive than anthropogenic emissions.

The Ln scenario is in line with the 2033 Paris climate agreements. In this scenario there is little deviation from the reference scenario over time. The number of days with low discharges (<1800 $m^3/s$) remains similar as in the current situation with around 160 days. The lowest discharge in an average year is around 1500 $m^3/s$.
The Hd scenario however shows structurally lower discharges in a steady decline until 2100, after which the trend flattens. Extreme low discharges <600 $m^3/s$ appear and summers in an average year have minimum discharge of 1000 $m^3/s$ in 2150, which is 750$m^3/s$ lower than in the reference scenario. Furthermore the low discharge peak shifts as much as one month earlier where the peak also lasts longer. This is supported by the trend that there are more days with discharge <1800 $m^3/s$ further into the future.

### 1b. How does this discharge change affect the water depth?

Based on the analysis of annual, as well as daily discharge/water depth there will be no scenario with improved navigability (=less low water depth events). The worsening of navigability depends on the climate scenario where stabilisation in line with current navigability conditions is the 'best case' scenario.

The location with the lowest water depth of the navigation route determines the maximum loaded draught of vessels. For the River Waal RKM 885 at Nijmegen is found the most critical location, based on known Qh relations and the bed profile of 2018. The water depth shows the same patterns as for the discharge, with an Ln scenario stable through time and a dry extreme Hd scenario.
Low water depth as 2.8 meter occur in the Hd scenario up to 3 times as much as in the reference scenario, including outliers to <1.6 meter, which matches the lowest recorded water depth in 2018. In the Hd scenario, the lowest observed average depth declines from 3.5 meter in the reference case tot 3 meter in 2050 and <2.5 meter after 2100. Again, Ln is fairly constant in time having a lowest average water depth of 3.5 meter. An average future year does not match the annual discharge pattern as observed in 2018, especially not the duration of drought in 2018. The lowest water depth in an average 2150 Hd does however match sections of the 2018 drought. It should be mentioned that it is not inconceivable that individual years are as bad or worse than 2018. In general, the water depth during low discharge tends to decrease in the future. This is expected to cause problems for inland navigation.

### *2. What impact can climate change have on the transport function of the River Waal?*

Due to climate change the transport function of the River Waal deteriorates, but no unambiguous answer can be given on how severe it worsens, which is mainly explained by the difference in climate scenarios. Additionally the effects differ per vessel and cargo type, adding to the complexity of grasping the effects of climate change. This unpredictability makes it not straightforward to consider canalization based on the changing transport function.

### 2b. What transport function change is expected based on water depth change

The transport function change is explained in terms of individual vessel loading rate and corridor cargo transport capacity. The daily average loading rate in a representative future year under climate change shows the same patterns as the daily average water depth. The quantitative effects on loading rate differ per vessel. The considered climate scenario has major implications on future loading rate. In an Ln scenario the daily average loading rate does not differ significantly from the reference period 1990-2020. Nonetheless for the largest vessels such as as 135x17.5 meter CEMT class VI+ this implies a restriction to loading rate with a minimum of 50% up to 7 months. In an Hd scenario this is worse where for a most common 110x11.4 meter CEMT class Va vessel the average minimum loading rate declines from 60% in 2050 to 40% in 2150. The duration of loading restriction doubles. The strongest decline is observed between 2050 and 2100.

During low discharge (<1800 $m^3/s$) there is a rather constant spread in loading rate of 15% between an Ln and Hd scenario, starting from 2050. After 2100 development remains fairly constant. For large vessels above CEMT V however this is a stable low level with roughly 60% loading rate on average. This applies amongst others for tankers and barges.

For this research a full computation of corridor cargo transport capacity was a step too far. Projection of historic transport characteristics on future a future under climate change showed that annual average transported volume in tonnes decreases, independent of climate scenario. The severity does depend on climate scenario where in the most severe Hd scenario the average decrease is twice as much as the 'second worst' Hn scenario. A breakdown in dry and liquid bulk however shows two different paths. In the most severe 2150 Hd scenario the annual average transport volume in dry bulk only decrease to -3% with respect to the reference scenario, whereas for liquid bulk this steadily declines to -12% in 2150.
The difference is explained by the number of trips. For decreasing navigability the theoretical number of trips with dry bulk vessels strongly increases to +25% in 2150 Hd. The resilience in the fleet compensates for decreasing loading rate, allowing a small total cargo transport loss. For liquid bulk this is not the case, since the loss of transported volume is not compensated by only +3% of additional trips in 2150 Hd. Insufficient resilience in the fleet implies loss of cargo. However, it must be stated that

there are factors outside the scope of this study, such as congestion and lack of capacity in the fleet that complicate this resilience.

### *3. What considerations lead to the decision on canalization?*

There is no clear answer to give as to which considerations are leading in the decision on canalization. This research studied the effect of climate change on navigation and transport function of the River Waal. Both pose considerations that should be taken into account when discussing canalization. The goals for the navigation function are well formulated and quantified. They set limits, which are exceeded, which could substantiate the necessity of canalization. The goals for the transport function are not uniform and not quantified. This is crucial to assess the performance of the future River Waal and substantiate the necessity of canalization.

#### 3a. What limits are prescribed by (inter)national regulations?

In order to comply with TEN-T requirements, the River Waal should at least be suitable as a CEMT IV waterway and guarantee a year-round draught of 2.5 metres. The 2.5 meter requirement is not met in the present (annual average 20 days undershoot) and it will not do so in the future (up to 80 days in 2150 Hd).
The CCNR prescribes for the entire River Rhine a minimum river profile, where the Dutch section River Waal should guarantee a water depth of 2.8 meter at OLR conditions. A water depth that on long term average is undershot for 20 days. The 2.8 meter requirement is not met in the present (annual average 40 days undershoot) and it will not do so in the future in the future (>100 days in 2150 Hd).

#### 3b. What limits of previous canalization practices can be applied to the River Waal?

The River Meuse and Lower-Rhine are two examples of rivers in the Netherlands that have been canalized in the past. After canalization of the River Meuse, sufficient water depth was created for a then normative vessel year-round. The current normative vessel CEMT VIc 6-barge push convoy is experiencing at least 180 days with limited draught now and in all future scenarios. At best, deployment of these vessels is allowed for maximum 250 days as described in the Rhine Police Regulations. If a whole year round water depth of 4.3 meter is required to serve a fully loaded CEMT VIc class normative River Waal vessel, in the same line as the demands for a then normative vessel on the River Meuse, than it is clear that this requirement is not met by far at present as well as in all future scenario's.
The future River Waal will not undershoot it's set required navigational requirements to the extend as was the case on the Lower-Rhine and IJssel before canalization. There are however scenario's where the (un)availability of water depth for a most common vessel on the future River Waal will match that of a then most common vessel on the Lower-Rhine and IJssel before canalization.

#### 3c. What is the necessity of canalization based on navigational limits?

- The River Waal currently does not meet the navigational requirement set by the TEN-T and will not do so in any future climate scenario. Canalization of the River Waal would guarantee year-round sufficient water depth to comply with the navigational requirements set by the TEN-T;
- The River Waal currently does not meet the navigational requirement set by the CCNR and will not do so in any future climate scenario. Canalization of the River Waal would guarantee year-round sufficient water depth to comply with the navigational requirements set by the CCNR;
- A water depth of 4.3 meter to accommodate a normative vessel on the River Waal is not met at bottleneck location RKM 885 for 200 days in the reference scenario and develops to 180-230 days in 2150. Canalization of the River Meuse caused year-round sufficient water depth for a then normative vessel. Canalization of the River Waal would make this possible for the current normative vessel, a CEMT VIc 6 barge push combination;
- In addition, a current normative vessel is not allowed to sail for 120 days in the reference scenario and >180 days in 2100, due to traffic safety concerns in a smaller and congested fairway. Canalization would guarantee normative vessels be allowed to sail year-round;
- The compliance with the current navigational requirements at OLR conditions for the River Waal is not half as bad as the River Lower-Rhine and IJssel complied with then navigational requirements at OLR conditions before canalization of the Lower-Rhine. Comparison between compliance with then and current navigational requirements does not necessitate canalization of the River Waal;

- Between 2033 and 2050 in any dry climate scenario, the days with sufficient water depth to accommodate a most common vessel CEMT Va, 110x11.4x3.5m on the River Waal will be less than for a then most common vessel on the River IJssel before canalization of the Lower-Rhine. Canalization of the River Waal would guarantee sufficient water depth for the most common vessels to sail year-round;
- Between 2050 and 2100 in an Hd scenario, the days with sufficient water depth to accommodate a most common vessel on the River Waal will be less than for a then most common vessel on the River Lower-Rhine before canalization. Canalization of the River Waal would guarantee sufficient water depth for the most common vessels to sail year-round.

### 3d. Which considerations should be taken into account in the decision on canalization?

This research step-by-step outlined the effects on climate change on the navigation and transport function of the River Waal. Within each step, considerations can be identified that contribute to the discussion on the necessity of canalization. There is no clear answer to give as to which considerations are ultimately leading. It's the clearest to evaluate per topic.

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## 6.2. Recommendations

This section presents some recommendations that follow from the discussion and conclusion and serves as initiators for follow-up research.

### Implications of other drought measures

As mentioned in Chapter 1, in addition to canalization, there are other measures that can be taken to mitigate low water problems. While they are not all solutions to the problem, they can serve as mitigating measures. For example, optimizations could be carried out in the logistics system, incorporating redundancy among freight forwarders and clients. It is interesting to see the impact of measures on navigation/transport developments and compare them with the results already found in this research. Whether or not other measures are adequate adds to the considerations in the discussion of whether canalization is relevant.

### Additional navigation/transport limitations

This research found a limited number of limits related to navigation, based on previous canalization practice and regulations. It is recommended to expand this and look for more limits to the system, which can demonstrate the relevance of canalization from an even broader view. Especially for the transport function of the River Waal this has proven difficult, due to the lack of concrete goals. It asks for policy that describes what deterioration is accepted and what not. A recommended method is therefore to identify themes relevant to the river's transportation function. Then set goals within those themes. These targets need to be quantified and then, using the same steps as followed in this research, it needs to be determined whether these targets are met in future climate scenarios.

### River bed morphology

This research assumed a stable bed profile in the future, based on the 2018 bed profile. In reality, erosion occurs annually, changing the bed profile. The bed profile determines the location and severity of bottleneck locations. Erosion of the entire bed profile apart from hard layers or points causes a relative water level decrease at these points, making the bottleneck more problematic. In addition, there may also be shifts in bottleneck location or new locations added, making Nijmegen no longer critical. With this, the statistics of occurring water depths, as determined in this research, change in the future. It is recommended to include river morphology in determining future water depths.

### Extreme value analysis

In characterising discharges and water depths in the future due to climate change, only average statistics, the average per year and an average year were considered. Extreme values have not been considered herein. Extreme values such as those that occurred in 2018 are precisely what cause major financial damage, which should be prevented through canalization. It is therefore recommended to look at extreme years or circumstances in addition to averages, such as a whole dry year that occurs once every 10 years or the persistence of a low water level for a longer period that occurs once every 50 years. Care should be taken that such a determination is carried out with statistical accuracy. Firstly, it is already a matter of modelling, not measurement. That gives a certain unreliability. In addition, a fictitious time series will always have to be made to determine return periods. Different methods are used within the literature on drought problems due to climate change.

### Modelling corridor cargo transport capacity

Section 3.3.3 has already elaborated on the possible determination of corridor cargo transport capacity through simulation, e.g. with OpenCLSim. In this research, only a first-effort qualitative analysis was done based on historical information. Through modelling, a more complete picture of future developments in cargo transport under climate change can be drawn. This would include changes in the fleet (type and number of vessels), but also changing demand for cargo transport. Modelling is suitable for threshold-based research, which fits well with the research question on limits to navigability/transport that can argue the necessity of canalization. It is recommended that the future development of inland shipping be identified through simulation.

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# A

# Appendix A: Annual average discharge threshold undershoot

Table A.1 shows for every considered future climate scenario the annual average undershoot of characteristic discharge threshold undershoots at the River Waal. The number of undershoots of low discharge values tend to increase in High (H) scenario's and remain constant in Low (L) scenario's. In almost all scenario's the annual average undershoot of Q = 1020 $m^3/s$ is above 20 days, which is above the OLA definition set by the CCR.

**Table A.1:** Annual average discharge threshold undershoot

| | **Discharge [m3/s]** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Scenario** | **600** | **700** | **850** | **1020** | **1100** | **1400** | **1800** |
| reference | 0 | 1 | 3 | 14 | 22 | 76 | 157 |
| 2033L | 0 | 1 | 7 | 23 | 33 | 91 | 166 |
| 2050Hd | 1 | 3 | 12 | 35 | 48 | 111 | 183 |
| 2050Hn | 1 | 1 | 7 | 22 | 30 | 83 | 156 |
| 2050Md | 1 | 2 | 10 | 27 | 39 | 99 | 174 |
| 2050Mn | 0 | 1 | 5 | 18 | 26 | 82 | 158 |
| 2100Hd | 2 | 11 | 33 | 61 | 74 | 136 | 198 |
| 2100Hn | 1 | 4 | 15 | 33 | 42 | 91 | 149 |
| 2100Ld | 0 | 1 | 9 | 27 | 38 | 100 | 178 |
| 2100Ln | 1 | 1 | 6 | 20 | 29 | 87 | 164 |
| 2100Md | 1 | 3 | 14 | 36 | 50 | 116 | 188 |
| 2100Mn | 1 | 2 | 8 | 23 | 32 | 84 | 154 |
| 2150Hd | 4 | 15 | 39 | 66 | 79 | 138 | 199 |
| 2150Hn | 1 | 5 | 17 | 36 | 46 | 94 | 150 |
| 2150Md | 1 | 4 | 17 | 41 | 54 | 120 | 189 |
| 2150Mn | 1 | 2 | 8 | 22 | 31 | 83 | 157 |

# B

# Appendix B: Validation Qh relation interpolation

The data source used in this research for the Qh relations only gave the Qh relations for Q = 700, 1400 and 1800 $m^3/s$. For this research however, intermediate discharge values (and 600 $m^3/s$ exterior) where also deemed relevant thresholds. When applying a linear interpolation, a result as in Figure B.1 for the blue lines is obtained. The linear interpolation is a simplified assumption, since it is known that Qh relations are slightly non-linear. Assuming a linear relation however significantly reduced the complexity of calculations, since otherwise a Qh relation had to be determined for every RKM.

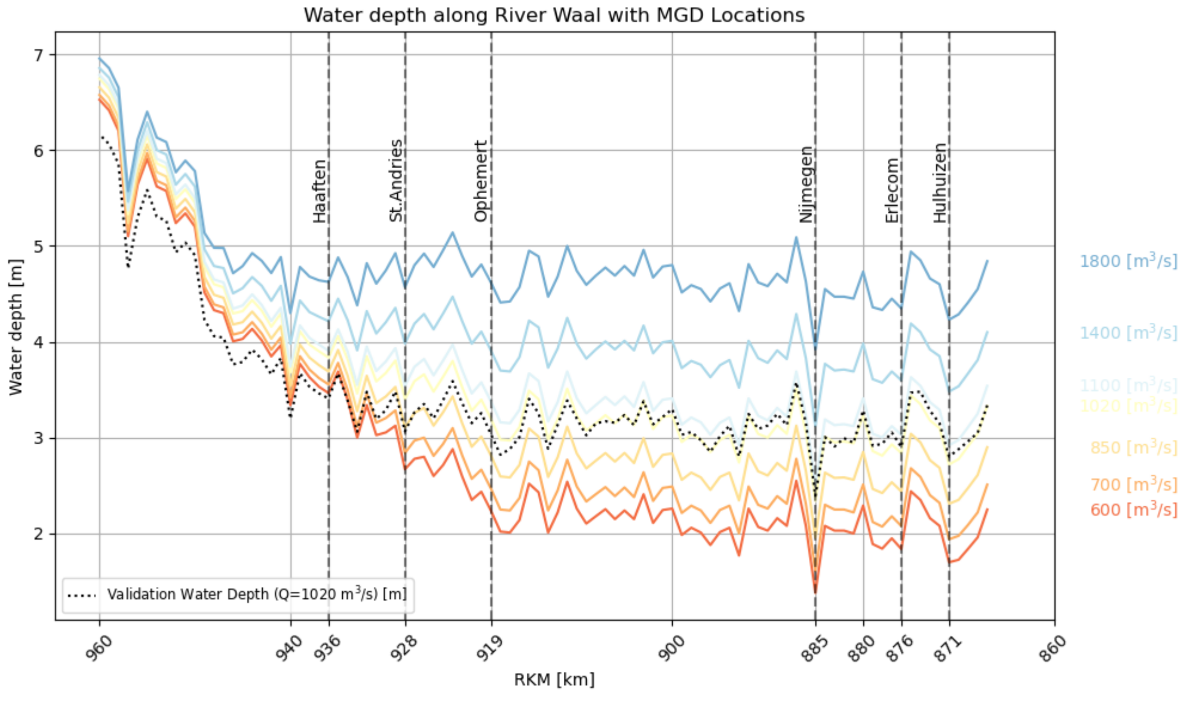


**Figure B.1:** Validation Qh relation, comparison plot

Figure B.1 is only used to determine the RKM with the minimum water depth by means of visual inspection, therefore a linear Qh relation assumption was deemed valid. As a validation of the assumption a measured water depth for Q = 1020 $m^3/s$ is plotted over Figure B.1 as a dotted line. Furthermore the difference in computed and actual and computed water depth is visible in Figure B.2. The difference at the top 3 bottleneck locations is around 5 centimeters, which is considered sufficient for determining the bottleneck RKM. Location RKM 885 at Nijmegen is the critical bottleneck in the River Waal.

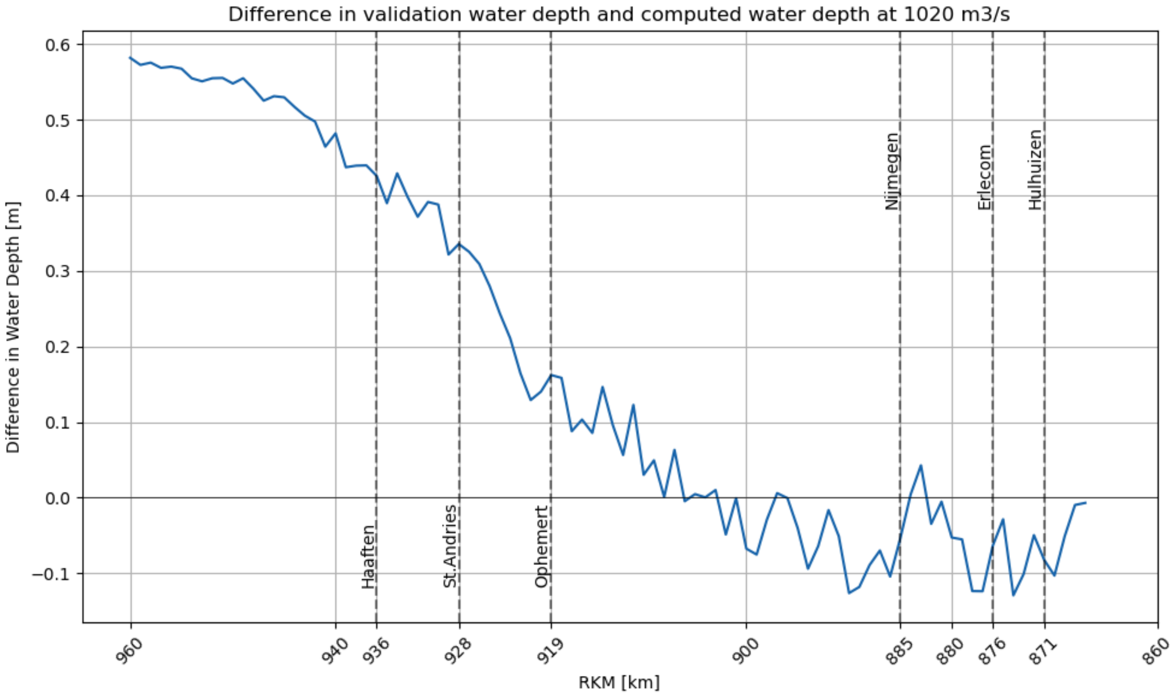


**Figure B.2:** Validation Qh relation, difference plot

# C

# Appendix C: Annual average water depth undershoot at RKM 885

Table C.1 shows for every considered scenario the annual average undershoot of characteristic water depth thresholds at the River Waal. The requirement by the CCR is that a water depth of OLR 2.8 meters is undershot on average a maximum times of 20 days per year. RKM 885 is a known bottleneck, where it's clear that already in the reference scenario this is met. Furthermore in every future scenario this undershoot increases tot a maximum of 106 days in 2150Hd. The minimum in the this year is 52 days, which is more than double the requirement.

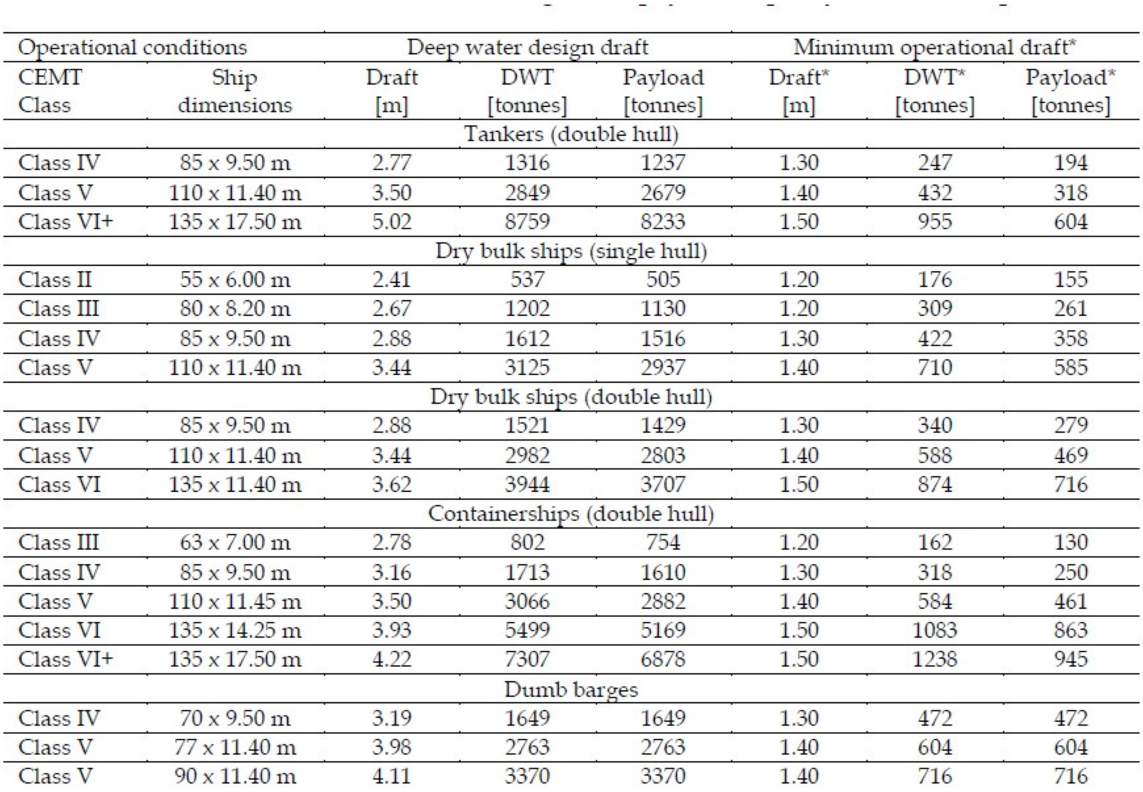
**Table C.1:** Annual average characteristic water depth undershoot at RKM 885

| | **Water depth [m]** | | | | | |
|---|---|---|---|---|---|---|
| **Scenario** | **1.6** | **2.0** | **2.5** | **2.8** | **3.5** | **4.5** |
| reference | 1 | 4 | 22 | 43 | 109 | 221 |
| 2033L | 1 | 8 | 32 | 58 | 123 | 226 |
| 2050Hd | 2 | 14 | 48 | 76 | 143 | 234 |
| 2050Hn | 1 | 8 | 30 | 52 | 114 | 213 |
| 2050Md | 2 | 11 | 38 | 65 | 132 | 229 |
| 2050Mn | 1 | 6 | 26 | 50 | 114 | 215 |
| 2100Hd | 10 | 36 | 74 | 102 | 165 | 240 |
| 2100Hn | 3 | 17 | 42 | 63 | 115 | 196 |
| 2100Ld | 1 | 10 | 37 | 64 | 135 | 235 |
| 2100Ln | 1 | 7 | 29 | 53 | 120 | 225 |
| 2100Md | 3 | 15 | 49 | 79 | 149 | 238 |
| 2100Mn | 2 | 9 | 31 | 54 | 113 | 210 |
| 2150Hd | 14 | 41 | 79 | 106 | 167 | 238 |
| 2150Hn | 4 | 19 | 45 | 67 | 119 | 191 |
| 2150Md | 4 | 19 | 53 | 83 | 152 | 236 |
| 2150Mn | 2 | 9 | 30 | 52 | 115 | 211 |

# D

# Appendix D: Effect of low water on deadweight and payload capacity of inland ships

The method developed by Van Dorsser et al. (2020) estimates the loading capacity of vessels in tonnes based on the available water depth. Figure D.1 is a computation by (Van Dorsser et al., 2020) to determine the minimum and maximum draft and capacity for various types of vessels and dimensions. The elaborated version of this method in Python, which is used in this research was tested against this table.



| Operational conditions | | Deep water design draft | | | Minimum operational draft* | | |
|---|---|---|---|---|---|---|---|
| CEMT Class | Ship dimensions | Draft [m] | DWT [tonnes] | Payload [tonnes] | Draft* [m] | DWT* [tonnes] | Payload* [tonnes] |
| | | Tankers (double hull) | | | | | |
| Class IV | 85 x 9.50 m | 2.77 | 1316 | 1237 | 1.30 | 247 | 194 |
| Class V | 110 x 11.40 m | 3.50 | 2849 | 2679 | 1.40 | 432 | 318 |
| Class VI+ | 135 x 17.50 m | 5.02 | 8759 | 8233 | 1.50 | 955 | 604 |
| | | Dry bulk ships (single hull) | | | | | |
| Class II | 55 x 6.00 m | 2.41 | 537 | 505 | 1.20 | 176 | 155 |
| Class III | 80 x 8.20 m | 2.67 | 1202 | 1130 | 1.20 | 309 | 261 |
| Class IV | 85 x 9.50 m | 2.88 | 1612 | 1516 | 1.30 | 422 | 358 |
| Class V | 110 x 11.40 m | 3.44 | 3125 | 2937 | 1.40 | 710 | 585 |
| | | Dry bulk ships (double hull) | | | | | |
| Class IV | 85 x 9.50 m | 2.88 | 1521 | 1429 | 1.30 | 340 | 279 |
| Class V | 110 x 11.40 m | 3.44 | 2982 | 2803 | 1.40 | 588 | 469 |
| Class VI | 135 x 11.40 m | 3.62 | 3944 | 3707 | 1.50 | 874 | 716 |
| | | Containerships (double hull) | | | | | |
| Class III | 63 x 7.00 m | 2.78 | 802 | 754 | 1.20 | 162 | 130 |
| Class IV | 85 x 9.50 m | 3.16 | 1713 | 1610 | 1.30 | 318 | 250 |
| Class V | 110 x 11.45 m | 3.50 | 3066 | 2882 | 1.40 | 584 | 461 |
| Class VI | 135 x 14.25 m | 3.93 | 5499 | 5169 | 1.50 | 1083 | 863 |
| Class VI+ | 135 x 17.50 m | 4.22 | 7307 | 6878 | 1.50 | 1238 | 945 |
| | | Dumb barges | | | | | |
| Class IV | 70 x 9.50 m | 3.19 | 1649 | 1649 | 1.30 | 472 | 472 |
| Class V | 77 x 11.40 m | 3.98 | 2763 | 2763 | 1.40 | 604 | 604 |
| Class V | 90 x 11.40 m | 4.11 | 3370 | 3370 | 1.40 | 716 | 716 |

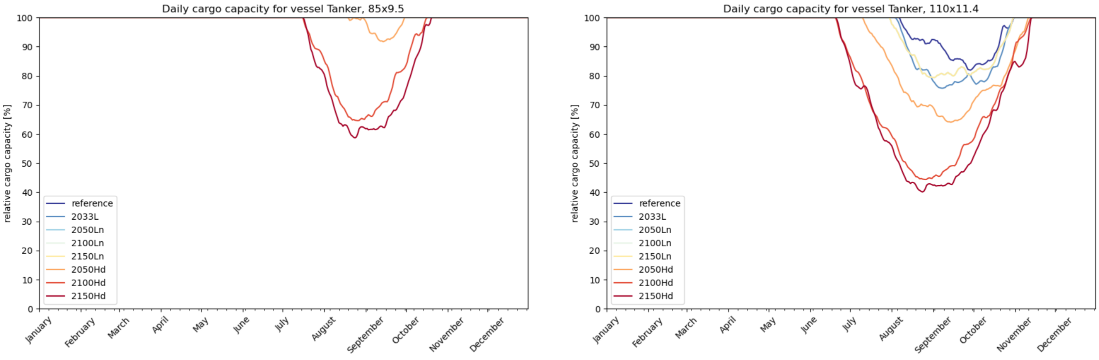
**Figure D.1:** Effect of low water on deadweight and payload capacity of inland ships, adopted from Van Dorsser et al. (2020)

# E

# Appendix E: Modelled daily loading rate of vessels

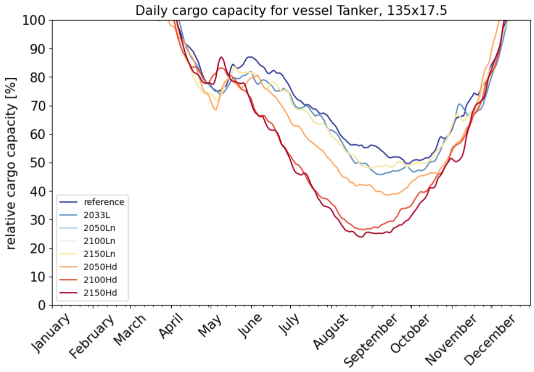
Using the method by Van Dorsser et al. (2020) tot estimate loading rate of vessels, the daily average loading rate is determined for a selection of vessel types and sizes in the reference scenario, as well as an Ln and Hd scenario in representative future years 2050, 2100 and 2150. Shown in Figure E.1 for tankers, Figure E.2 for single hull dry bulk vessels, Figure E.3 for double hull dry bulk vessels, Figure E.4 for container vessels and Figure E.5 for dumb barges.

## E.1. Tanker



(a) 85x9.5m, CEMT IV

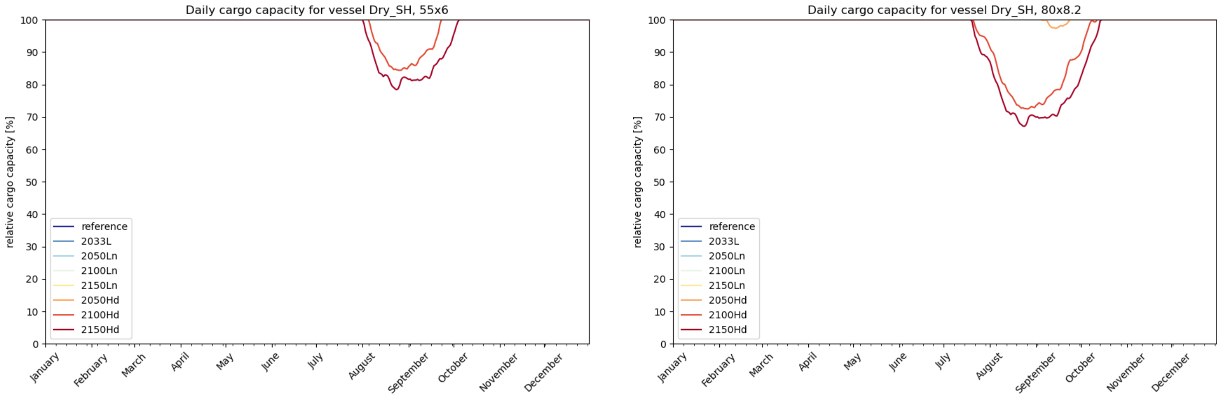
(b) 110x11.4m, CEMT V



(c) 135x17.5m, CEMT VI+

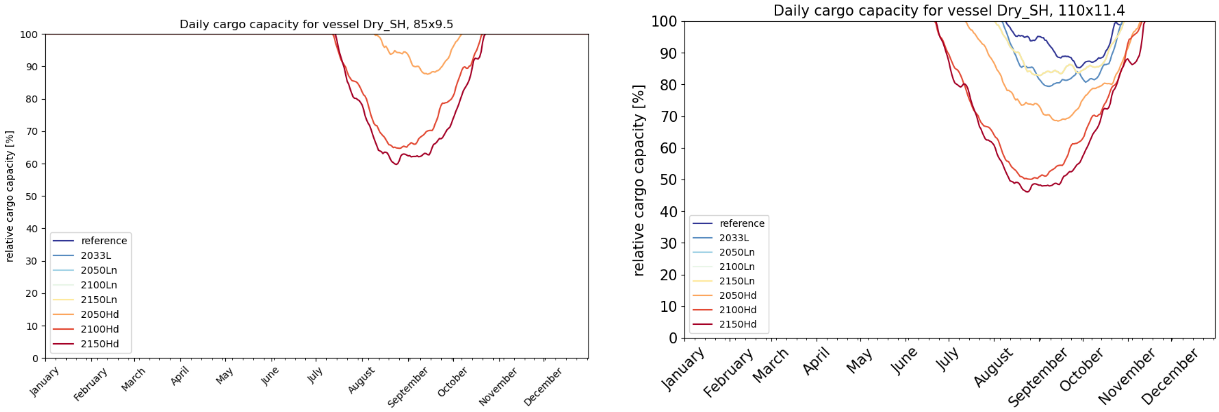
**Figure E.1:** Daily average cargo capacity for vessel Tanker

## E.2. Dry bulk (single hull)



(a) 55x6m, CEMT II

(b) 80x8.2m, CEMT III

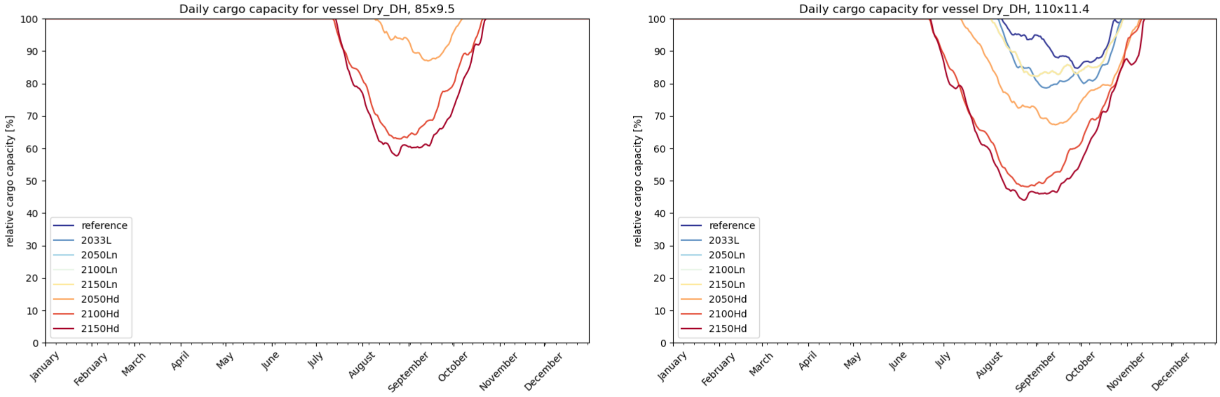


(c) 85x9.5m, CEMT IV

(d) 110x11.4m, CEMT V

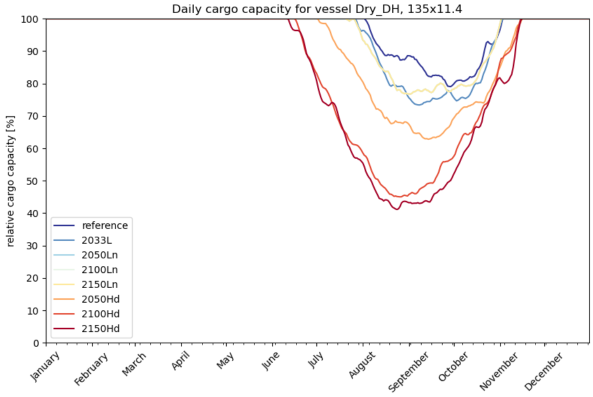
**Figure E.2:** Daily average cargo capacity for vessel Dry bulk (single hull)

# E.3. Dry bulk (double hull)



(a) 85x9.5m, CEMT IV

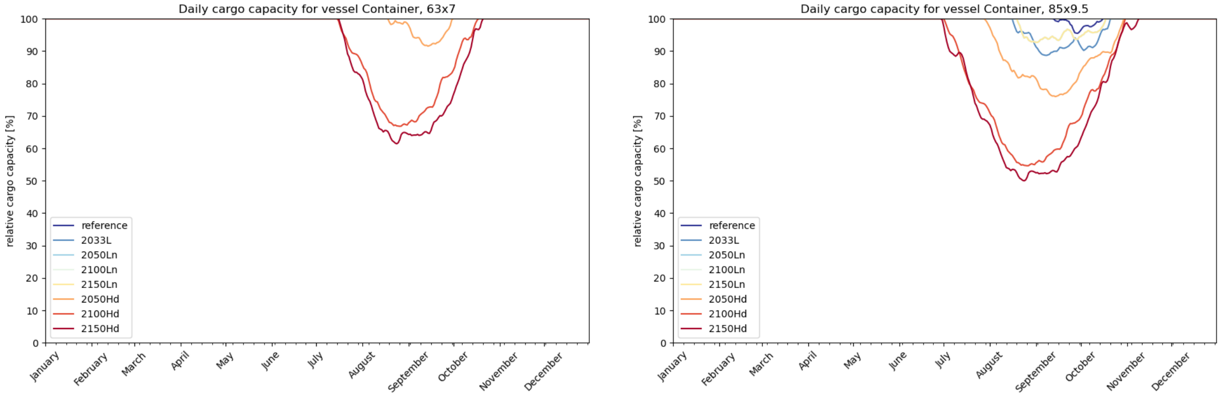
(b) 110x11.4m, CEMT V



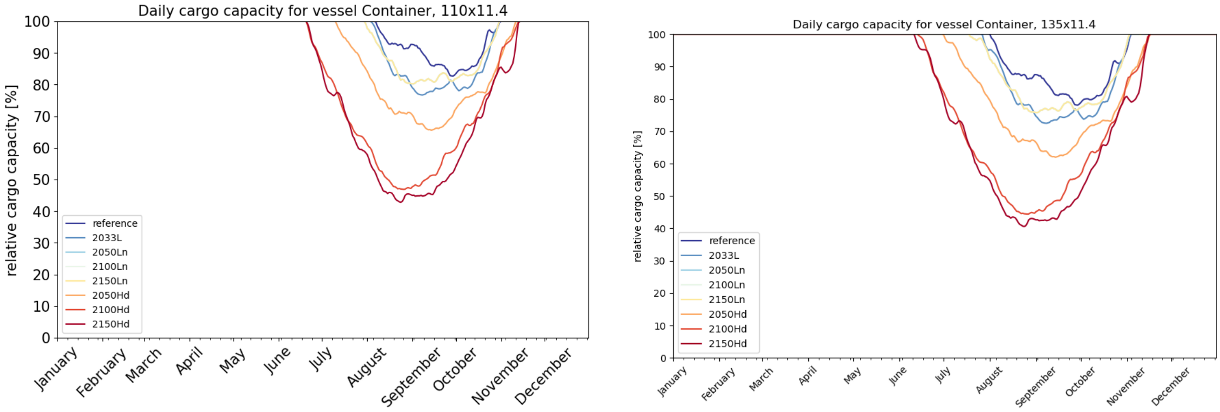
(c) 135x11.4m, CEMT VI

**Figure E.3:** Daily average cargo capacity for vessel Dry bulk (double hull)

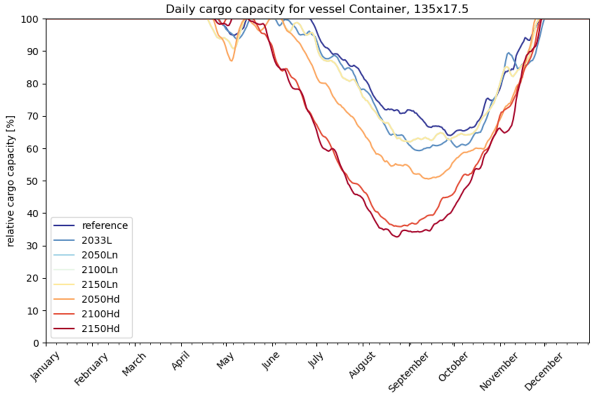
# E.4. Container vessels



(a) 63x7m, CEMT III (b) 85x9.5m, CEMT IV



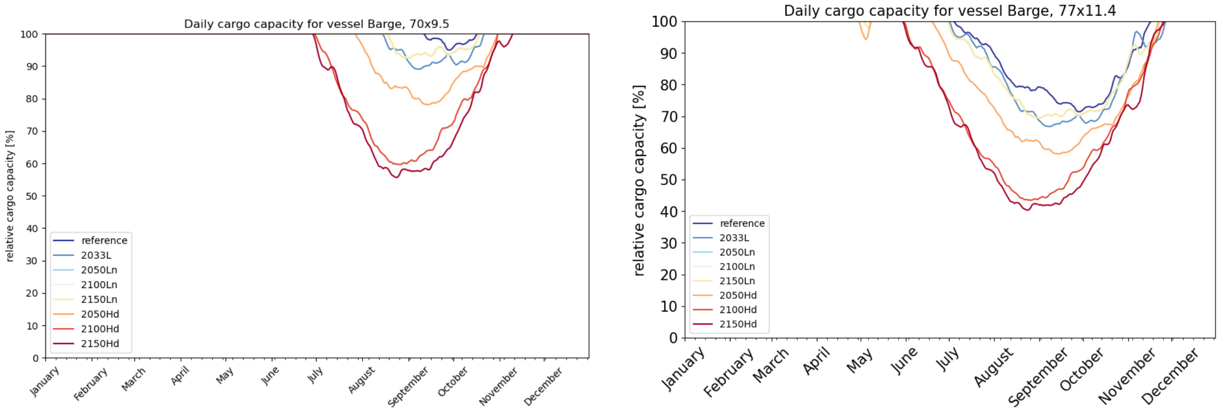
(c) 110x11.4m, CEMT V (d) 135x11.4m, CEMT VI



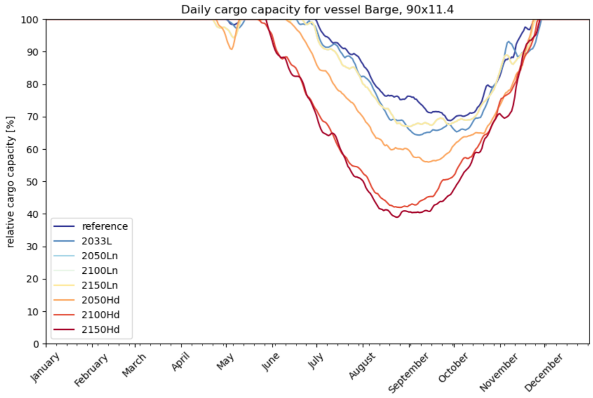
(e) 135x17.5m, CEMT VI+

**Figure E.4:** Daily average cargo capacity for vessel Container

## E.5. Dumb barges



(a) 70x9.5m, CEMT IV (b) 77x11.4m, CEMT V



(c) 90x11.4m, CEMT V

**Figure E.5:** Daily average cargo capacity for vessel Barge

F

# Appendix F: Future undershoot of 1600 $m^3/s$ discharge threshold push convoys

Figure F.1 displays the undershot of discharge level 1600 $m^3/s$ at Lobith in the future climate scenario's. 1600 $m^3/s$ is the discharge threshold below which push convoys banned on the River Waal, due to deteriorating navigability of the river in combination with navigating vessels.

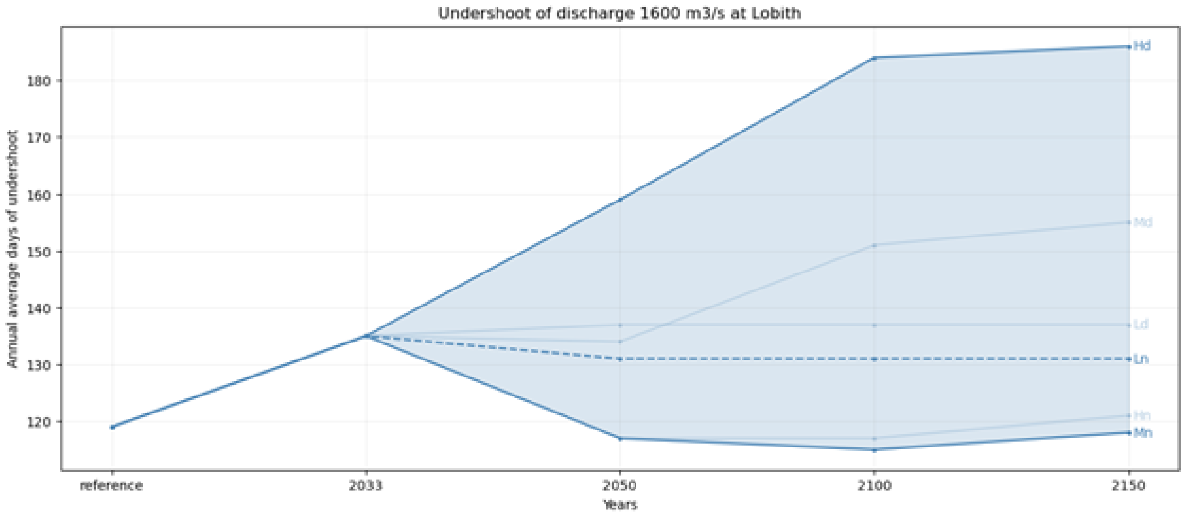


**Figure F.1:** Undershoot of 1600 $m^3/s$ discharge threshold allowing push convoys

In the best case in the future, push convoys are banned for 120 days, which is in line with the current situation. In the worst case 2150 Hd. Push convoys are banned more than 180 days, half of the year.

# G

# Appendix G: Future development of OLA 2022

Figure G.1 displays the undershot of discharge level 1020 $m^3/s$ at lobith in the future climate scenario's. The current OLA definition of 20 days this discharge is highlighted.

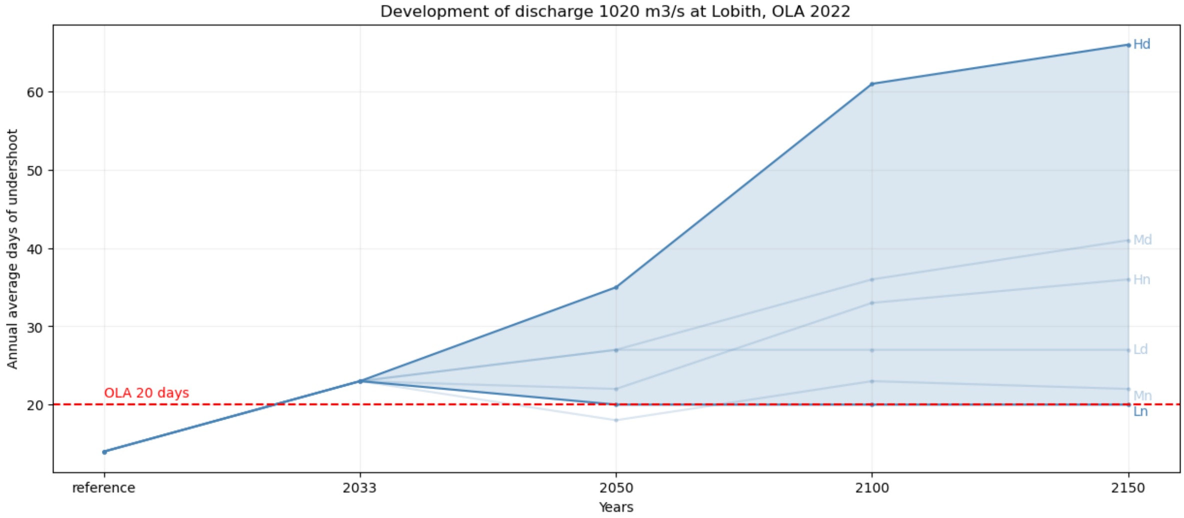


**Figure G.1:** Development of undershoot current OLA 2022

In the Ln scenario a discharge level of 1020 $m^3/s$ is annualy undershot an average of roughly 20 days. This is in line with the current definition of the OLA 2022. In the higher scenario's however the undershot of 1020 $m^3/s$ increases to more than 20 days. Therefore it is likely that in the future the OLA value is adjusted downwards to a discharge value that is undershot on average 20 days.

# H

# Appendix H: Navigation profile River Rhine CCR

The intended waterway profile for the River Rhine as prescribed by the CCR. For the Dutch section River Waal (from RKM 863 onward) a water depth of 2.8 meter in the fairway at OLR conditions is required.

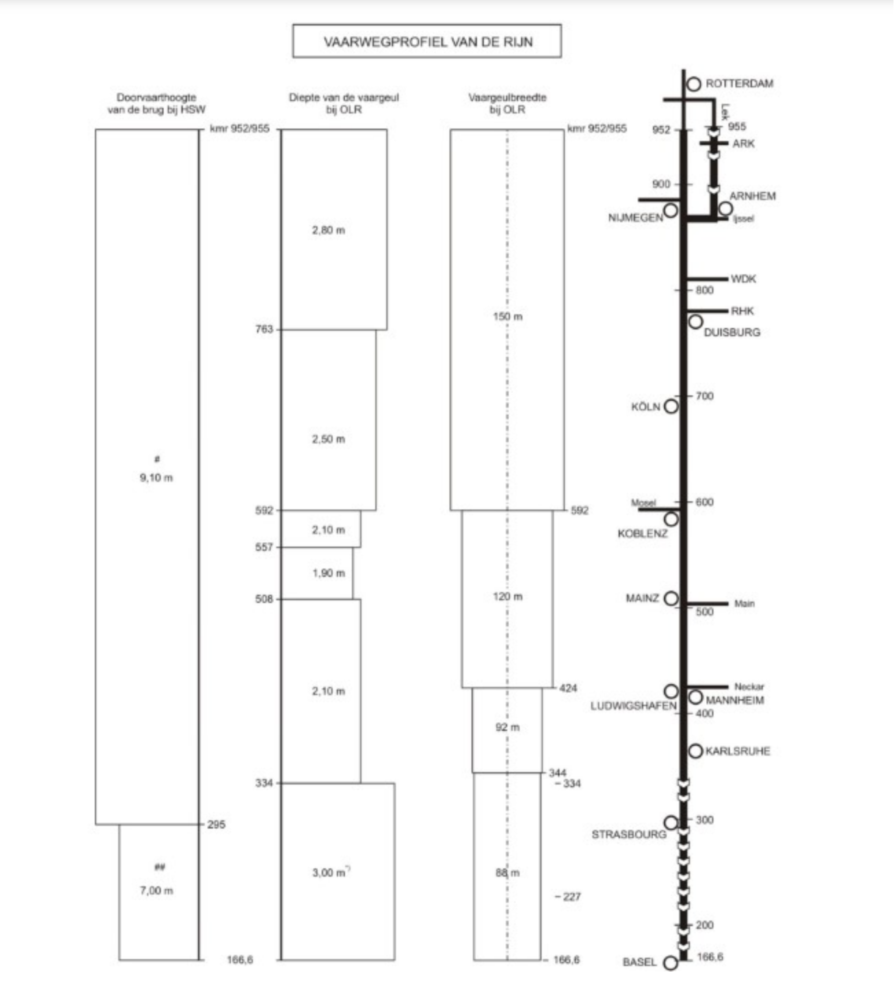


**Figure H.1:** Navigation profile River Rhine (CCR, 2012)