The impact of low water levels on inland waterway transport

An economic risk assessment of shipping on the Rhine

(Picture: Herman Engbers)

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Colophon

This document describes the final version of the Bachelor Thesis report of Arend Timmer, for completing the Bachelor Civil Engineering at the University of Twente.

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Preface

Here it is, the final version of my bachelor thesis. I am proud of the research that you can find in this report. The past three months I enjoyed working towards the completion of my Civil Engineering Bachelor.
This thesis was commissioned by Royal HaskoningDHV. It was a dream coming true to work in the same office where my father used to work over 15 years ago. I enjoyed the pleasant working environment and colleagues this company had to offer. Seeing how a professional Civil Engineering consultancy operated was interesting and I learned a lot during office hours.

A special thanks to Ric Huting for being a supportive and thoughtful supervisor from Royal haskoningDHV. Your insights and guidance were much appreciated. I would also like to thank Rutger Siemes, my supervisor from the University of Twente. The weekly coffee talks and the quick responses aided me towards completing this thesis to my liking.

I hope you enjoy reading my bachelor thesis report.

Sincerely,

Arend Timmer
27 January 2023

Summary

In 2018 a severe dry period occurred, only for it to happen again in the summer of 2022. The dry period of 2022 caused the lowest water level to date on the Rhine at Lobith [NOS, 2022]. Dry periods and the resulting low flows on the Rhine are a growing problem.

While the main focus on the Rhine was often on flooding it is also important to realise that the low-flow periods have a large impact on the Netherlands [van Hussen et al., 2018]. This thesis has expanded on the consequences of low-flow periods on the inland shipping industry and the welfare loss that happens due to this. Lower water levels cause transportation prices to rise and this causes welfare loss for the Dutch and German economies. This thesis tries to find the risk of low-flow periods on the Rhine. This is done by combining low-flow statistics with an economic impact assessment. Additionally, climate change was assessed to see if climate change will have an influence on the low-flow statistics of the Rhine.

The first step of the thesis, the low-flow statistics, was done by using 101 years of historical discharge data of the Rhine. By plotting the so-called 'Low Flow Frequency Curve' of the Rhine at Lobith the current probabilities of low flows were determined. The influence of climate change was found using literature research. The effect of climate change depends on which climate change scenario is used. The most severe climate change scenario increased the chance of low flows by less than 1% and the most severe climate change scenario increased the chance by over 60%

The second step, the economic impact assessment, was done using historical inland vessel data. Looking at the difference in water level and the draft of a ship, this thesis determined the transportation efficiency of different types of ships. If the efficiency dropped below a certain threshold, cargo loss occurred. This 'lost' cargo is used as the output of the economic impact assessment, this shows how much cargo is lost due to the lower water levels on the Rhine. This lost cargo ranges from 0 tons, at the water level where every ship can sail with maximum capacity, to over 20 million tonnes, at the water level of 1.9m where only the smallest ship can sail with very limited capacity.

At the end of this thesis, the probabilities found by the low-flow statistics are combined with the output of the economic impact assessment, to gain the risk of low-flow periods. Included are several climate change scenarios, since they have different low-flow statistics they also have different risks. The total risk of the current climate is equal to $9,80 * 10^6$ tons of cargo and the risk of the worst climate change scenario is equal to $1,58 * 10^7$ tons.

Additionally, a less substantiated method was used to find a monetary value for the economic impact. This method used the 'Low water surcharge' at Emmerich to see what the increased transportation price would be during low-flow periods. This only looked at the extra price of transported cargo, not lost cargo transportation due to transportation efficiency loss. Therefore the monetary damage is on the low side. The current yearly risk was found to be equal to €4.500.0000 and in case of the worst climate change scenario, this could increase up to 150% to €11.400.000 yearly.

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1 Introduction

The Netherlands is a unique country when it comes to rivers. It can be seen as one big delta of large European rivers, think of the Meuse and especially the Rhine. These large rivers have always offered great opportunities for the Dutch. One of these benefits is the transportation of goods. Large rivers offer cheap and easy transportation, resulting in a beneficial trade environment. The commerce on these large rivers has always been very beneficial for the Dutch economy [CBS, 2020]. Transport using inland waterway transport is desired by the Dutch government and the European commission. This desire includes a model shift from truck transport to ship transport since an inland waterway vessel causes a lot fewer emissions per ton of cargo. Additionally, there is still unused space on the rivers, while the road network is under a lot of pressure. Therefore a transition from road transportation to inland waterway transportation is taken into account in the coalition agreement between the Dutch government and the European Green Deal. Aimed at relieving the crammed road network, improving transportation safety, and reducing emissions [BureauVoorlichtingBinnenvaart, 2023] [Harbers, 2022].

However, inland waterway transport comes with its own risks. In 2022 the Netherlands experienced severe dry periods, which caused extremely low discharges of the rivers. The result was historically low water levels of the Dutch rivers. On the Rhine, the lowest water level was measured, since the Dutch began measuring water levels, of 6.48m NAP [NOS, 2022]. Climate change is linked to enhancing these dry periods, both in duration and severity [Weiland et al., 2014].
The effects of low water levels on inland waterway transportation are damaging. As stated before, river transportation plays an important part in the Dutch economy. Low water levels hinder ships and are thus disadvantageous for the Dutch economy. Ships can take less cargo with them, or smaller ships need to be used. Lower water levels also mean a smaller river width, resulting in congestion and dangerous situations. All leading to higher unit transport prices. In 2018 the water level of the Rhine at a bottleneck near Nijmegen was lower than the target water level for 156 days. Additionally, for 21 days the water level was so low that a part of the shipping fleet couldn't even sail [van Hussen et al., 2018]. The result was a decreased transportation efficiency, which increased the transport prices of the shipping industry. 2018 saw a revenue increase of 17% for the shipping industry, while 5% less cargo was transported in that year [CBS, 2018]. The disruption of the distribution processes that rely on inland waterway transport along the Rhine is increased during these low water level periods due to the increase in cost and decrease in transported goods [van Hussen et al., 2018].
This research thesis was instructed by the Dutch civil engineering consultancy Royal Haskoning DHV. The client ordered this research to be conducted because both the economic and environmental effects of low water levels are not established knowledge. Therefore they want this research to try to explore this relatively unknown field of Dutch civil engineering, acting more as an exploratory study to bring attention to this field and to try and establish a method that can be expanded on in the future.

The main structure of this report is as follows. The report has five main chapters. Chapter 1, the introduction, was written to give more context to the problem, determine the research objective plus questions and give the main framework of this research thesis. Chapter 2 will give insight on the methodology used in this thesis and the data used in this thesis. Chapter 3 will give the results of the data and methodology described in the previous chapter. Short interpretations will be included with the results, the rest of the discussions can be found in chapter 4. Additionally, in this chapter, a second method can be found that was used in the final weeks of this thesis, and thus lacked the substantiation to be included in the main structure of the report. At last, there is the conclusion and recommendation of this thesis in chapter 5.

Chapter 2, 3 and 4 are all divided based on the research questions. The structure of this will be as follow: first current low flow statistics of the Rhine will be determined. It will try to include potential effects of climate change to see if these low water statistics change in the future. The low water level probabilities are needed to find the risk of low water levels. After that, the economic impact of low water levels on inland waterway shipping on the Rhine will be looked at. In the end, the low water statistics will be combined with the economic impact to get a total risk of low water levels on inland waterway transportation. Each of these chapters is thus structured in a low-flow statistics part, then an economic impact part and at last a risk assessment part. Each of these chapters also has a section called 'The hydrological year of 2022' in this section the method of this thesis is applied to the hydrological year of 2022. This chapter will not be used to verify this thesis method, since it is only one year that will be checked. But it is merely present to see the results of this method on the most recent severe dry period.

1.1 Thesis context

1.1.1 Study Area

The study will focus on a section of the Rhine river. The Rhine has a lot of cargo traffic, in 2006 63% of the total inland waterway cargo volume in Europe was transported along the Rhine. [Jonkeren et al., 2014]. This makes the Rhine the most interesting European river to assess the impact of low water levels on. The Rotterdam-Duisburg trajectory is the busiest of the Rhine [van Slobbe et al., 2016]. Therefore the starting point of the study area will be the port of Rotterdam, and the end of the study area will be Duisburg. Duisburg is located at the beginning of the Ruhr area. Subsequently, during droughts, the port of Rotterdam is the biggest exporter of cargo along the Rhine and the ports of the Rühr area are the biggest importer of cargo along the Rhine. The result is that this trajectory of the Rhine experiences the most economic damage during droughts [Schasfoort et al., 2019]. The study area is visualised in figure 1.

Figure 1: Map of the study area
[Worldinmaps, 2021]

The study area is large, therefore some idealizations have to be made, to make sure that this thesis fits in the time available. These idealizations will be assessed thoroughly and will be added in such a way that further research could easily expand on it and reduce some idealizations to make future research better representative of the Rhine as a whole.

For simplistic reasons, the decision was made to take Lobith as the only bottleneck along the Rotterdam-Duisburg trajectory of the Rhine. This decision was made because Lobith has a lot of data available and lots of research papers are about the Rhine at Lobith. Seeing Lobith as the only bottleneck means that the water level at Lobith determines the transportation efficiency of ships that sail from Rotterdam to Duisburg. This way only the water levels at Lobith need to be known to assess the economic impact.

For further research, more bottlenecks should be assessed to get a more realistic view of cargo transportation from Rotterdam to Duisburg. Again, for this research, only one bottleneck will be used. The method that will be applied at Lobith can be easily applied to different bottlenecks, making it easier for further research to be conducted.

1.1.2 Historical low flow periods

The discharge data of the last 20 years at Lobith are visualized in figure 2. Especially in 2018 and 2022, you can see an extremely dry period. These extreme low water periods affect the inland waterway transportation on the Rhine. Low water levels have always caused problems in The Netherlands. Moreover, it seems that extreme dry periods are happening more often. Some unwanted effects of these dry periods are congestion at bottlenecks, ships restricted to carrying less cargo, and ships needing to make more trips to meet supply chain demands. This figure shows that in the past decade in 2011, 2015, 2016, 2018, 2020, and in 2022, daily average discharges of less than 1020 m3/s were measured at Lobith. The 1020 m3/s discharge drought threshold was derived from the OLA (Overeengekomen Laagwater Afvoer; Agreed Low water Discharge) [Jans, line]. The OLA is determined every 10 years by Rijkswaterstaat and was determined for 2022 to be 1020 m3/s [Jans, line]. OLA is the discharge value agreed upon that 5% of the time the discharge at Lobith is lower than the OLA. This is not a legal boundary but merely an indicative boundary. In 2022 it was even worse; a new record discharge of less then 700 m3/s for several days was measured this summer [Rijkswaterstaat, 2022].

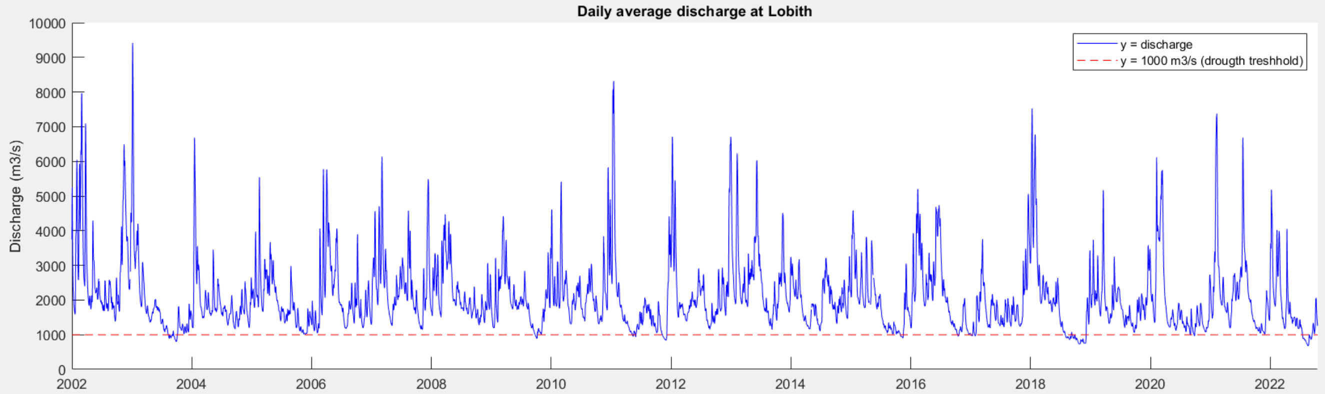


Figure 2: Daily average discharge at Lobith
[Rijkswaterstaat, 2022]

These low water level periods cause an economic impact. Research shows that using climate change scenarios from the Royal Netherlands Meteorological Institute (KNMI), costs of transportation could be increased up to 75% during dry periods [Jonkeren et al., 2014]. This paper used an economic model to see what the effects of a lower Rhine discharge would be. Also using the principle that transportation efficiency lowers during dry periods. Then using an economic model that uses this loss in supply to determine higher transport prices. The climate change effect is incorporated using the increased precipitation and temperature based on the KNMI climate change scenarios.

This problem is not a new problem, in 2003 during a severe drought, damages were estimated to be €91.000.000 from one bottleneck in the Rhine at Kaub. The paper concludes that ”climate change, annual welfare losses as a result of low water levels via the inland waterway transport sector will rise” [Jonkeren et al., 2007]. Luckily 2002 was a very wet year, therefore the drought impact of 2003 was limited due to filled groundwater reservoirs [de Wit, 2004].
Extreme water levels are often linked with climate change with extreme water levels occurring more frequently, lasting longer, and being more extreme, e.g. when you look at the data from WaterInfo over the past 50 years [Rijkswaterstaat, 2022]. Climate change has a potentially negative effect on the high and low-flow statistics of the Rhine. The worst climate change scenario for an increase of discharge found that climate change could increase discharge by 13,0%. However, the decrease of discharge in the worst climate change scenario would be up to 33,3% [te Linde et al., 2018]. Showing that climate change might have a greater effect on extremely low discharges. Determining the welfare loss due to low-flow periods in future climate scenarios could give a good insight if countermeasures are needed, and how much money would be worth investing.

1.2 Research Gap

Using literature and the context of this thesis the research gap was determined.
There is no established method to calculate the probability of extremely low discharges. Secondly, as stated in the section before there are a lot of papers regarding low water levels on the Rhine and the economic damage it causes to the shipping industry [Jonkeren et al., 2014] [Jonkeren et al., 2007]. Even papers taking into account various climate change scenarios [Beuthe et al., 2014]. Nevertheless, a clear risk assessment that takes into account different types of ships and climate change scenarios is missing.

1.3 Problem Statement

Dry periods result in low water levels on the Rhine. This affects the inland waterway transport along the Rhine. Ships can carry less cargo, endure more congestion, and need to make more trips. Resulting in economic damages. Climate change seems to play a role in the increased frequency and duration of dry periods. The exact impact that climate change has on low water levels is still unknown and an established method to determine future low water flow statistics is not present. The welfare loss caused by low water levels in the inland shipping industry is also yet to be determined.

1.4 The Research Objective

To assess the economic impact during extremely low discharges in the Rhine.

1.5 Research Questions

Research questions were followed from the research objective.

- *Q1: How can low-flow statistics be determined?*
    - *Q1.1: How can current low-flow statistics be determined?*
    - *Q1.2: How can climate change be taken into account when determining low-flow statistics for the future?*

The first research question is covering the first part of the research; determining the low-flow statistics. First, this will be done using historical data, this will give the current low-flow statistics at Lobith. After that, it will be looked at if climate change can be incorporated into the low-flow statistics. Incorporating climate change into the low-flow statistics at Lobith will give future low-flow statistics.

- *Q2: What will be the impact of extremely low water levels on inland waterway transport?*
    - *Q2.1: What is the welfare loss due to the effect of low water levels on inland waterway transport?*

In the second research question the impact that the inland shipping industry experiences during low water levels will be assessed.

- *Q3: What is the risk of welfare loss due to low flows limiting transportation efficiency of the inland waterway industry?*
    - *Q3.1: How will climate change affect this risk in the future?*

The last research question combines the outcome of the two previous research questions. This question will answer the risk of welfare loss when inland ships are limited in transporting goods due to low water levels. Combining the low-flow probabilities with the impact that occurs during these low-flow periods will give the total risk of low-flow periods. This also gives the opportunity to compare the risk of present and future low water statistics. This shows what extra risk is being created by climate change for the inland shipping industry.

1.6 Report outline

The structure of the remainder of this report will consist of four more chapters, which are divided into subchapters based on the research questions. Chapter 2 will expand on the data and the methodology used in this thesis. Chapter 3 will show the results of this thesis. Chapter 4 will include a discussion and at last, chapter 5 will be the conclusion and recommendation. The recommendation is split into a recommendation based on this thesis's findings and a recommendation for the client on how to improve the economic risk assessment of low-flows on inland waterway transport.

1.6.1 Research Framework

Following the research objective and the research questions, the main research framework can be made. This can be seen in figure 3.

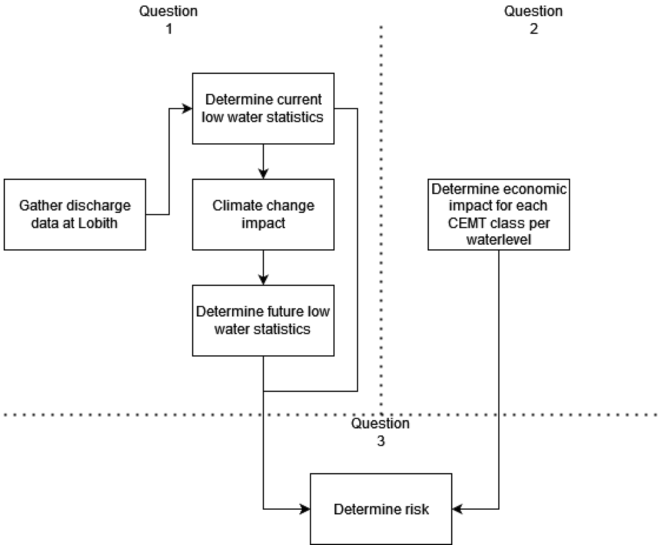


Figure 3: Research framework

2 Methodology

2.1 Data

2.1.1 Discharge data (Q1.1)

The discharge data for this thesis was obtained from Waterinfo.nl [Rijkswaterstaat, 2022]. Waterinfo is an open data source, operated by Rijkswaterstaat. Rijkswaterstaat is the Dutch government executive institution of the Dutch Ministry of Infrastructure and Water Management of the Netherlands.
The discharge data of the past 101 years were requested and delivered in an excel by Waterinfo. This data had some inconsistencies with how many measurements were taken each day. Till 1996 measurements were taken daily, from 1996 till 2012 measurements were taken each hour, and since 2013 measurements are taken every 10 minutes. From 1922 till 2022 the daily average discharges were determined after outlying measurements were removed ($Q = 10^{38}$), resulting in 101 years of discharge data.

Low-flow frequency curve

The desired output of the low-flow statistics is a Low-Flow Frequency Curve (LFFC). This LFFC shows the return period in that the flow of a river falls below a given discharge. This is based on a series of annual minimum flows [Smakhtin, 2001]. Important for this LFFC is that the annual minimum flows are independent of each other. A normal hydrology year is typical from October to September, since then the annual high flows are independent of each other. Since this thesis is all about annual low flows, the hydrological year shifts 6 months, from April to March. This results in the year switch being away from the Rhine's low flow period, which is October and November [van Brenk, 2021] [de Wit, 2004]. Shifting the typical hydrological year with 6 months resulted in independent annual minimum flows. An example of a LFFC can be seen in figure 4. In this figure, you can clearly see that the flow expressed in discharge is plotted against the probability that this annual minimum flow occurs. The figure also shows that lower flows have a lower probability of occurring, this is also to be expected from the LFFCs that will be made for this thesis.

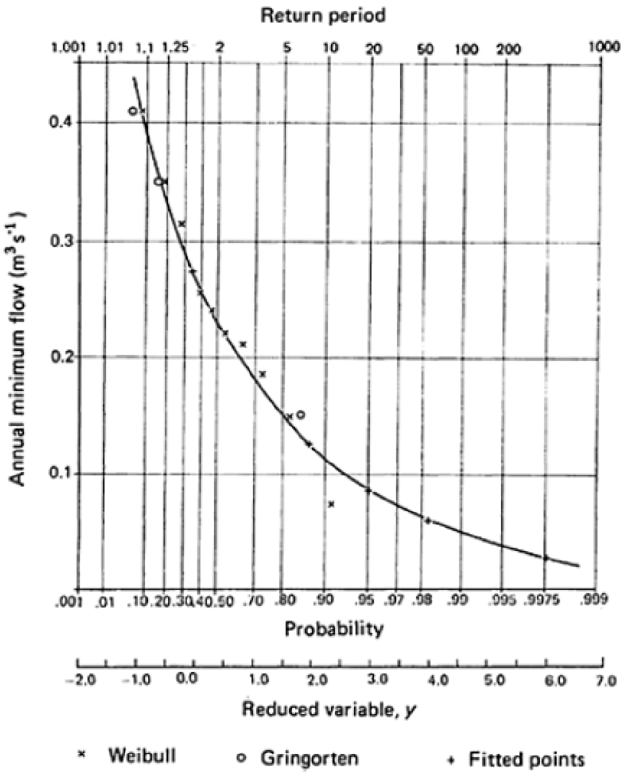


Figure 4: Example of a Low Flow Frequency Curve, obtained from [Shaw, 1994]

Annual low flow period duration

The series of annual minimum flows need to be given a duration. The duration of the annual minimum is important because one could look at the daily average minimum flow. Yet, this is too short. If the water level at Lobith is very low for a day and then jumps back up to acceptable levels it would not cause that much economic damage. Therefore a longer period with an accompanied average minimum of that year needs to be obtained. This period will be equal to 7 days.

The 7 days was based on eighteen interviews of experts (Rhine river managers in both the Netherlands and Germany), stating ”Interviewed stakeholders consider a period of more than 7 days with water depths below 2.1m as damaging for the economy, because of limits in storage capacity of critical goods, like coal for power generation.” [van Slobbe et al., 2016]. A discharge lower than 2.1m is hindering the transportation of even the most critical goods for the economy. Anything lower than that will seriously damage the economy. Additionally the 7 day period makes it easier to link the economic impact with the low-flow statistics, more over this later in chapter 2.5.

Thus the data used for the statistical analysis will be the highest discharge during the lowest annual flow with a duration of 7 days. Resulting in 101 data points that each shows the weekly maximum discharge of the annual minimum flow.

Q-h relationship at Lobith

The gathered data is the discharge at Lobith, expressed in cubic meters per second (m3/s). Nevertheless, the output of the low-flow statistics needs to be water levels and the probability of each water level. To go from discharge to water level the Q-h relationship of the Rhine at Lobith needs to be known. This Q-h function is needed to plot the LFFC of the Rhine at Lobith. The translation from discharge data to water level is needed to determine the impact on inland waterway transportation.

A Q-h relationship can be found when certain discharges and their corresponding water levels are known. This was obtained for Lobith from the site of Rijkswaterstaat [Rijkswaterstaat, 2021]. Through these Q-h points a fitting function was found using excel. This function can be seen in function 1, and the fitted graph can be found in figure 5.

$$Q(h) = 12{,}731h^3 - 340{,}65h^2 + 3618{,}4h - 12156 \qquad (1)$$

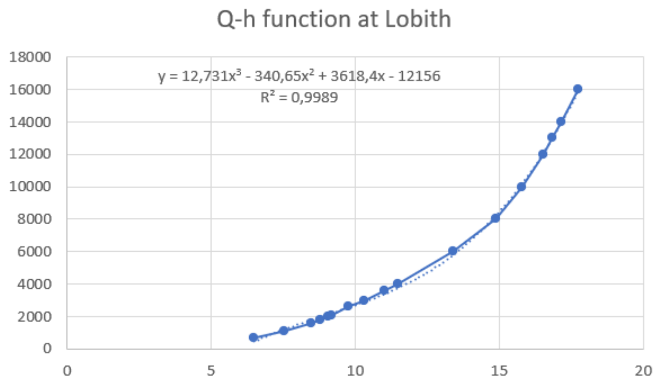


Figure 5: Fitting of the Q-h function of Lobith, data points obtained from [Rijkswaterstaat, 2021]

Uniform water level data

The problem that arose when determining the Q-h relationship at Lobith was that the water level is expressed in m+NAP. NAP stands for 'Normaal Amsterdams Peil', this is the reference point for most Dutch height measurements. It is approximately the average water level of the North sea. Looking at figure 6, the economic impact will be calculated using the difference between the draft (m) and the water level h2 (m). However, the output water levels obtained from Q-h relationship are expressed in h1 (m+NAP). Therefore the height of the NAP at the bottom of the Rhine at Lobith needs to be determined.

The NAP of the bottom of the Rhine at Lobith was obtained by using the water level discharge point from the OLA. This threshold is defined as a discharge of 1020 m3/s and a water level of 2.8 m. This was added in the Q-h relationship function 1, where the h was equal to 2.8+NAP. Different NAP heights were iterated until the output Q gave 1020 m3/s. The best fit NAP that was found is equal to 4.45 m.

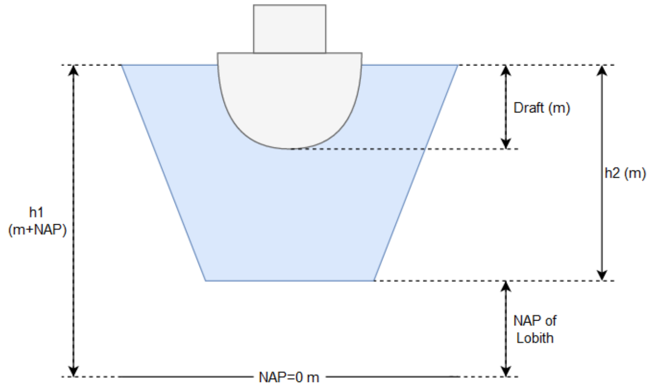


Figure 6: Visualisation of the data's NAP problem

2.1.2 Climate change effect data (Q1.2)

Low flow periods on the Rhine, being the result of severe droughts, are not uncommon if you look at the history of the Rhine. At the same time, many are concerned that climate change is increasing the frequency, duration, and intensity of these low flow periods [Vinke et al., 2022]. This would lead to more economic damages due to the loss of transportation efficiency along the Rhine. Climate change and inland waterway transportation have been linked in several papers. This is done using the KNMI'14 climate change scenarios [van den Hurk et al., 2014]. Each scenario is based on a set of variables that differ in value in each scenario, the exact variables can be seen in chapter four of the scientific report. The KNMI made four different climate change scenarios projected for the years 2050 and 2085. The 2014 scenarios are defined in four different pools. The first two pools are the global temperature rise, where this could be a moderate increase (G) or a high/warm increase (W). The last two pools are the change in precipitation, this could either be a strong response (H) (wetter winters and drier summers) or a relatively weak response (L) (smaller changes during both seasons). This overview is visualized in table 1. Later on in the research, an extra climate change scenario will be considered called "WHdry". As the name suggests, this scenario is based on WH but is more extreme. This scenario is based on the findings of IPCC, an organization of the United Nations to assess climate change.

Scenario	Global temperate rise	Change in precipitation
G_L	Moderate	Low change
G_H	Moderate	High change
W_L	Warm	Low change
W_H	Warm	High change

Table 1: General description of the KNMI'14 climate change scenarios, obtained from [van den Hurk et al., 2014]

The Rhine is a meltwater-rain river, expected is that the Rhine will become more dominated by rain due to the increase in world temperature. The consequence of this transition will be that more water is available in the winter due to less water being stored as snow in the winter. And less water is available in the summer and autumn since there is less meltwater and more evaporation. Moreover, the prediction is that precipitation will become more extreme; wetter winters and drier summers are to be expected. Leading to higher flows during winter and fall and lower flows during summer and autumn [Jonkeren et al., 2014]. The KNMI'14 scenarios reinforce this claim. Figure 7 shows that three (not G_H, this one shows an increased discharge in the fall) KNMI'14 climate scenarios will increase the discharge at Lobith in the winter and spring, and decrease the Rhine's discharge in the summer and fall.

This potential decrease of discharge during the summer and autumn is where the problem lies with climate change and the consequences on inland waterway transportation.

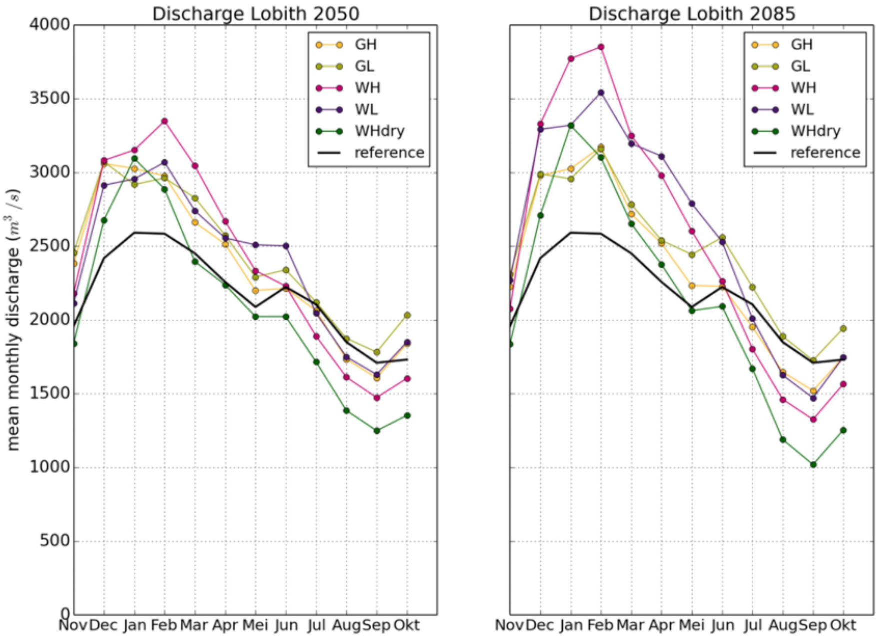


Figure 7: Monthly average discharge at Lobith for both 2050 and 2085 for the four KNMI'14 climate scenarios, obtained from [Weiland et al., 2014]

KNMI 2023 scenarios

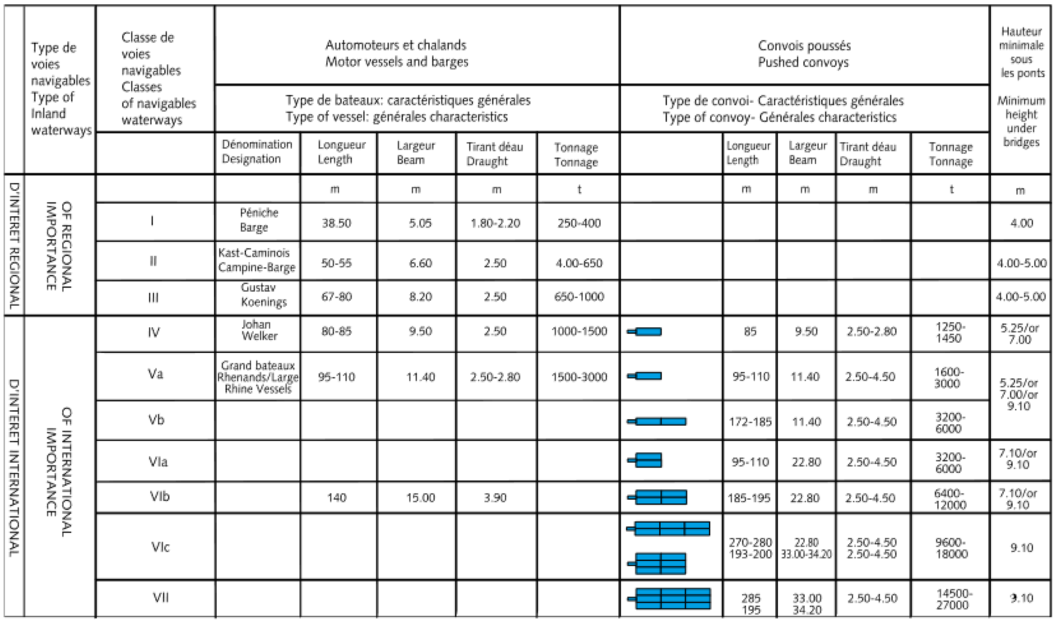
New KNMI climate change scenarios will be released in the year 2023. This is one year short for this thesis. For further research, it is advised to look at the KNMI '23 scenarios for more typical results. The KNMI scenarios are based on the climate change reports from IPCC. The KNMI '23 scenarios are based on the AR6 [IPCC, 2022] report that was released in 2022 [Klijn et al., 2012]. The KNMI '14 scenarios are based on the AR5 report [IPCC, 2013] from IPCC released in 2013. Therefore looking at both the AR5 report and the AR6 report, potential changes in the KNMI '23 scenarios towards the '14 scenarios can be discussed.
The summaries of both the AR5 and AR6 reports were scanned to see if there was a big difference between the two. The main conclusion that was drawn in the AR6 report is that there is now more evidence for the concern raised in the AR5 report. The difference lies in proof of concerns, instead of the severity of concerns. Therefore based on this comparison, it is believed that the KNMI '23 scenarios will not differentiate a lot from the KNMI '14 scenarios. Of course, in the future, use the KNMI '23 scenarios if possible.

2.1.3 Economic impact data (Q2.1)

CEMT classes

For this part of the thesis, the so-called CEMT classification system for inland ships will be used. This stands for Conférence Européenne des Ministres des Transports [Koedijk, 2020] and is a European classification used for different types of inland waterway vessels. All the different CEMT classes can be found in table 2. The draft of the ship is especially of interest to this thesis. This is the distance between the waterline and the bottom of the hull (keel). This draft is used to check whether the ship can sail during low water level periods.

The CEMT classes that are used in this research are all the CEMT classes that sail pass Lobith. These were obtained from IVS [Rijkswaterstaat, 2023]. IVS stands for 'Informatie- en Volgsysteem voor de Scheepvaart' or 'Information and follow system for de shipping industry' and is operated by Rijkswaterstaat, it keeps track of the load and the location of all the cargo ships that use Dutch waterways. The results can be seen in table 3, included is the number of ships with cargo that sail past Lobith each week. The week chosen was the last week of August from the year 2022, since this is the week when the typical dry period starts. More explanation of why this week was chosen will be explained later on.



	Type de voies navigables Type of Inland waterways	Classe de voies navigables Classes of navigables waterways	Automoteurs et chalands Motor vessels and barges					Convois poussés Pushed convoys					Hauteur minimale sous les ponts Minimum height under bridges
			Type de bateaux: caractéristiques générales Type of vessel: générales characteristics					Type de convoi- Caractéristiques générales Type of convoy- Générales characteristics					
			Dénomination Designation	Longueur Length	Largeur Beam	Tirant déau Draught	Tonnage Tonnage		Longueur Length	Largeur Beam	Tirant déau Draught	Tonnage Tonnage	
D'INTERET REGIONAL	OF REGIONAL IMPORTANCE			m	m	m	t		m	m	m	t	m
		I	Péniche Barge	38.50	5.05	1.80-2.20	250-400						4.00
		II	Kast-Caminois Campine-Barge	50-55	6.60	2.50	4.00-650						4.00-5.00
		III	Gustav Koenings	67-80	8.20	2.50	650-1000						4.00-5.00
D'INTERET INTERNATIONAL	OF INTERNATIONAL IMPORTANCE	IV	Johan Welker	80-85	9.50	2.50	1000-1500		85	9.50	2.50-2.80	1250-1450	5.25/or 7.00
		Va	Grand bateaux Rhenands/Large Rhine Vessels	95-110	11.40	2.50-2.80	1500-3000		95-110	11.40	2.50-4.50	1600-3000	5.25/or 7.00/or 9.10
		Vb							172-185	11.40	2.50-4.50	3200-6000	
		VIa							95-110	22.80	2.50-4.50	3200-6000	7.10/or 9.10
		VIb		140	15.00	3.90			185-195	22.80	2.50-4.50	6400-12000	7.10/or 9.10
		VIc							270-280 193-200	22.80 33.00-34.20	2.50-4.50 2.50-4.50	9600-18000	9.10
		VII							285 195	33.00 34.20	2.50-4.50	14500-27000	9.10

Table 2: CEMT classification from 1992 for waterways west of the Elbe [Koedijk, 2020]

Transportation efficiency

Next up is determining the transportation efficiency of these CEMT classes at different water levels. This is done by obtaining the draft data of each CEMT class, when the ship is empty and when the ship is fully loaded. The transportation efficiency is then done based on Archimedes' principle: 'the upward buoyant force that is exerted on a body immersed in a fluid, whether fully or partially, is equal to the weight of the fluid that the body displaces' [Acadamy, 2014]. Using this principle the assumption is made that the volume of a ship increases/decreases linearly over its height. Such that when a ship is half full, its draft is half of the difference in the draft when empty and fully loaded. To clarify a visualisation of a ship was made where the empty draft was 1 meter and the full draft was 3 meters, see figure 9. If this assumption was the reality the ship would be a perfect cuboid. In reality, a ship's volume doesn't increase linearly over its height, especially at the back and the front of an inland ship. This can be seen in figure 8 where a typical ship built by the shipyard RensenDriessen is shown just before the ship is let down in the water. This assumption is further reinforced by a low water report from Contargo. Contargo is a German logistics company that made a report for dry periods and inland waterway transportation about increasing transport costs [Contargo, 2017]. Figure 10 was obtained from this tech report and this shows also an almost linear relationship between water level and transport efficiency.

Figure 8: A typical inland vessel out of the water to showcase the profile of the ship [Driessen, 2021]

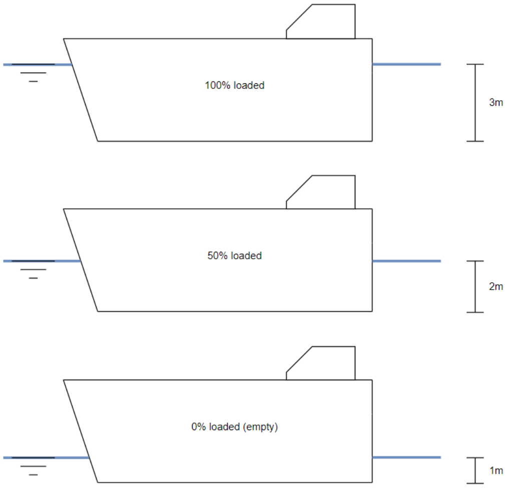


Figure 9: The assumption based on Archimedes' principle visualised with a ship

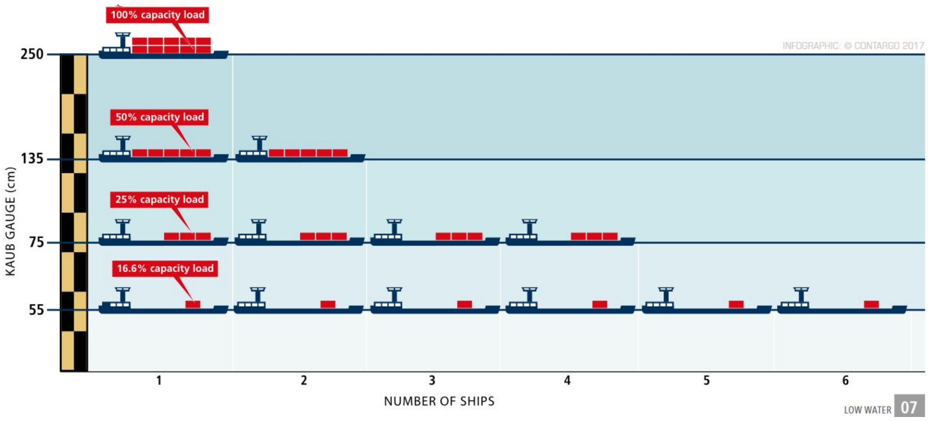


Figure 10: Transport efficiency of a ship at the Kaub bottleneck in Germany for different water levels, derived from [Contargo, 2017]

For each CEMT class the drafts when empty and the drafts when full were obtained using table 2 and other tables derived from that report [Koedijk, 2020]. This data can be seen in table 3. Included in the draft data of the ships is a safety factor of 32 cm [Kriedel et al., 2021] to ensure that the ships always have some space between their ship and the bottom of the river. For the capacity, the average capacity of each CEMT class type was also derived from the CEMT report [Koedijk, 2020]. To conclude, per CEMT class it is known how many ships there are in the last week of August, what their drafts are with a safety factor included and how much cargo each CEMT class can carry.

CEMT class	# of ships	Draft empty + sf (m)	Draft full + sf (m)	Avg capacity (tons)
III	16	1,82	3,02	935
IV	73	1,92	3,32	1505
Va	247	2,12	3,82	2980
Vb	58	2,12	4,32	5500,5
VIa	75	2,32	4,32	5125
VIb	66	2,32	4,32	10250

Table 3: Draft and cargo capacity data of each CEMT class, the # of ships is based on the real-life CEMT data in the last week of August in 2022

Water levels of interest

The water levels of interest for this thesis are the ones that affect the cargo capacity of the CEMT classes. An important remark of defying economic loss during droughts is that economic impact is not present immediately when a ship has 99% efficiency. Extra transportation prices occur roughly below 83% [Contargo, 2017], thus this thesis also uses 83% as a threshold. Therefore the interval of the water levels of interest lies between the water level where the smallest ship can still transport goods and the water level where the biggest ship experiences cargo loss due to lost transport efficiency. This is the CEMT class VI. Using table 3, this water level can be calculated as:

$$h = draft_{empty} + 0,83 * (draft_{full} - draft_{empty}) = 2 + 0,83 * (4 - 2) = 3,98m \tag{2}$$

The lowest draft is from CEMT class III and is equal to 1.82m. Therefore based on table 3 the water level interval was determined to be 1.9m to 3.9m. Within the interval the water level data points have a 0.1m difference, resulting in 21 different water levels.

2.1.4 Risk assessment data (Q3)

The third research question, which is determining the risk of low water periods on inland waterway shipping, does not need new data. The risk is calculated using the probabilities obtained from the low water statistics combined with the economic impact results.

2.1.5 The hydrological year of 2022

Low-flow statistics of 2022

The discharge data that will be looked at from 2022 is from the first of April till the 11th of November. The discharge data after the 11th of November was not requested because, at the time of the request, it was the 11th of November. This is not a problem since the lowest water level was measured in August. The result is the historical daily average discharge data from the first of April till the 11th of November in the year 2022.

Economic impact of 2022

For the economic impact the CEMT data from table 3 will be used. Additionally, historical daily CEMT data will be used. This historical daily CEMT data includes the number of ships of each CEMT class that passed Lobith from the first of April till the 2nd of October 2022. There is no explanation that the data stops on the 2nd of October, this was just the end of the data obtained. This data is more realistic since it takes into account that the number of ships per CEMT class changes based on the water levels of the Rhine. This can be seen nicely in figures 11 and 12. When looking at the dry period in 2022, roughly between July and October, you can clearly see how the number of trips these two classes make past Lobith reacts to a lower water level. The larger ship, the CEMT class VIc, completely stop being used in the dry period. Probably because the extra costs start to out weight the benefit due to the lower transportation efficiency of these large ships. CEMT class Va is used more in the dry period. Possibly is that the smaller ships need to compensate for the lost transportation capacity of the larger ships.

One notable thing about the historical CEMT data is CEMT class VIc. This class is not included in the thesis method, because CEMT class VIc is not sailing in the last week of August (see figure 11). Nonetheless, this class is included when determining the impact based on real-life CEMT data. CEMT class VIc will still be used in the historical data approach, and the thesis will still not use CEMT class VIc due to the absence in the last week of August. This is based on an assumption that due to the lower water level, other CEMT classes take over the load from the absent CEMT class VIc in the last week of August. Therefore the absence of CEMT class VIc in this thesis is not seen as a problem. To get realistic results CEMT class VIc will not be excluded when looking at the historical CEMT data.

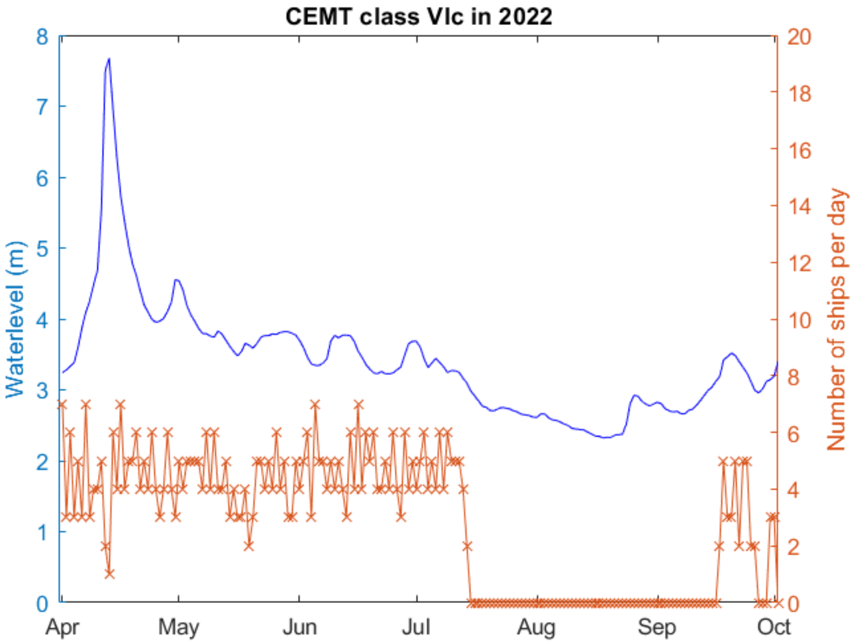


Figure 11: The number of CEMT VIc ships that sailed past Lobith with cargo in 2022

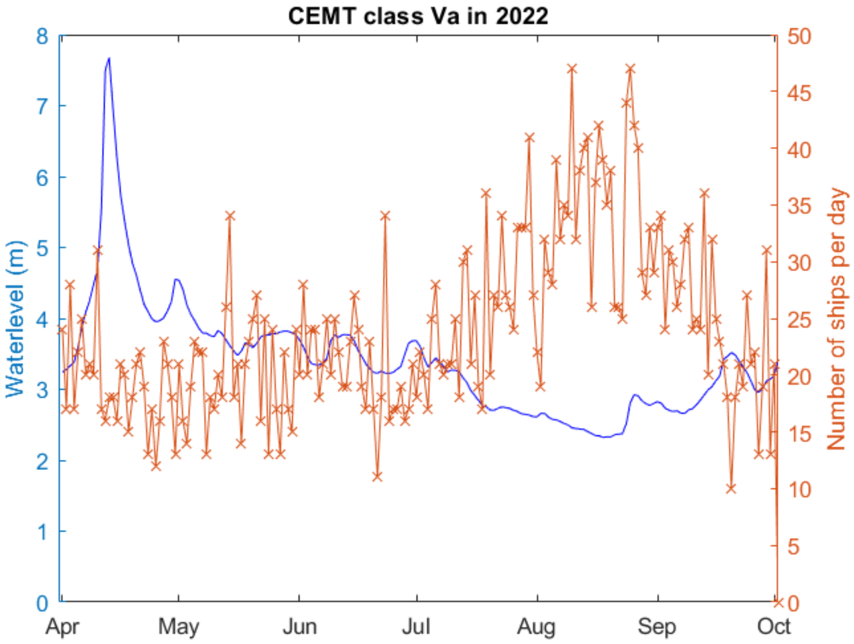


Figure 12: The number of CEMT Va ships that sailed past Lobith with cargo in 2022

2.2 Low-flow statistics (Q1.1)

To determine the risk of low water levels on inland shipping along the Rhine, the LFFC is needed from the Rhine at Lobith. This LFFC will be obtained in this chapter using the Gumbel VIII distribution in reverse. The Gumbel VIII distribution differs from the usual Gumbel VI distribution, which is commonly used when assessing high-flow statistics, by having a fixed lower limit. This fixed lower limit is needed because there shouldn't exist a probability that a certain discharge is lower than 0 m3/s [Shaw, 1994]. The lower limit is also in this case 0 m3/s.

2.2.1 Gumbel VIII distribution

The reverse Gumbel VIII distribution (from now on called VIII distribution) needs to include a fixed lower limit. Therefore the slightly adjusted distribution function can be seen in function 3.

$$P(X) = exp(-((X - \epsilon)/(\theta - \epsilon))^k) \tag{3}$$

Where:

- *P(x) is defined as the probability that the annual minimum of 7 days at Lobith will be lower than X*
- *ϵ is the minimum flow and is equal to zero ($X \geq 0$)*
- *X is the threshold discharge*
- *θ is the characteristic drought*

The variable k is used in this EVIII distribution and is found using the $\bar{Q_m}/s_m$ quotient. k can be found using 1/k, since $\bar{Q_m}/s_m$ is a complex function of 1/k. In Shaw's book, the exact function is not given. However, a table is given where different $\bar{Q_m}/s_m$ quotients and the corresponding 1/k variable values are given. Based on this table a function in excel was found that approximated this table as well as possible, this can be seen in figure 13.

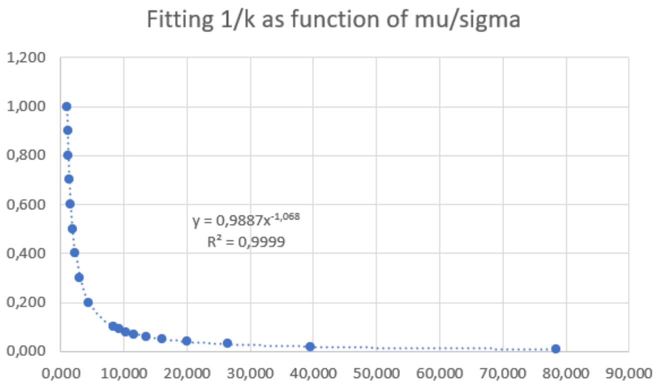


Figure 13: Approximation of the $\bar{Q_m}/s_m$ 1/k function, the data from the table was obtained from [Shaw, 1994]

The function between 1/k and μ/σ can be seen in equation 4.

$$\frac{1}{k} = 0,9899 * (\frac{\mu}{\sigma})^{-0,936} \tag{4}$$

Where:

- *k is the wanted variable for the Gumbel VIII distribution*
- *μ is the mean of the historical low-flow data set*
- *σ is the standard deviation of the historical low-flow data set*

The characteristic drought θ can be calculated, with the sample mean of the low-flow data set and the 1/k value derived from function 4, using function 5.

$$\theta = \frac{\bar{Q_m}}{\Gamma(1 + \frac{1}{k})} \tag{5}$$

Using the obtained θ it is possible to take the logarithm of probability function 3. But before this is done it is first important to note that for the Gumbel VIII function, $(X/\theta)^k$ is made equal to e^y. Such that:

$$P(X) = exp(-e^y) \tag{6}$$

Where:

- *y is called the reduced variate, for a probability range of $0,001 \geq X \geq 0,999$ y is equal to $2 \geq y \geq -7$.*

If you take function 3, assuming that ϵ is equal to zero, and function 6 you get function 7.

$$exp(-e^{y}) = exp(-(\frac{X}{\theta})^{k}) \tag{7}$$

Taking logarithms of this equation gives equation 8.

$$ln(Q) = ln(\theta) + \frac{1}{k}y \tag{8}$$

Function 6 can be rewritten as function 9

$$y = -ln(-ln(P)) \tag{9}$$

Simplifying function 8 and combining it with function 9 gives the final formula to plot the Gumbel VIII distribution.

$$Q(P) = \theta * e^{\frac{1}{k}*y} = \theta * e^{\frac{1}{k}*(-ln(-lnP)))} \tag{10}$$

This formula needs to be written as P(Q), since the discharge will be known and the P needs to be calculated. Rewriting the function gives function 11

$$P(Q) = -e^{-e^{ln(Q/\theta)/\frac{1}{k}}} + 1 \tag{11}$$

2.2.2 Weibull probability fitting

The Gumbel VIII distribution should give a good fit for Weibull and Gringorten probabilities of the data. For this thesis, only the Weibull distribution will be taken into account since the Gumbel VIII distribution gives the best fit to the Weibull probabilities [Shaw, 1994]. The Weibull probabilities of the data set can be calculated using formula 12.

$$P(X) = \frac{r}{N+1} \tag{12}$$

Where:

- *r is the rank of the data point in the set, based on ascending order.*
- *N is the total amount of data points.*

The Weibull probabilities do not have to perfectly fit the Gumbel VIII distribution. They are both calculated differently and are not related to each other. The Gumbel VIII distribution does take the quantitative value of a data point into account, whereas the Weibull distribution only looks at the rank of that data point in the data set. That is the main difference between the two, therefore slight differences are to be expected. Still it would be good for the validity of the Gumbel VIII distribution if the two probabilities gave a good fit to each other.

2.3 Climate change effect (Q1.2)

The effects of the KNMI'14 scenarios on low-flows of the Rhine have been assessed by [Weiland et al., 2014]. An extra scenario called $W_{H,dry}$ was added to better fit other climate model projections (see also figure 7). In this case the CMIP5 climate model from Intergovernmental Panel on Climate Change (IPCC). The implications of climate change on low flows were expressed using the 'long term annual lowest seven-day flow' (NM7Q) and the average number of days per year that the discharge at Lobith would be less than 1000 m3/s ($\#D_{Q<1000}$).
This information is useful for including climate change in this research, especially the NM7Q data. Because the method for the LFFC uses also exactly the 'annual lowest seven-day flow' (NM7Q) as data.
The only difference is that NM7Q is equal to the average discharge of the annual lowest flow week, and for this thesis, the highest discharge of this week is used to act as a threshold. However, the difference within the annual lowest flow week is not significant (e.g. in 2022 $< 3,6\%$). Therefore the assumption is made that the % increase/decrease of NM7Q values compared to the NM7Q reference value obtained from the historic flow data at Lobith, can be applied to the threshold used in this thesis.
The percentage difference between the NM7Q of the reference climate (1992 till 2022) and the NM7Qs of the 2085

		2050					**2085**				
	Reference (1951-2006)	G_L	G_H	W_L	W_H	$W_{H,dry}$	G_L	G_H	W_L	W_H	$W_{H,dry}$
NM7Q (m3/s)	1010	1095	1030	1020	960	825	1085	990	995	915	735
% change	-	8,42%	1,98%	0,99%	-4,95%	-18,32%	7,43%	-1,98%	-1,49%	-9,41%	-27,23%
$\#D_{Q<1000}$	23	14	18	19	23	46	15	22	19	27	61
% change	-	-39,13%	-21,74%	-17,39%	0,00%	100,00%	-34,78%	-4,35%	-17,39%	17,39%	165,22%

Table 4: NM7Q and $\#D_{Q<1000}$ results for each climate scenario in 2050 and 2085 and the % difference with the reference point [Weiland et al., 2014]

Climate scenario	NM7Q (m3/s)	Percentage difference
Current (1992-2022)	1095	0
GL (2085)	1085	-0,87
GH (2085)	990	-9,55
WL (2085)	995	-9,09
WH (2085)	915	-16,40
WH,dry (2085)	735	-32,85

Table 5: Difference between the current climate and future climate change scenarios

climate scenarios can be found in table 5. You can see that the worst climate change scenario has an effect of 32,85% on the NM7Q value of the current climate.

The percentages of table 5 can be used in function 11 by multiplying the Q with 1/(1+%), the % needs to be negative in this case.
To conclude, these are the steps that will be taken to determine the low-flow statistics of the Rhine at Lobith, both for the current climate and the other climate scenarios:

1. Determine water levels of interest. In this case, there are 21, from 1.9m to 3.9m with 0.1m intervals.
2. Add NAP to these water levels
3. Rewrite the water levels as a discharge using the Q-h relationship
4. Take the 21 discharges and use them in function 11. For the climate change scenarios, you include the factor of that scenario on the discharges before using it in function 11
5. The end result is 21 probabilities based on the 21 water levels of interest. Each water level will have a different probability based on the climate scenario used.

2.4 Economic impact (Q2.1)

2.4.1 Defining economic impact during droughts

In the previous chapter, the water level probabilities during low flow periods were obtained. Now it is time to determine the economic impact that occurs during droughts. The economic impact that this thesis will focus on only is the loss of transportation efficiency. During low water levels, ships aren't able to transport at maximum cargo capacity. This leads to more shipping trips with less cargo, increasing the transportation price [Vinke et al., 2022]. Since inland cargo ships can take less load with them, they can ask for more money. Subsequently, they can ask for low water allowances from the government. Therefore during the severe drought of 2018, the revenue of inland shipping in The Netherlands was up 17% compared to 2017. This shows that the inland shipping industry actually makes more money during droughts. The Dutch and German economies suffer from the increased transportation prices. So instead of defying the economic impact as the impact on the inland waterway companies, it is defined as the welfare loss that occurs during droughts due to loss of transportation efficiency and the subsequent increased transportation prices. This economic loss will be determined using the loss of transportation efficiency due to lower water levels. The main framework that this thesis follows for the economic impact can be seen in figure 14.

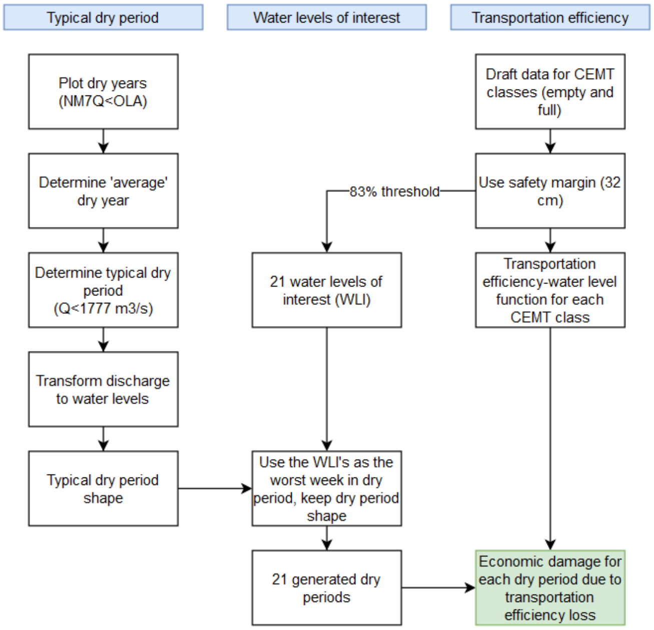


Figure 14: Framework of the economic impact in this thesis

2.4.2 Economic impact of lost cargo efficiency

Using table 3 it is possible to plot the cargo capacity for different water levels per CEMT class. This is done in figure 15.

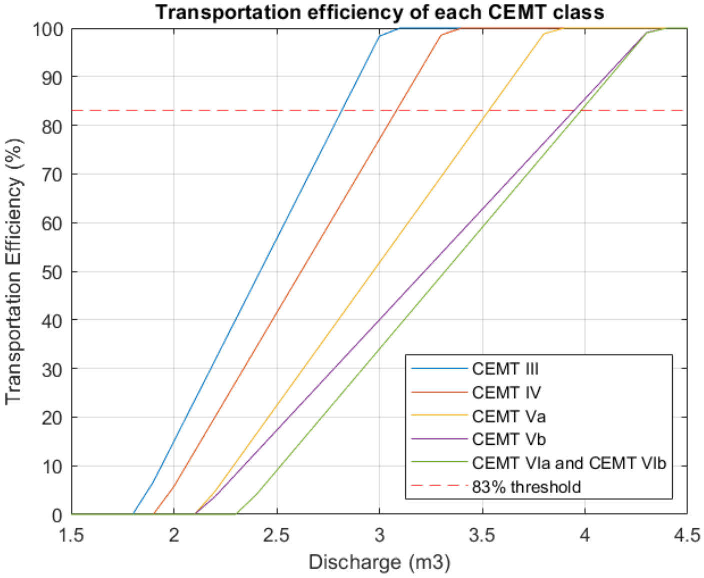


Figure 15: The transportation efficiency of each CEMT class during different water levels

These transportation efficiency functions of each CEMT class will be used together with the maximum capacity of each CEMT class to determine the loss of cargo due to lower water levels than the maximum draft of the ship.

2.4.3 Defining a typical dry period

A LFFC only gives the probability of an annual weekly discharge minimum. Important to realise is that there are more weeks in a dry period than just one. In 2018 the OLA was not reached for 156 days [van Hussen et al., 2018], showing us that dry periods can be months in length.
It is extremely hard to predict how long a dry period is, and how severe each week within this dry period will be. This thesis will assess this problem by using historical discharge data, as described in the data chapter. Only dry years will be used to define a typical dry period since hydrological years exist that have high flow throughout the year. For this thesis a dry year was defined as a year where the NM7Q would be equal to or lower than the OLA (1020 m3/s). So years where at least one consecutive week, the discharge would be below 1020 m3/s. From the 100 years from 1922 to 2021, 36 years were considered a dry year using this criterion. The year 2022 was not included in this part, as it did not complete a full hydrological year. See figure 16 to see all the dry years plotted in one graph. From all these plots the average plot was taken, this can be seen in figure 17.
Very important is to define when a dry period starts. To determine this you have to look back at the CEMT data and look at when the first CEMT class experiences economic loss. This is the 3.98m previously determined for the water levels of interest. The 3,98m translates to 1777 m3/s using the Q-h relationship equation 1. Therefore this 1777 m3/s threshold has been plotted in figure 17. Additionally, the boundaries of the dry period from a typical dry year have been plotted.

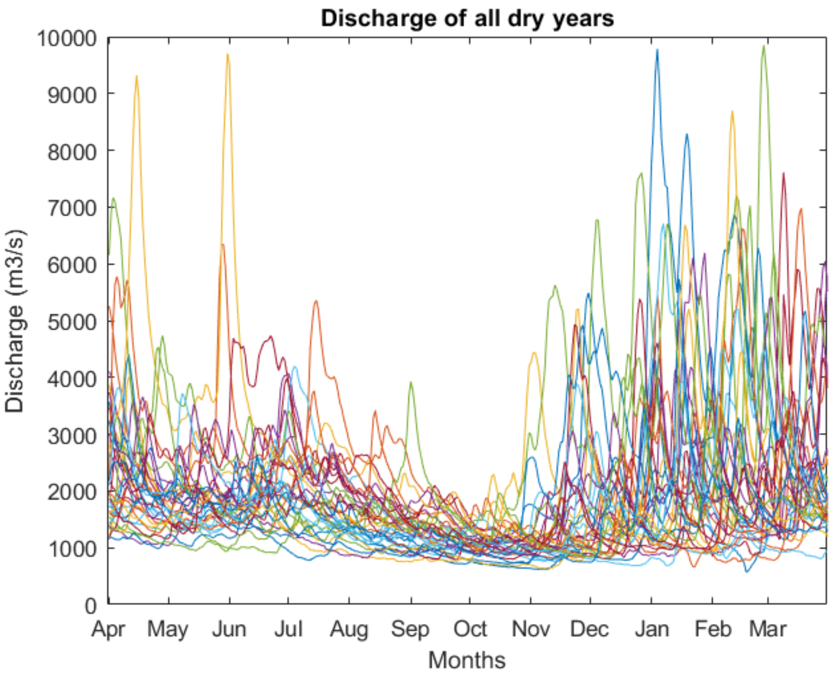


Figure 16: All dry years from 1922 till 2022 visualised

Water levels during dry period
This dry period from figure 17 needs to be translated to a water level before the economic loss calculation method can be continued. This was done by switching the x and y input from figure 5, the h-Q relationship (the inverse of the Q-h relationship) can be seen in function 13.

$$h(Q) = 30^{-12}Q^3 - 10^{-07}Q^2 + 0,002Q + 5,4621 \tag{13}$$

Shape of a typical dry period
The translation of the dry period's discharge values to water levels can be seen in figure 18. Note that both relationship functions' fit is not perfect for low water levels/discharges. This explains why the highest water level in figure 18 is not exactly 3.98 but a bit higher. The difference is really small and therefore negligible. Also, the Rhine's profile is constantly changing so getting the Q-h relationship perfectly fitting is simply impossible, small deviations in the Q-h relationship are to be expected.

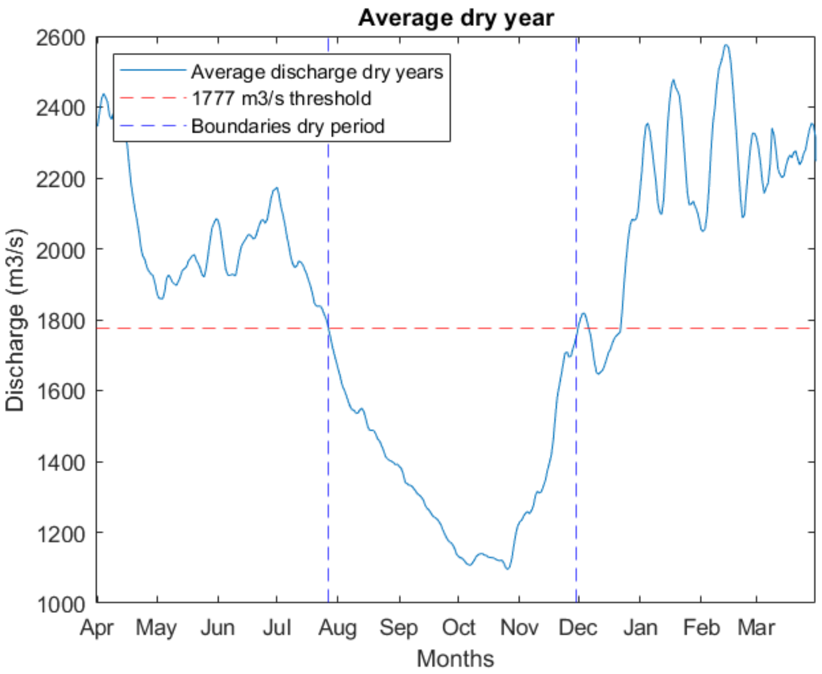


Figure 17: The average of all the dry years from figure 16 to visualise the average dry year. Included are the 1777 m3/s threshold and the boundaries of the dry period.

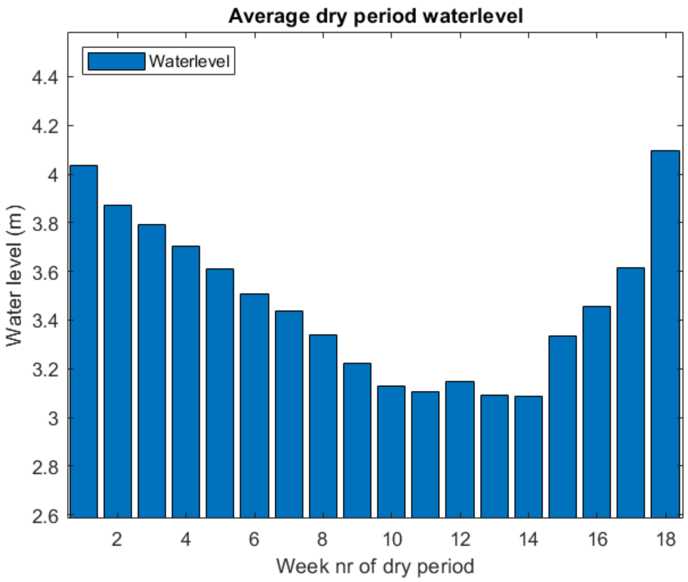


Figure 18: The 'shape' of a typical dry period

Now the shape and the length of a typical dry period are known. The next step is using this dry period and its characteristics and applying this to different conditions. The condition that will change for different levels of severity for dry periods is the lowest week, also known as the NM7Q. Important to note is that the typical dry period consists out of a weekly water level and not daily. This was done because the output of the low-flow statistics is in weeks, therefore to combine both later on for the risk assessment, the dry period must be expressed in weeks.

Combining the typical dry period with the low water statistics

Using the low flow statistics (LFS), probabilities were found for different water levels at Lobith. These water levels are defined as 'annual lowest seven day flow' (NM7Q). For the economic impact assessment, it is important to link the typical dry period with this output from the LFS. It is not representative to directly use the LFS output, since a dry period's duration is often longer than one week. Therefore the typical dry period seen in figure 18 will be applied to the LFS output. To do this some assumptions have to be made. These assumptions can be found below, together with some explanations to make this part more clear.

- The NM7Q value and the probability obtained from the LFS will be seen as the lowest week in the dry period. This is logical since the duration of the NM7Q is a week (remember 'annual lowest seven day flow'). The typical dry period consists out of 18 weeks, the lowest week is week 14. Therefore week 14 will be equal to the NM7Q water level.
- For simplicity reasons the duration of the dry period will always be 18 weeks, equal to the duration of the typical dry period.
- The highest week, week 18, will always be equal to the water level when the first CEMT class experiences economic loss. Therefore week 18 will always have a water level of 3.98 m (see equation 2).

In short, the highest week (week 18) will always be equal to 3.98m. The lowest week (week 14) will always be equal to NM7Q, this water level will change from 1.9m to 3.9m (water levels of interest). The probability of the whole dry period is based on this NM7Q value using the LFS method.

For this economic impact method, several NM7Q water levels will be used since these weeks are assigned to a probability/return period. As input the NM7Q water levels will be equal to the water levels of interest, so 21 water levels will be used from 1.9m to 3.9m. The final output from the dry period generation is 21 dry periods each having a different lowest week (NM7Q) and each having its highest water level week in week 18 (equal to 3.98m). These dry periods are plotted in figure 19. Important to note is that each of the 21 dry periods has a return period equal to the return period of week 14 (the lowest week). This is calculated by using the water height from week 14, transforming this to a discharge and then calculating the probability of this discharge using the Gumbel VIII distribution from the LFS.

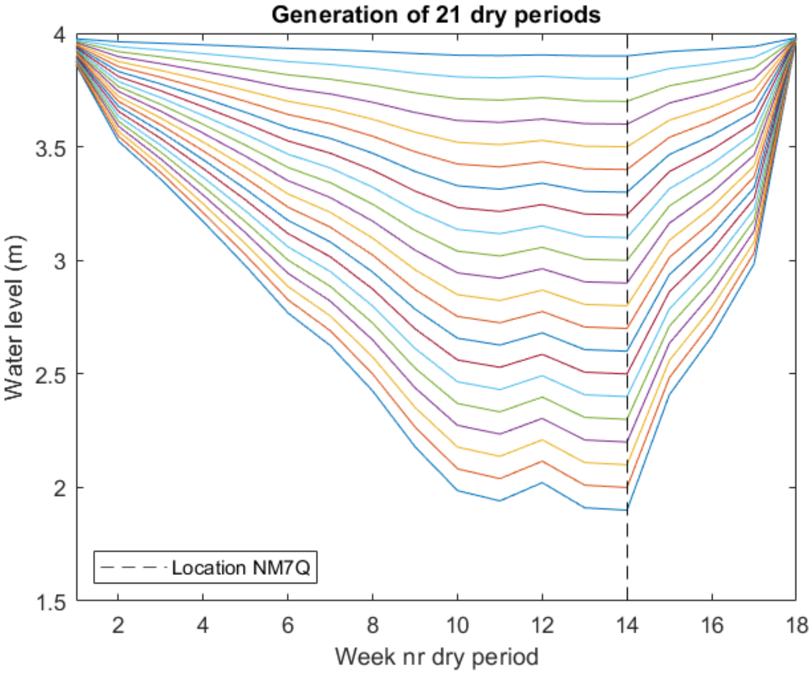


Figure 19: Plots of each dry period used in the economic assessment, all based on the water levels of interest

2.4.4 Damage calculations

Each week in each of the 21 generated dry periods has a different water level. Meaning that each week a CEMT class will have a different transportation efficiency. The economic impact that each CEMT class experiences during a week with a certain water level only occurs when the efficiency of the CEMT class falls below 83%. The economic impact can thus be expressed as lost load due to efficiency loss. At water level h (assuming that this water level causes a transport efficiency lower than 83%) the economic impact for a ship can be calculated using equation 14. The efficiency can be obtained following the method used to obtain figure 15. Lost load and the Load capacity of a ship are all expressed in tons.

$$Lostload(h) = Loadcapacity_{full} * 0,83 - Loadcapacity_{full} * Efficiency(h) \tag{14}$$

So for each week during each generated dry period, the economic impact can now be calculated per ship per CEMT class.

Number of vessels per CEMT class

The dry period consists of 18 weeks, and for each week the economic impact will be calculated assuming that the water level stays the same within the week. To calculate the economic impact during the 18 weeks of the dry period the number of ships per CEMT class per week need to be known. The reference week was decided to be the first week of the dry period, looking at figure 17 you can see it is the last week of August. What is meant with reference week is that the number of vessels of each CEMT class that week would be the same for the other weeks during the dry period. No fluctuation occurs for the number of vessels of each CEMT class during the dry period. The CEMT data was requested from IVS [Rijkswaterstaat, 2023] and can be seen in table 3 on page 11.

2.5 Risk Assessment (Q3)

The method used for the risk assessment is very straightforward. Risk is equal to the probability that something will occur multiplied by the impact when that something will occur. In this case, the probability is obtained from the LFS and the impact is obtained from the Economic Impact method. The only question is how the probability from the LFS will be combined with the economic impact.

As said before, the economic impact will be calculated using a generated dry period. The week with the lowest water level in this dry period is also the lowest week of that whole hydrological year. The probability obtained from the LFS is the probability of a NM7Q or 'annual lowest flow during one week'. Thus the probability of the dry period occurring is equal to the probability of the lowest week in the dry period. This can be calculated using the Gumbell VIII distribution from the LFS.

2.5.1 Example for clarification

To give a better understanding an example will be given for a dry period with a water level of 2.5m in week 14. The lost load will be given per different CEMT class to see if the CEMT classes react differently to the dry period. The results can be seen in figure 20.

This figure shows nicely that when the water level drops the economic impact increases for each CEMT class. Per CEMT class is also nicely shown that the larger vessels, the ones with higher drafts, endure more efficiency loss and therefore have a bigger economic impact. Now for the probability; the NM7Q of this year is equal to 2.5m, and adding the NAP=4.45m to it gives a water level of 6,95m. Using the Q-h relationship from function 1 it gives a discharge of 811 m3/s. The discharge is used as input for the Gumbell VIII distribution to determine the probability/return period. Using function 10 a discharge of 811 m3/s gives a probability of 12,86%.

Thus we have a probability that this drought will occur. 12,86% translates to a return period of roughly 8 years. It is now possible to multiply this probability by all the occurred economic impacts. Again, important to note is that week 14 (the lowest week) gives the probability of the whole dry period. Since the dry period is adjusted according to the lowest week value.

This method of combining the impact with the probability of the water level of week 14 (NM7Q) will be applied for each water level of interest (1.9m to 3.9m).

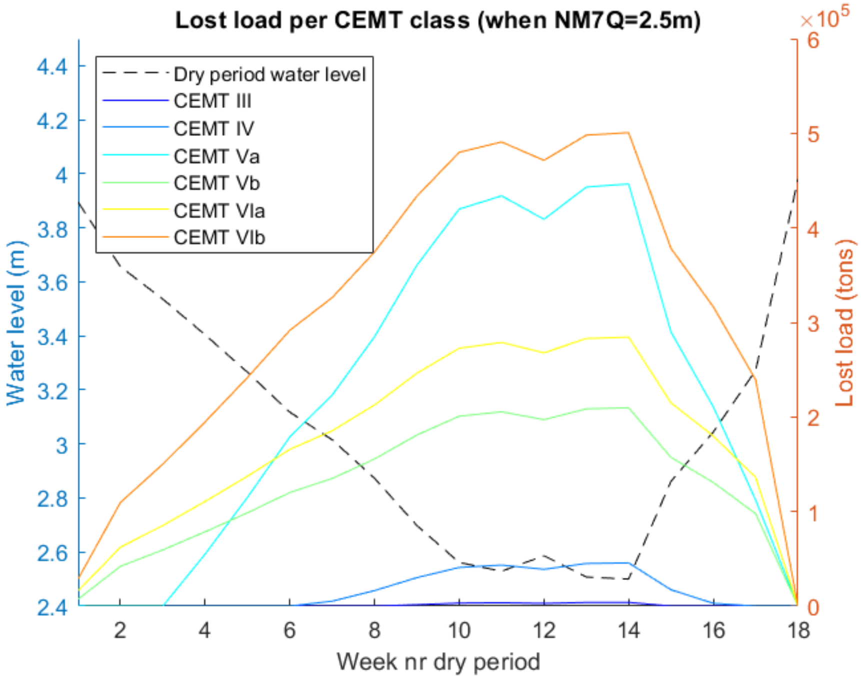


Figure 20: In blue the water level during a dry period with NM7Q=2.5m and in orange the lost load due to efficiency loss for all the CEMT classes at certain water levels

2.5.2 Total risk calculation

At last, the economic impact of each dry period will be plotted against the probability of occurrence. The area underneath the graph is the total risk. The area will be approximated using the rectangular approximation method. This method is visualised in figure 21. Note that this approximation method is only used on the impact-probability graphs in the results chapter, chapter 3, to get the final risk.

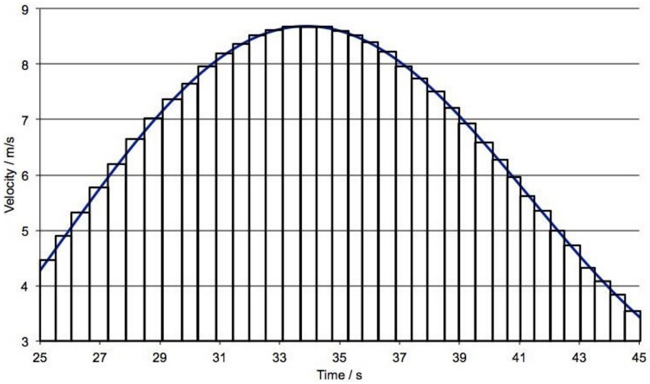


Figure 21: Rectangular approximation method visualised, obtained from [Int, 2023]

2.6 The hydrological year of 2022

2.6.1 Low-flow statistics of 2022

To get the low-flow statistics for 2022, the lowest week of 2022 needs to be known. The lowest week of this hydrological year is from 16 to 22 August when looking at the Waterinfo data. Thus the NM7Q of 2022 is equal to the highest discharge of this week. This NM7Q can then be applied to the low-flow statistics method described earlier.

2.6.2 Economic impact of 2022

Three approaches

In this thesis, the generated dry period has been used together with CEMT data from the last week of August 2022, to determine the economic impact. To check if this is also applicable to the economic impact of 2022, three approaches will be used. The first approach will use the generated dry period of 2022 and the CEMT data used in this thesis (based on the last week of August 2022). The second approach will be using historical discharge data, but still uses the CEMT data based on the last week of August. The third and last approach will use the historical discharge data of 2022 with the historical CEMT data of 2022. Since the daily average water level is known it is possible to see the economic impact each day, based on how many ships sail each day past Lobith. A clear overview of the three approaches can be seen in table 6.

Approach	Water levels used	CEMT data
1	Generated dry period of 2022	From table 3
2	Daily historical data of 2022	From table 3 divided by 7
3	Daily historical data of 2022	Historical daily CEMT data from IVS

Table 6: The three approaches used for the hydrological year 2022

The generated dry period of 2022

The generated dry period is based on the shape that was determined by averaging all the dry years of the past century. The shape found in figure 18 was also applied to the hydrological year of 2022. The lowest discharge is 677 m3/s on the 18th of August. Translated to a water level, using the h-Q relationship, gives a water level of 2,32m. Week 14 of the dry period of 2022 will thus have a water level of 2,32m. The generated dry period of 2022 can be seen in figure 22.

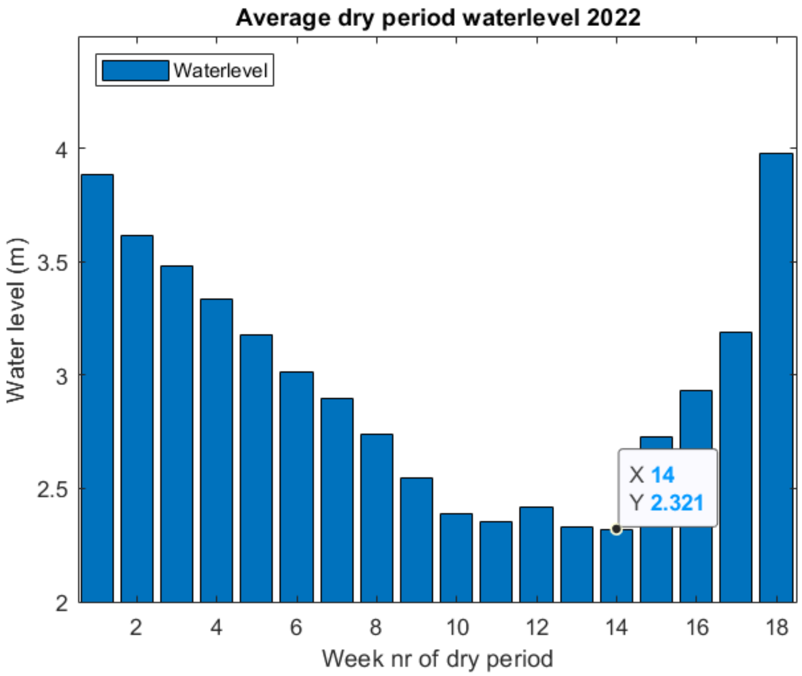


Figure 22: The generated dry period of 2022, with the lowest week being equal to the 677 m3/s

Damage calculations of the three approaches

Each approach uses the same principle that is used in this thesis when it comes to calculating damage. The same Archimedes principle described previously will be used in each approach. In the case of approach 1, the principle will be applied to the generated dry period of 2022. In the case of approaches 2 and 3, the principle is applied to each daily average discharge, that is available, of the hydrological year of 2022 .

3 Results

3.1 Low flow statistics (Q1.1)

The method to determine the low-flow statistics at Lobith was applied to the flow data at Lobith from 1922 till 2022. Additionally, the Weibul probabilities points were calculated to validate the Gumbel VIII distribution. These all can be seen in figure 23. You can see that most Weibul points remain within the 95% interval of the Gumbel VIII distribution. The points outside of the interval can be explained since the Weibul probability is based on the rank of the data in the data set, not the quantitative value.

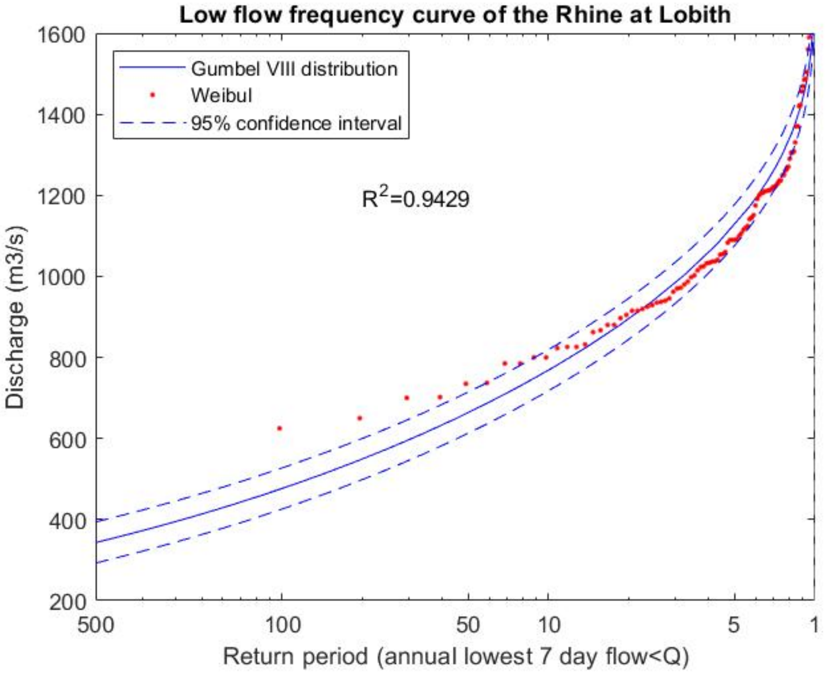


Figure 23: Gumbel VIII distribution of the annual lowest seven-day flow at Lobith from 1922 till 2022

3.1.1 Duration of annual low flow

To see how the distribution reacts to different durations of annual low flows, the Gumbel VIII distribution was also plotted for 1 day, 14 days and 28 days (using only the current climate). The results can be seen in figure 24. You can see that the graph behaves as expected. Longer durations give higher NM7Q's and thus give higher probabilities.

3.1.2 Discharge to water level

Using the Q-h relationship of the Rhine at Lobith, it is possible to translate the discharge to water levels. This enables giving probabilities to the water levels of interest. This was done using the previously determined NAP and the Q-h relationship that is given in function 1. Additionally, the final Gumbel VIII distribution function (function 10) needs to be rewritten as P being a function of Q instead of Q being a function of P. The rewritten function can be seen in function 15.

$$P(Q) = -exp(-exp(ln(10Q/\theta)/\frac{1}{k})) + 1 \tag{15}$$

3.2 Climate change effects (Q1.2)

For the results, the KNMI scenarios of 2085 will be used, since they give a bigger difference than the 2050 scenarios. This will give a better overview of the future low-flow statistics of the Rhine. For each 2085 climate change scenario, the percentage difference was used from table 5 from page 16. The results can be seen in figure 25.

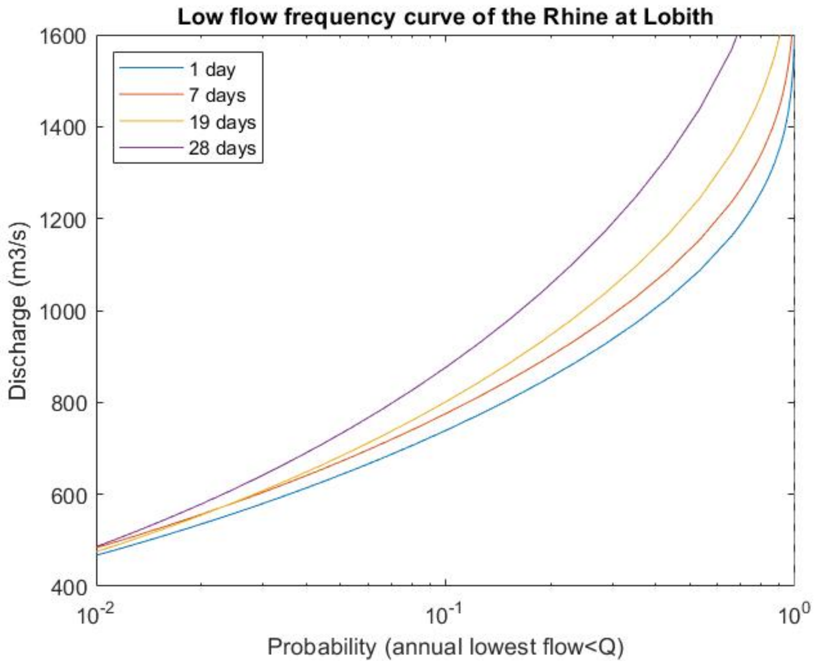


Figure 24: Gumbel VIII distributions of the annual lowest flow of 1 day, 7 days, 14 days and 28 days at Lobith from 1922 till 2022

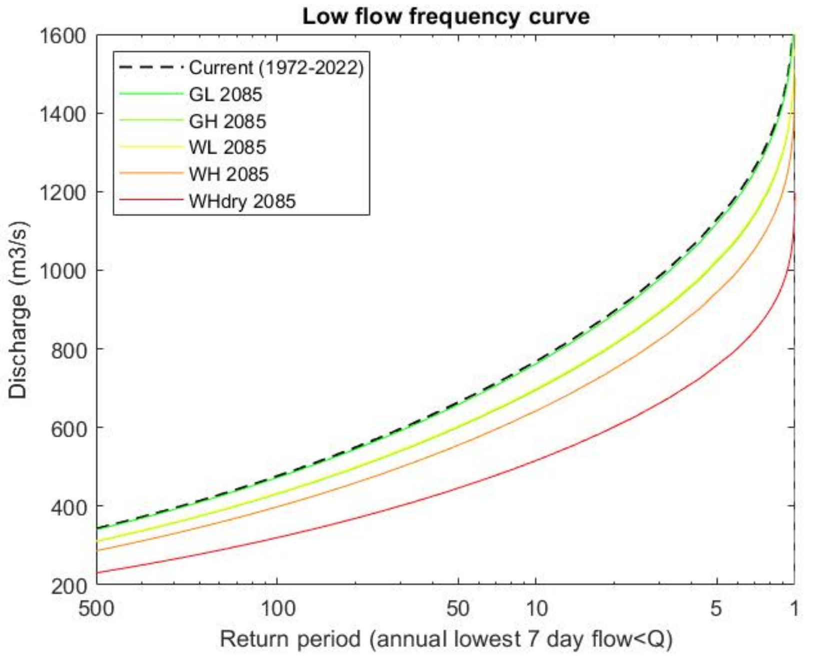


Figure 25: The effect of the KNMI'14 scenarios on the LFFC of the Rhine at Lobith

Additionally, from looking at figure 25, the decision was made that scenarios GL 2085 and GH 2085 will not be used from now on. Since their results are almost identical to the reference scenario and the WL 2085 scenario respectively.

The different climate scenario LFFCs from figure 25 will be used in this thesis to determine the different risk increases due to climate change. For each climate scenario and the current climate, the probabilities of the water levels of interest are calculated, so from 1.9m till 3.9m, using the Q-h relationship. The final LFFC of the current climate and all the climate change scenarios of interest, expressed in water levels, can be seen in figure 26.

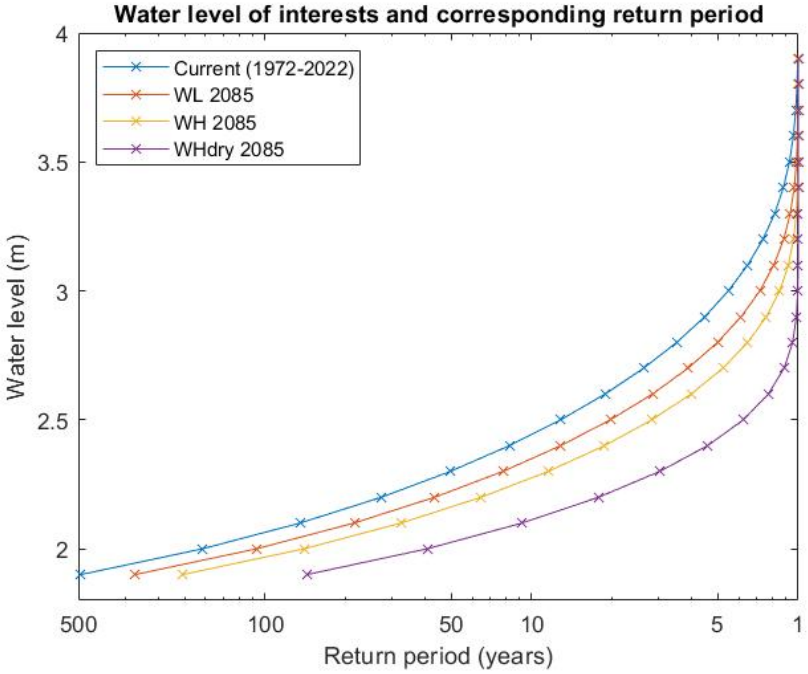


Figure 26: LFFC of each climate scenario on the interval of the water levels of interest

3.3 Economic impact (Q2.1)

Using the dry periods and the economic impact method it is first of all possible to determine the economic impact per CEMT class vessel. This can be seen in figure 27. Notice how the large vessels endure the most lost load. This is due to their deeper draft and their higher load. Important to note is that the x-axis is not the depth at which that economic impact occurs. The x-axis shows the NM7Q value of the generated dry period. If you look at figure 19 on page 20 you can see all the generated dry periods. The x-axis of figure 27 are indicating the severity of the dry period based on the worst week, this is week 14. So the x-axis shows a generated dry period. A lower NM7Q value indicated a more severe dry period, hence the increase in damage.
After this, it is possible to determine the total economic impact by multiplying the economic damage per CEMT type by the number of vessels of that CEMT type. This number can be found in table 2 on page 10. The result is figure 28. If you look at both figure 27 and 28 you can clearly see that the share of CEMT class Va increased a lot in the second figure because there are a lot of ships of that class. You also see the share of CEMT class Vb decreasing, because there are fewer ships of this class. And notably, the CEMT class III ship almost disappears from the figure. There are only 16 CEMT III ships sailing past Lobith each week, and they have the lowest draft, thus this class experiences almost no economic damage in comparison with the larger vessels.

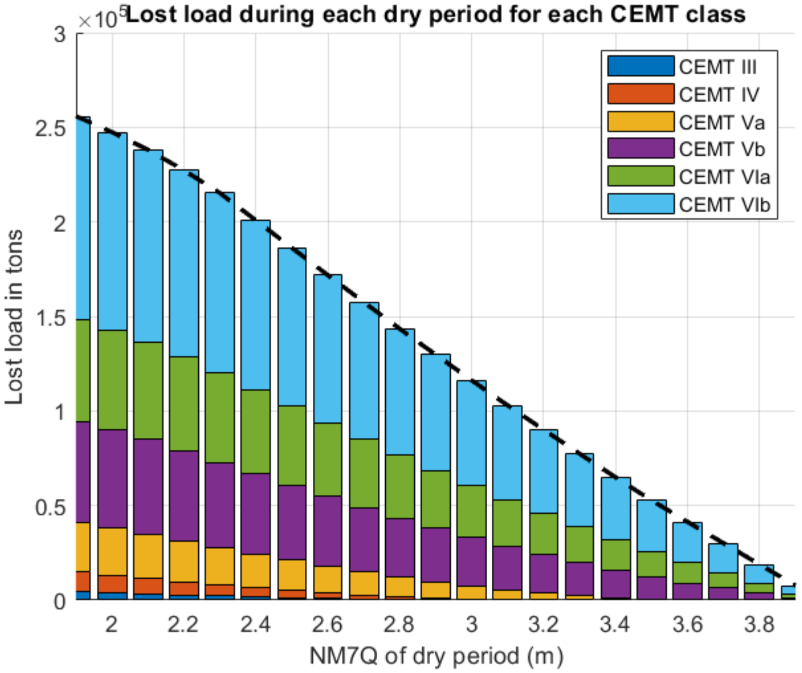


Figure 27: Economic impact of each CEMT class per dry period, where NM7Q is equal to week 14 (see chapter 2.4 for explanation). This economic impact is for **one ship** of each CEMT class type.

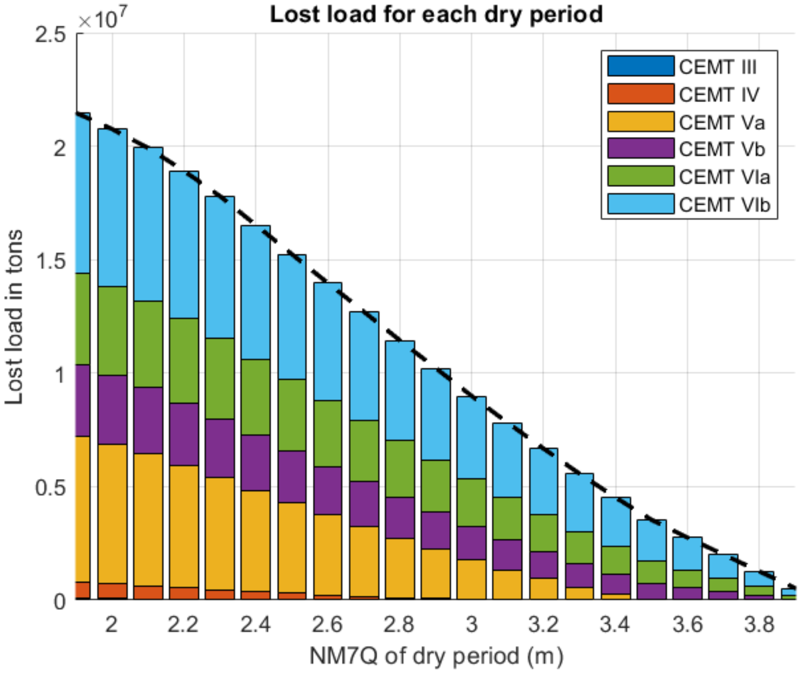


Figure 28: Economic impact of **all** the CEMT ships per dry period, where NM7Q is equal to week 14 (see chapter 2.4 for explanation). The black dotted line is the total economic impact.

3.4 Risk assessment (Q3)

The final step of this thesis is combining the economic impact for each NM7Q water level from figure 28 with the return period/probability found for each climate scenario found in figure 26. Figure 29 shows the combination of the two graphs. This graph shows that the economic impact is the same for each climate change scenario, for this method this is logical since the water levels of interest have always been the same. Climate change has an effect on the probability of water levels, not the severity of water levels in the method of this thesis. You can also clearly see that the climate change scenarios decrease the return period of certain water levels.
The final risk graph can be found in figure 30 where the economic impact is plotted against the probability.
If the final figures are unclear the data is added in table 8. In this table, you can see all the 21 generated dry periods with the corresponding economic impact and return probabilities.
The area under the graph in this plot gives the total risk for each climate change scenario. You can see clearly that the area under each climate change scenario increases when compared to the current climate. This is to be expected since the probability of low water levels is increased due to climate change. The area was approximated using the rectangular approximation method. The results can be seen in table 7. Showing that the risk increases more than the NM7Q from table 5. Take for instance the WHdry 2085 scenario, the NM7Q increase was only 32.85%, but the risk increase is equal to 61.39%.

Scenario	Total risk (tons)	Increase (%)
Current (1972-2022)	$9,80 * 10^6$	-
WL 2085	$1,15 * 10^7$	18,42
WH 2085	$1,29 * 10^7$	31,68
WHdry 2085	$1,58 * 10^7$	61,39

Table 7: Final risk of each climate change scenario and the current climate. Included is the increase of the total risk compared with the current climate.

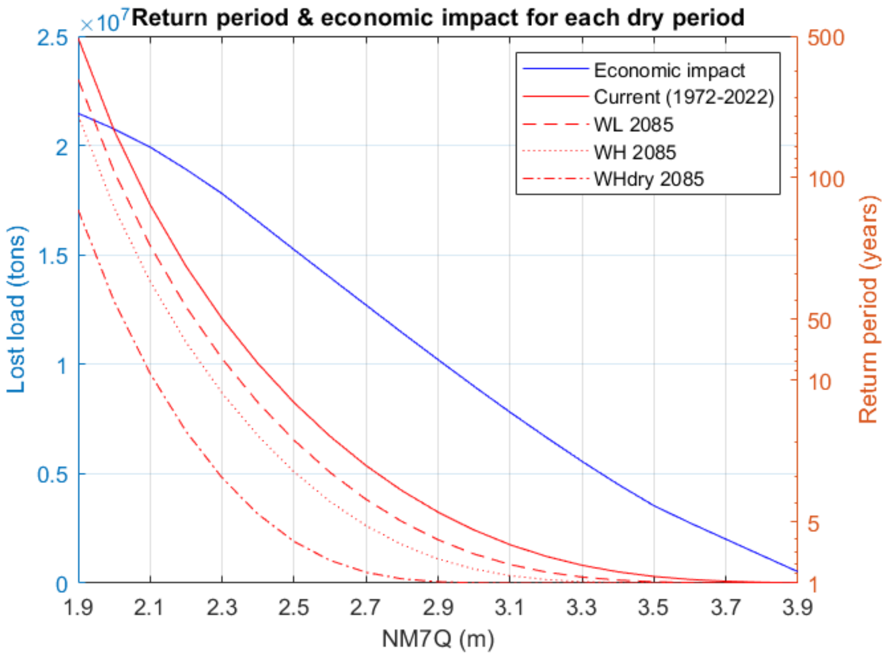


Figure 29: Return period and the economic impact of each dry period, sorted by the NM7Q of each dry period

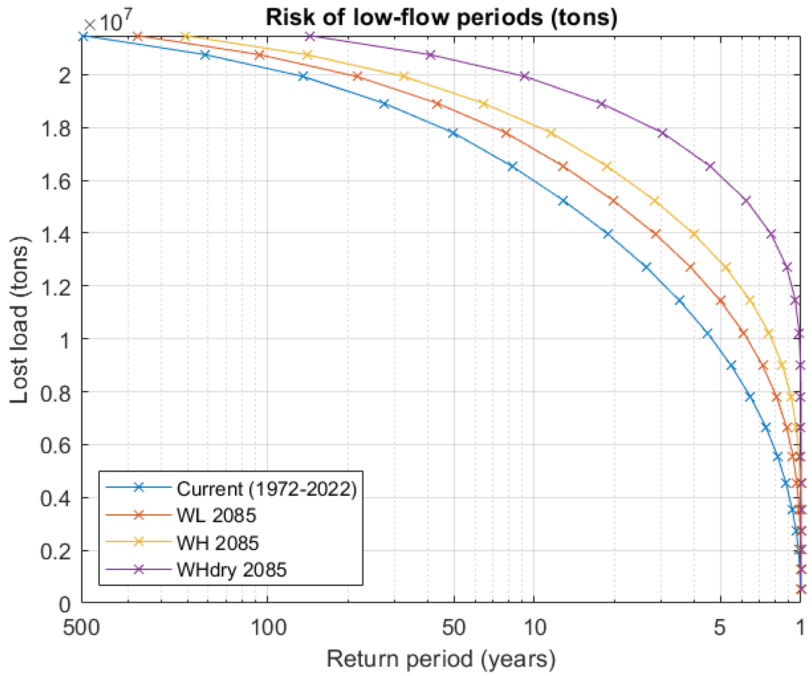


Figure 30: Multiplying the economic impact with the probability of figure 29 gives the total risk of each climate change scenario.

		Return period per climate change scneario (year)			
NM7Q of dry period (m)	Economic impact (tons)	Current (1972-2022)	WL 2085	WH 2085	WHdry 2085
1,9	2,15*10^7	488,8	306,1	202,9	69,5
2,0	2,08*10^7	171,1	107,3	71,2	24,6
2,1	1,99*10^7	73,6	46,2	30,8	10,8
2,2	1,89*10^7	36,5	23,0	15,4	5,6
2,3	1,78*10^7	20,2	12,8	8,7	3,3
2,4	1,65*10^7	12,1	7,8	5,3	2,2
2,5	1,52*10^7	7,8	5,1	3,5	1,6
2,6	1,40*10^7	5,3	3,5	2,5	1,3
2,7	1,27*10^7	3,8	2,6	1,9	1,1
2,8	1,14*10^7	2,9	2,0	1,5	1,0
2,9	1,02*10^7	2,2	1,6	1,3	1,0
3,0	8,99*10^6	1,8	1,4	1,2	1,0
3,1	7,81*10^6	1,5	1,2	1,1	1,0
3,2	6,67*10^6	1,4	1,1	1,0	1,0
3,3	5,56*10^6	1,2	1,1	1,0	1,0
3,4	4,52*10^6	1,1	1,0	1,0	1,0
3,5	3,54*10^6	1,1	1,0	1,0	1,0
3,6	2,75*10^6	1,0	1,0	1,0	1,0
3,7	2,01*10^6	1,0	1,0	1,0	1,0
3,8	1,26*10^6	1,0	1,0	1,0	1,0
3,9	5,21*10^5	1,0	1,0	1,0	1,0

Table 8: Dry periods from figure 19 with the corresponding economic impact and return periods. This table represents the data from figure 29. If you plot the economic impact for each dry period against the return periods of that dry period, you will get figure 30

3.5 The hydrological year of 2022

3.5.1 Low-flow statistics of 2022

The lowest week of this hydrological year was from 16 to 22 August, the highest discharge of that week is equal to 702 m3/s, this threshold will be used to find the return period of 2022. The results of the low-flow statistics of 2022 can be found in table 9. This shows that currently, the year 2022 had a low flow period that is expected every 15 years. In case of the worst future climate scenario, this could increase to a return period between 2 and 3 years.

NM7Q (m3/s)	Current Climate	WL 2085	WH 2085	WHdry 2085
702	15,31	9,77	6,65	2,63

Table 9: Return period in years of the hydrological year 2022

3.5.2 Economic impact of 2022

The economic impact of each approach can be seen in table 10. Included in the table is the percentage difference to see the difference with the method used in this thesis (approach 1 uses this thesis method).

Approach	Economic impact (tons)	Percentage difference
1 (18 week dry period)	$1,75 * 10^7$	-
2 (01-04 till 11-11)	$1,87 * 10^7$	+6,50%
3 (01-04 till 02-10)	$1,42 * 10^7$	-18,99%

Table 10: Results of the different approaches from the hydrological year 2022

The results of approach 3 can be plotted nicely to see the effect of the Archimides principle in action when looking at the daily discharge and CEMT data of the hydrological year 2022. Approach 3, which uses the economic impact of real-life CEMT and discharge data, is visualised in figure 31. Here you can clearly see that in the dry period the economic impact increases due to the loss of transportation efficiency due to low water levels. Logically the amount of transported goods decrease in this dry period. The area of the red line represents the value found in table 10.

When looking at approaches 1 and 2, the difference between the two approaches is in the water levels used, the CEMT assumption was the same. Comparing these two approaches isolates the dry period generation assumption, and compares this assumption with historical discharge data. This is also good to do for the year 2022, since 2022 is a year that was not taken into account when determining the shape of this typical dry period (because the 2022 data was not a complete hydrological year). You can say that the dry period generation gave pretty good results compared to the historical discharge, with only a difference of 6,50%. The dry period assumption can also be plotted against the historical water levels to show the good fit, this can be seen in figure 32.

To see the effect of the CEMT assumption used in this thesis approaches 2 and 3 were compared, comparing these two approaches isolates the CEMT data assumption. In this comparison, approach 2 would only use discharge data till the 2nd of October, to make the two approaches comparable. The result of approach 2 till the 2nd of October is $1,69 * 10^7$ tons of cargo as damage, the difference between this impact and the one of approach 3 (see table 10), is equal to 10,60%. You can see that for the year 2022 the influence of the CEMT data assumption is a bit more (10,60% > 6,60%) than the dry period generation.

The effect of the combination of the two assumptions can be seen if you compare approach 1 with 3. The difference is equal to 18,99%. The difference would be less if more real-life CEMT data was available because, in the month of October, there were also discharges below 1777 m3/s. Resulting in a higher impact than the $1,42 * 10^7$ tons found for approach 3. Nevertheless, the extra impact due to missing data in October is expected to be limited, 19% still indicates that the combination of the generated dry period and using CEMT data from the last week of August gives a good fit. Overall this thesis method seems to be a good application to the hydrological year of 2022. However, again, this does not say a lot since this is only one year.

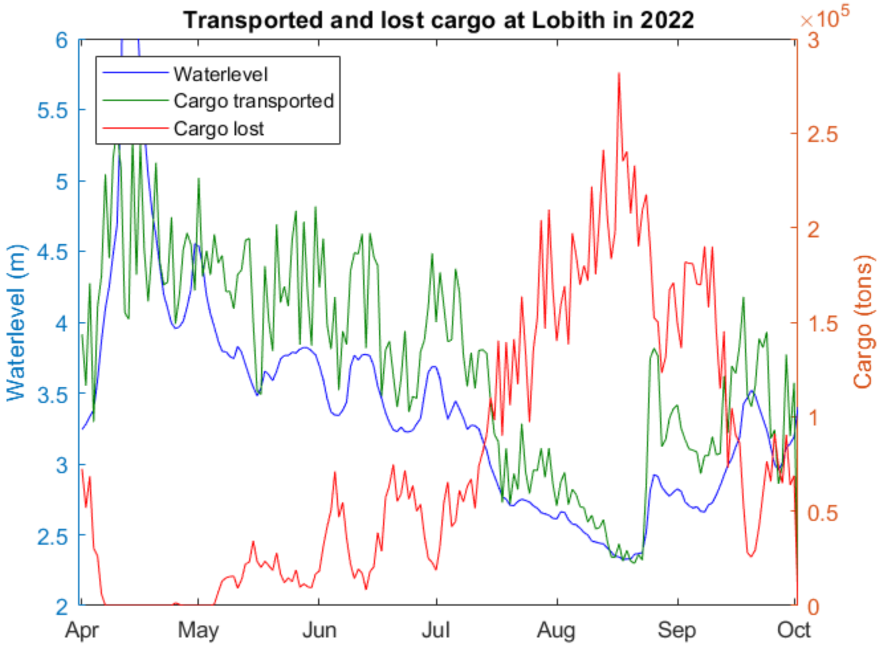


Figure 31: Transported cargo and lost cargo according to the method used in this thesis and IVS data

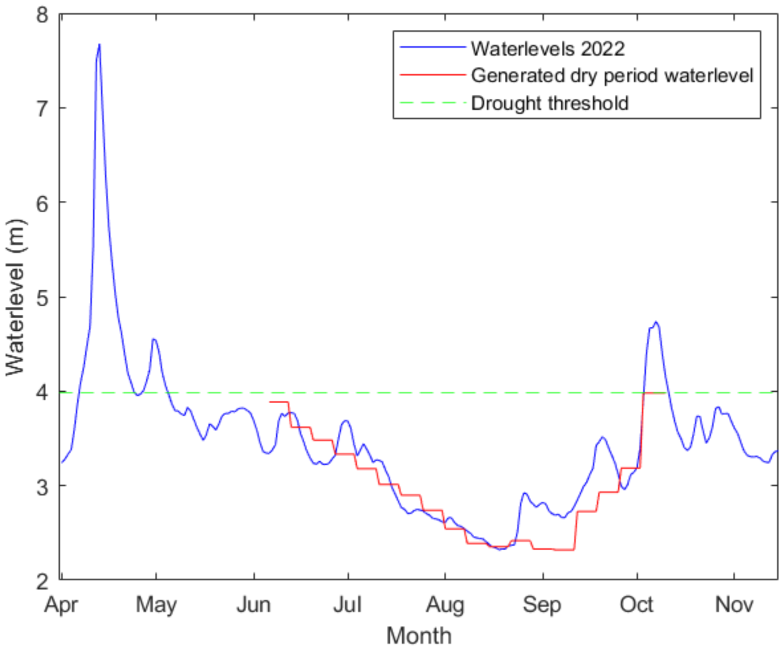


Figure 32: Historical data plotted against the typical dry period based on 2022 data

4 Discussion

So far this thesis has come up with data, methods and results that combined the low-flow statistics of the Rhine with the economic impacts during these low flow periods. The combination of the latter gives the final risk due to loss of transportation efficiency as a result of low flow periods. In this chapter, the limitations, assumptions and strengths of these data, methods and results will be assessed.

4.1 Low-flow statistics (Q1.1)

The data used for determining the low-flow statistics were obtained from Waterinfo.nl [Rijkswaterstaat, 2022]. This data source is deemed trustworthy since it is operated by the government executive institution of the Dutch Ministry of Infrastructure and Water Management. The method used to obtain the low-flow statistics of the Rhine at Lobith was the method found in the Hydrology book by Shaw [Shaw, 1994]. This method is relatively old, dating from the previous century. A more recent and more substantiated method that could be used within the time span of this thesis was not found during the preparation phase of this thesis. The method described by Shaw has some research validating the method. However, these research papers are dating from the 80s. This shows that the LFFC method lacks recent studies backing it up. A more substantiated method by recent studies is advised, a more detailed advise on a different low-flow statistics method can be seen in chapter 5.3.1.

4.2 Climate change effect (Q1.2)

The method used to include climate change in the low-flow statistics was based on the research results found in a KNMI climate scenario assessment done by Deltares [Weiland et al., 2014]. In the end, it is only the difference between the NM7Q values of each climate change scenario found in table 5 expressed in percentages that are used to assess the effect of climate change in the future on low-flow statistics. Climate change is a much more complex process than simply changing one value in one function.

However, this simple multiplication can be used because the output of the LFFC is expressed the same as the NM7Q obtained from the KNMI climate change scenarios assessment, namely 'annual weekly lowest flow'. The problem with this is that this method, to include climate change in the low-flow statistics, is only useful when expressing the output of the low-flow statistics in a week.

On the bright side, when [te Linde et al., 2010] researched the effect of the KNMI '06 climate change scenarios on the low-flow statistics of the Rhine, he also found that in case of the worse climate change scenario, it would decrease the Rhine's discharge by 33.3%. This is close to the results found in table 5.

4.3 Economic impact (Q2.1)

4.3.1 Lobith as the bottleneck

For simplicity reasons Lobith was chosen as the place where the discharge data was obtained and where the Q-h relationship was applied to. In reality, there are other more significant bottlenecks along the Rotterdam-Duisburg Rhine trajectory that would dictate the transportation price.

4.3.2 CEMT classes

The CEMT data that is used in the economic impact is primarily obtained from the CEMT class guidelines. This information is reliable since it is registered by, again, Rijskwaterstaat. This section of the thesis uses a lot of assumptions. The most significant assumptions will be assessed.

Number of ships per CEMT class used

The composition of CEMT classes was determined on the real-life data of the last week of August 2022. Since the dry period starts around this time. In reality, the composition of the amount of CEMT class vessels would change depending on how low the water level is. In the worst week, week 14, more CEMT III trips are expected since this CEMT class has the lowest draft and therefore less economic impact. In the highest week, week 18, more CEMT VI trips are expected to sail since they can carry the most cargo. This conclusion is substantiated by figure 33. In this figure, it is clearly shown that the number of trips per CEMT class changes during dry periods. This figure was obtained from research done by a PhD candidate of TU Delft. By ignoring the fluctuation of CEMT types depending on the water level, this thesis method probably overestimates the economic impact during dry periods.

This assumption has probably the biggest impact on the final result. If you look at figure 33 you see that during the low-flow period of 2018 CEMT class VI ships stopped completely transporting goods. Looking at the results of the economic impact of this thesis in figure 28, this would mean that the light blue bar of CEMT VI would not be there, since no CEMT VI ships would be transporting goods. And probably the bar of the other vessel types would be higher because they would increase their amount of trips to compensate for the lack of CEMT VI ships.

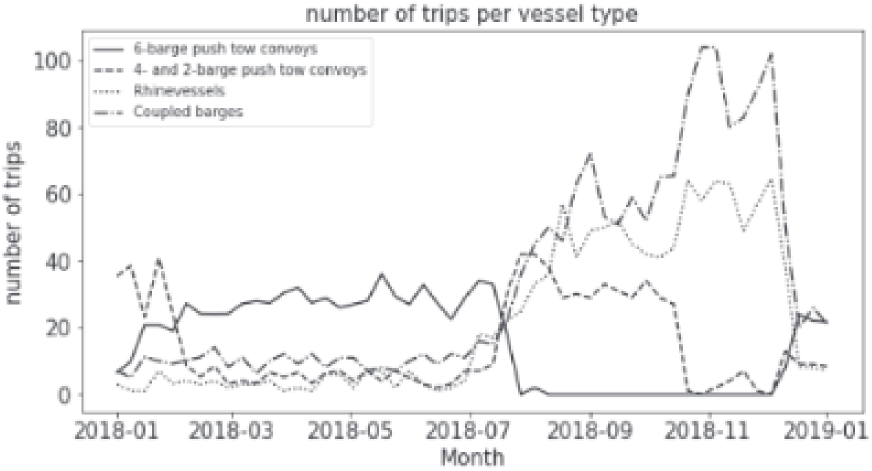


Figure 33: Number of trips for four different vessel types during the dry period in 2018 along the Rhine at Lobith, obtained from [Vinke et al., 2022]. Note that during the dry period, the large vessels stop making trips and the smaller vessels increase their number of trips to compensate.

Lower transportation efficiency-threshold
At some point ships won't sail because their transportation efficiency is so low it is not profitable anymore. If you look at the IVS data you can see that the VIc vessels stop transporting when the transportation efficiency is around 20%, see figure 11. For further research, it is good to check the economic impact assumptions against real-life data. Maybe it is possible to give each CEMT class a probability function for the capacity to model it even more accurately.

Sailing direction of the ships
The Rhine flows from Germany to the Netherlands. Vessels sailing from the Netherlands to Germany experience more resistance, take longer to make the trip and therefore have a higher transportation cost. So a dry period would result in more economic damage if, during this dry period, more ships transport upstream. Taking this into account would not alter the results that much probably but it is good to consider this.

Exclusion of delay damage
Other minor assumptions are that queues at sluices and queues at other bottlenecks are not taken into account in this thesis. This would also cause some additional damage since that besides transporting less goods, ships also take longer to reach their destination during low-flow periods.

4.3.3 Generating dry periods

One of the biggest assumptions this thesis makes is the generation of a dry period. The assumptions that a dry period is always 18 weeks long, that the worst week is always week 14 and that the highest water level week, week 18, is always equal to 3.98m are all assumptions that were made to make the risk assessment possible. Historical data is used to determine this typical dry period, but in reality, each dry period various greatly is duration and severity.

The method becomes weird when the worst week (week 14) has almost the same height as week 18. This can be seen when looking at the least severe generated dry period in figure 19 on page 20. This assumption causes an almost constant water level of 4m. This is of course unrealistic since water levels of the Rhine are not constant over a period of 18 weeks.

4.3.4 The economy behind transportation

This thesis uses a very simple principle to determine the economic impact during low water levels. In reality the economy of the Rhine is a much, much more complex concept. The economic impact should be about increasing prices, because less cargo is being transported during droughts. An economy model based on the supply-demand principles is advised. This model will include much more factors to determine the economic impact.

4.4 The hydrological year of 2022

CEMT Data

As previously mentioned, in the historical CEMT data an extra class is taken into account. The CEMT class VIc is not included in this thesis method because it is absent in the last week of August in 2022. If the VIc is excluded from the historical CEMT data impact analysis the impact of approach 3 decreases from $1,42*10^7$ tons to $1,28*10^7$ tons. Increasing the difference to 24% between approaches 2 and 3. The increased difference shows that when including CEMT class VIc the results lie closer to each other. Therefore it is justifiable to include CEMT VIc in the historical data of 2022. Additionally, only the last week of August is used in this thesis and in the comparison against real-life CEMT data of 2022. For further research, it is advised to see if using other weeks in the dry period as the reference week for CEMT data would give a more realistic approach. This should then also be checked against more years than only 2022.

Dry period generation based on 2022 NM7Q

The generated dry period of 2022 is plotted against historical water levels in figure 22. You can also see why approach 2 gave a higher economic impact than approach 1. You see that the generated dry period of 2022 is actually too short, there are other weeks outside the generated dry period that lie under the 3.98 threshold. At last, the last 4 weeks of the generated dry period overestimated the drought. But overall the generated dry period does a good job of representing the economic damage of 2022.

Limited data set of IVS and Waterinfo.nl

The daily CEMT class data of 2022 was only obtained till the 2nd of October. The result is that there are 44 days less included in approach 3 than in approach 2. Approach 2 also has a limited data set only till the 11th of November. It is unknown if this would be a large issue since the discharge data of November past the 11th are unknown. However, the discharge of the 11th of November of 2022 is equal to 1254 m3/s (which is below the threshold of 1777 m3/s). This shows that there would probably still be an economic impact for the rest of November. The discharge data from the 2nd of October till the 11th of November is known, and this data shows that in the case of approach 3, there are 44 days missing which have a discharge below 1777 m3/s. The result is less impact when approach 3 was used. The effect of the missing data on approach 3 is unknown, but expected is that the historical discharge data after the 11th of November would further increase the economic impact of approaches 2 and 3.

Applicability of the results

An important note is that the results of 2022 can not be used to verify this thesis method against historical data. Only using one year is simply not enough. It is good to see that this thesis method is applicable for data from 2022, but this does not say that it will be for all the other years. Since 2022 had a very dry period it could be that the method is only applicable to years that experience significant dry periods. Other, less dry, years should be checked to see if the result is similar to the comparison with the year 2022. For further research, it is highly advised to check the method against more hydrological years. This way a properly substantiated verification of the method can be done.

4.5 Monetary damage of a dry period

The term 'lost tonnage' is a bit difficult to comprehend. Ideally, the economic impact is expressed in euros. This way everyone can easily understand the impact and risk of low water levels. To give a realistic price tag to a dry period is really hard to pull off. This requires a complicated economic model. More simple models could be used, as was done in the paper of [Jonkeren et al., 2007], still this thesis did not have the time to make such a model. Using shortcuts it is still possible to give a price tag to low water levels and inland shipping. this sub-chapter in the discussion will briefly assess a method that is able to give a monetary value to the economic impact of dry periods on inland shipping. This method is shortly assessed in the discussion since it lacks the substantiation of the other economic impact method. This sub-chapter could be seen as an additional exploratory chapter that stands apart from the rest of the thesis.

This method is not recommended to do for a real economic impact since it is based on only one source and a lot of extrapolation. At last, an extensive discussion, such as the other method got, is missing for this method. This decision was made because the focus of this thesis is the other method and not the one that will be described here below.

4.5.1 Contargo low water surcharge

The method uses the only source found about increased transportation fees due to low water levels. Namely, the source found on the Contargo site [Contargo, 2017]. This site gives "Low water surcharge" (LWS) for three different bottlenecks along the Rhine in Germany. LWS is an additional cost that is made to compensate for the disproportionate costs during low flow periods. The bottleneck that is best for this thesis is the bottleneck at Emmerich. Emmerich is a German village on the border with The Netherlands and is close to Lobith. Subsequently, it is the only bottleneck that is before Duisburg.

The first problem is that the water level at Emmerich is expressed in the Emmerich Gauge. To solve this problem, both the 2022 water levels used in this thesis were compared with the 2022 water levels found on the Contargo website. Only the water levels of interest were considered (1.9m-3.9m), see figure 34. The LWS was only given for 4 points. Lower than 70, 60, 50 and 40 cm (Emmerich gauge) gave a LWS of 40, 50, 60 and €80 respectively per 40 feet container. At lower than 30 cm (Emmerich gauge) shipping companies do not have to obligation anymore to transport anything at all. However, because this thesis uses a lot of water levels below that point, the assumption was made that the water level-LWS function would continue to the water level of 1.9m.
Using the relationship found in figure 34, the LWS points could be translated to water levels values at Lobith, this can be found in figure 35.

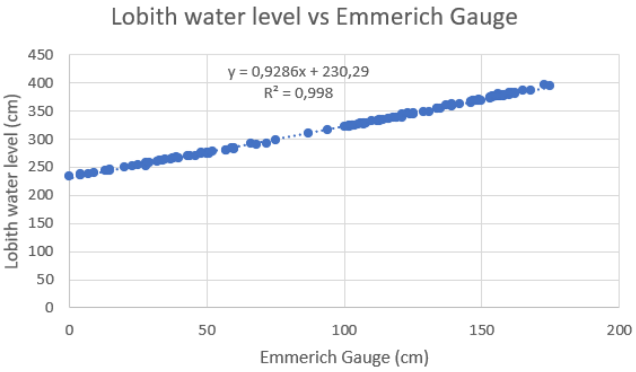


Figure 34: Relationship between water levels used in this thesis and the Emmerich Gauge water levels

The LWS is expressed as increased cost per 40' container. For this thesis, everything is expressed in tons. The maximum weight of a 40' container is 29 tons [Con, 2023]. It is now possible to express the LWS based on tons and based on Lobith water levels using both figures and the weight of a 40' container.
An important assumption was made to tackle the biggest flaw of this method. The biggest flaw of this method is that ships that can't sail anymore, due to their draft+safety factor being larger than the current water level,

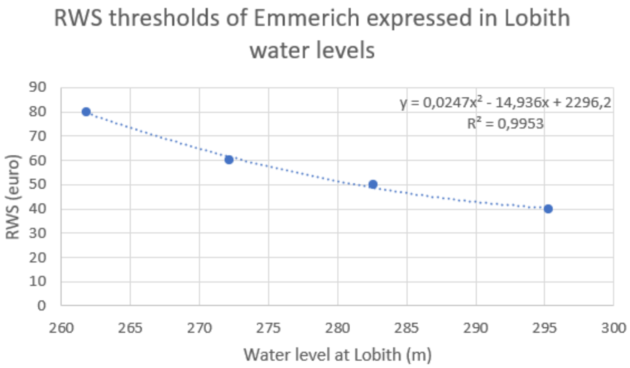


Figure 35: LWS points expressed in water level of Lobith, included is the waterlevel-LWS relationship at Lobith

will not transport anything and therefore they do not experience *any* LWS. To still have ships that don't sail experience economic loss, the assumption was made that each week a ship did not sail it would experience 10% of its maximum load * the LWS. This way ships that didn't sail for a week still experienced some economic damage.

4.5.2 Results

The LWS method to determine the economic impact can be seen in figure 36. This is expressed in monetary value and can thus be more easily interpreted.

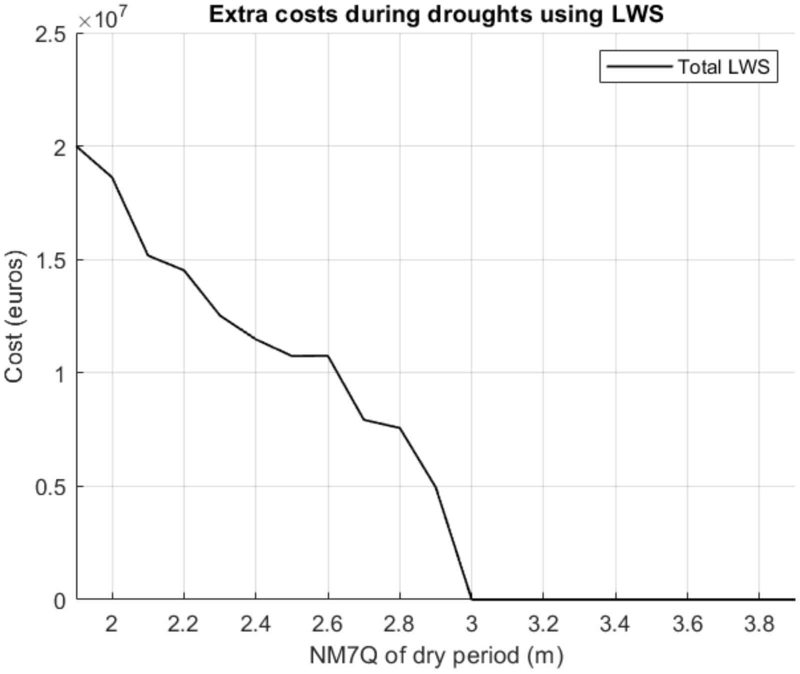


Figure 36: Economic impact expressed in monetary value due to the LWS.

4.5.3 Risk

This economic impact can also be used to find a final risk. This can be seen in table 11 and figure 37. You can clearly see when comparing the tables that the monetary impact method is much more sensitive to climate change than the lost tonnage impact. This can also clearly be seen in the difference between the two final risk figures. The reason that the climate change factors have less impact on the lost tonnage method is that when you look at figure 30, you can clearly see that with a low return period, there is already an impact. Whereas with figure 37 it has a more linear approach. This has to do with that the monetary impact only starts at 2.9m water level at Lobith. All the dry periods with a NM7Q higher than 2.9m have no impact. Thus the dry periods with low return period do not cause a monetary impact.

Scenario	Total risk (€)	Increase (%)
Current (1972-2022)	$0,45 * 10^7$	-
WL 2085	$0,62 * 10^7$	37,78
WH 2085	$0,79 * 10^7$	75,56
WHdry 2085	$1,14 * 10^7$	153,33

Table 11: Final risk of each climate change scenario and the current climate

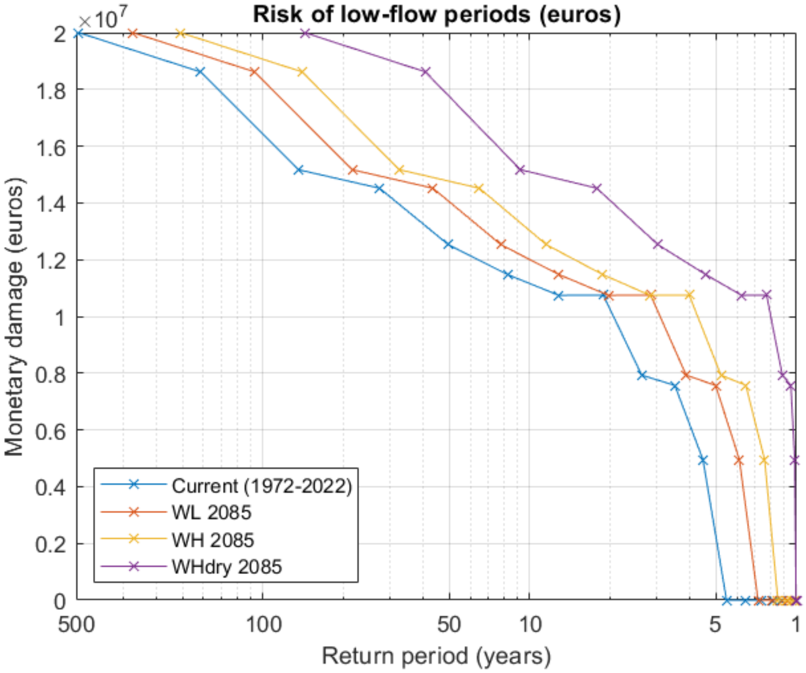


Figure 37: Total risk of each climate change scenario due to LWS, expressed in euros

4.5.4 Discussion

There are a lot of shortcomings when using this method. When you look at figure 36 you can see already some of them. After 2.9m NM7Q there is no more economic damage because the LWS is first introduced at 2,92m (in Lobith water level), so any water level 2.92m does not suffer extra costs. It could be that until that point the extra costs are accepted and no LWS is asked, but the sudden jump when reaching 2.9m seems weird.

Additionally, you see some weird points in the graph. Take for instance NM7Q 2.5m and 2.6m, there are almost equal. The economic impact of 2.6m is even lower than 2.5m. This is because at this point the increase in the LWS is in proportion to the decrease is efficiency. The price increases, the amount of transported cargo decreases, and the result is the almost exact same economic impact.

At last, this method does not take into account the extra costs when a ship doesn't sail. LWS is only charged on transported goods, not on goods that can't be moved. The cost of delay is excluded and if you think about it, it should be included. Possibly that causes much more economic impact also since the results from table 11 seem way too low. If the risk of the worst climate change on inland shipping would be only 11 million euros, it would not be of any concern in the upcoming years. 10 million per year is nothing compared to the over 2 billion euros of revenue that inland shipping yields in the Netherlands [CBS, 2018]. 10 million is only 0,5% of 2 billion, and that is when looking at the worst climate change. If you look at the difference between now and the worst climate change, the difference is even smaller; only 7 million euros. This method indicates that in 50 years climate change would only increase the risk of climate change on inland shipping by 7 million. This indicates that this method is probably underestimating the risk of inland shipping by a lot.

This is probably due to the disregard for the 'lost load', a small assumption was added to try to simulate extra cost for not transported cargo, but this seems to have too less of an impact. Where the method of this thesis looks at the lost tonnage, this method only looks at extra costs on the cargo that can be transported. Recommended is to combine the extra costs of the 'lost cargo' and the 'transported cargo'. This method of this thesis indicates how much load is lost due to lower water levels, but did not find a suitable price tag for this lost load. The monetary method shows the extra costs for the cargo that is still transported. In the end, if the price tag for lost load could be found, a combination of the two is advised.

5 Conclusion and recommendations

5.1 Conclusion

This thesis is about linking low-flow statistics with the economic impact during dry periods, the result is a risk assessment of low flows. The research objective of this thesis is as follows:

"To assess the economic impact during low-flow periods on the Rhine and see if climate change will have an effect on these low-flows"

The research objective was reached using several research questions.
The first research question was about low-flow statistics and the effect of climate change on the low-flow statistics of the Rhine. The current low flow statistics of the river Rhine can be seen in figure 23 on page 24. In this figure, you see the return period that the discharge of the Rhine is under that discharge for a week.

The results of the effect of climate change on the low flow statistics of the Rhine can be seen in figure 26 on page 26. In this figure, you can see clearly that lower water levels are expected to occur more often due to climate change. It is still the question of which climate scenario will be the reality in 50 years, only time can tell. However, looking at figure 25 on page 25 you can see that only the 'mildest' climate change scenario GL2085 will not have a visible effect on the low-flow statistics of the Rhine. All the other climate change scenarios will increase the probability of low flows.

The second research question was about the economic impact of these low flows. The economic impact during each generated dry period can be seen in figure 28 on page 27. The economic impact is expressed in lost cargo tonnage due to transportation efficiency loss.

You can clearly see that more severe dry periods cause more economic impact, especially for the larger ships. The ship type that experiences the most damage, when looking at one ship, during a drought can be seen in figure 27. This is CEMT class VIb since this ship is the largest. When looking at all the ships, the economic impact distribution can be seen in figure 28. Here you can see that CEMT class VIb still experiences the most economic damage. Class Va is close behind, because Va is the most common ship that sails by Lobith.

The final research questions combine the results of the first two. The final risk can be found in figure 30 and table 7 on page 28. Here you can clearly see that the risk of dry periods is increasing on the Rhine due to climate change. Where the current risk is $9,79 * 10^6$ tons, it could increase by up to 60% to $1,58 * 10^6$ tons in the case of the worst climate change scenario.

5.2 Recommendation based on thesis findings

The findings of this thesis give an interesting insight into the risk of dry periods of the Rhine. First of all, it is clear that climate change in most of the scenarios made by the KNMI will have a negative influence on the low-flow statistics of the Rhine. The expected is that dry periods will occur more frequently, increasing the risk of dry periods on inland shipping.

Employing smaller ships on the Rhine

Recommended is to keep smaller ships available to use when the water levels of the Rhine drop. This can be seen nicely in figure 27 on page 27, where the economic impact per is plotted per dry period for one ship. You can see here clearly that smaller ships experience much lower cargo loss. Take for instance as an example the dry period of NM7Q=2.5m. In the current climate, the return period of this dry period is just below 8 years, but this could increase in the future to 1,6 years (see table 8 on page 29). When looking at figure 15 on page 17 you can clearly see that CEMT class III keeps a transportation efficiency of over 55%. Meanwhile, CEMT class Va (the most used on the Rhine) barely has an efficiency of over 20% and the largest vessels, CEMT class VIb and VIc, only have an efficiency of 10%. The larger vessels also have more capacity, resulting in much higher 'lost tonnage' for these vessels at this dry period (again see figure 27).

If you take into account that in 50 years, in the case of the WHdry scenario, you could see this dry period every 1,6 years. The need for smaller vessels is of utmost importance for the future of inland shipping on the Rhine. Taking into account the past droughts of 2022 and 2018, where at one point the drought was so bad that many ships couldn't sail at all [Rijkswaterstaat, 2022]. The urgency and essence of employing more smaller ships on the Rhine is growing.

The final recommendation is to make a cost-benefit analysis, to see what the optimal fleet ratio is for all the CEMT classes. Determining if it is worth it to switch to a smaller ship-oriented fleet during low flow periods.

Temporary airbags for ships to increase buoyancy

The bottlenecks dictate the transportation efficiency of the whole trajectory during droughts. It could be worth temporarily increasing the buoyancy of large ships using airbags at these bottlenecks. This way the transportation efficiency is increased along the whole trajectory. The recommendation is to look if this is worth the effort and cost. This is more of an experimental idea, but it could give a solution to passing the bottlenecks with more cargo.

5.2.1 Final recommendation based on thesis findings

In the end, it is a difficult choice to make, employ large vessels that are more beneficial during normal water levels or smaller vessels in case of low water levels. This thesis showed that larger is not always better, especially when looking at future climate change scenarios. Make sure to take climate change into account since climate change will play a large role in future low-flow statistics and therefore will have a large influence on the economic impact of dry periods. The risk increase due to climate change is in the worst case equal to 61%. Over a period of 50 years this is equal to less than 1% per year. This not extremely much. Showing that there is still time available to adapt. The final recommendation is to not underestimate future low-flow periods of the Rhine and the impact it has on inland shipping. Be mindful of the growing risk of low-flow periods on inland shipping.

5.3 Recommendation for the client

This thesis has tried to link low-flow statistics with an economic impact assessment. As mentioned above, to ensure that this was done in the time span of this bachelor thesis a lot of simplifications have been made. Both in the low-flow statistics and the economic impact. In this sub-chapter, my advice will be given on the best solution for making a low-flow risk assessment for the inland shipping industry. During the 10 weeks of this thesis, a lot of literature research was conducted and some interesting findings were made. This chapter is not based on this thesis's findings, but more of a recommendation on how to improve the risk assessment of low water levels on inland shipping. This chapter is for the client, RoyalHaskoningDHV, to read and see where improvements can be made for the risk assessment.

5.3.1 Low-flow statistics - GRADE

This thesis used a method from the 80s to determine the low flow statistics of the Rhine. Due to time limitations and the availability of the discharge data using Waterinfo, this was the best method for this research. However, if the time and resources are available I highly advise looking into GRADE. GRADE stands for the Generator of Rainfall And Discharge Extremes.

GRADE is a model developed by Deltares, the KNMI and Rijkswaterstaat. The model uses a more physical approach to determine river discharges. Instead of using historical discharges, the model's main inputs are temperature and precipitation. These are stochastically generated based on historical observations. The model then used a so-called HBV rainfall-runoff model, the main components of this model are visualised in figure 38. In short, an HBV model determines a river's discharge based on dynamic sub-basins and parameters. Resulting in an integrated dynamic model that is able to predict the discharge of a river.

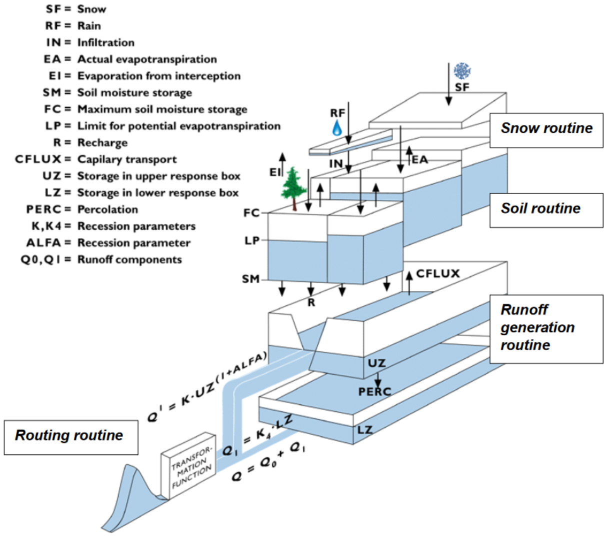


Figure 38: HBV rainfall-runoff model used by Deltares [Weiland et al., 2014]

The result is a more realistic determination of the river's discharge. What makes GRADE so great is that it can generate up to 50.000 years. The extrapolation used in the method of this thesis is therefore not needed. Another great benefit of using GRADE is that incorporating climate change is easier and more realistic. If you look back at table 1 you see that the KNMI climate change scenarios are based on precipitation and temperature change. This is also the input of the HBV model and thus the change that possible future climates will create are easily incorporated into the HBV discharge output. The NM7Q values of each climate change scenario of table 5, which are used to include climate change in this thesis, are also generated using an HBV model.

To conclude, the main benefits of using GRADE are the absence of extrapolation due to the generation of up to 50.000 years of discharge data. Secondly, it takes a more realistic approach to determine the discharge of a river. And at last, it is much easier to see the effects of climate change on the discharge of a river due to the usage of an

HBV model.

One thing important to note is that the GRADE model was actually developed to look at extremely high discharges. The model still has difficulties generating realistic extreme low discharges [van Brenk, 2021]. The recommendation is thus to find a way such that GRADE can be used accurately for low discharges.

5.3.2 Economic impact

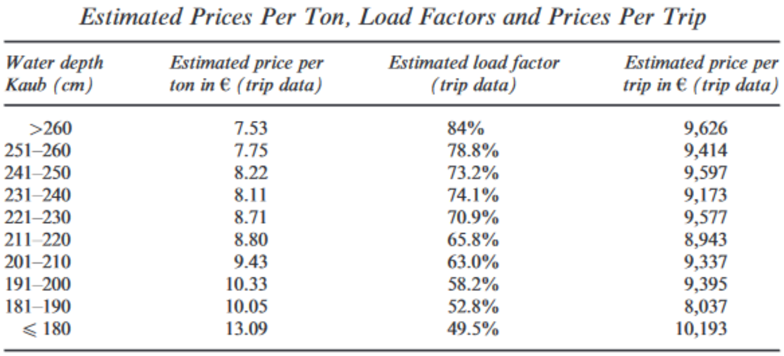
Again, the economic impact part of this thesis includes the most short-cuts and assumptions. I think it is possible, with more time available, that this part of the thesis can be improved. These improvements will be assessed below.

The dry period generation

Looking at the discharge data you see that the duration and severity of dry periods vary a lot. As said above, this thesis uses a typical generated dry period. This method removes partially the dynamic behaviour of a river. To get a way more realistic dry period generation it is again advised to look at GRADE. GRADE is able to generate 50.000 years of discharge data for a river. If the GRADE model is also made possible for extremely low discharges, then I would highly advise using this. One could easily make a model that uses GRADE and determines the dry periods of each year. The result is a more dynamic and realistic dry period generation. Where dry periods could occur at different times of the year and have different durations and severities. Making the GRADE dry periods much more realistic than the generated dry periods in this thesis.

Damage calculations

The Dutch and Germany economy are economies whose principles are based on capitalism, prices are based on supply and demand. This is also the case for the economy behind inland waterway transportation. In case of drought less cargo can be transported, increasing the cost of transport. The risk in this thesis is expressed as 'lost tonnage' not in monetary terms. Due to time constraints and the lack of knowledge surrounding economy models, this was the best way to express the effects of dry periods on the inland shipping economy. A great paper by Jonkeren [Jonkeren et al., 2007] did use an economic model to find the economic impact of dry periods. You can find a table from that paper in table 12. Here we can clearly see decreasing transportation efficiency (load factor) and increasing price per ton. I highly advise for further research to come up with a model that uses water level and CEMT information as input and transport price as output. This way the risk can be expressed in monetary values, instead of lost tonnage. Which is way more useful since everybody understands money. If the risk of low-flow periods is expressed in euros then it is easier to determine how much money should be made available to counter this increasing problem.



Estimated Prices Per Ton, Load Factors and Prices Per Trip

Water depth Kaub (cm)	*Estimated price per ton in € (trip data)*	*Estimated load factor (trip data)*	*Estimated price per trip in € (trip data)*
>260	7.53	84%	9,626
251–260	7.75	78.8%	9,414
241–250	8.22	73.2%	9,597
231–240	8.11	74.1%	9,173
221–230	8.71	70.9%	9,577
211–220	8.80	65.8%	8,943
201–210	9.43	63.0%	9,337
191–200	10.33	58.2%	9,395
181–190	10.05	52.8%	8,037
⩽ 180	13.09	49.5%	10,193

Table 12: Increasing transport prices due to lower water depth at Kaub, obtained from [Jonkeren et al., 2007]

5.3.3 Final model advice

This thesis has linked the economic impact with low-flow statistics of the Rhine. However, as mentioned above this can be done more realistically. Based on all of the recommendations above, a final piece of advice, as a framework that future research could try, was made. This can be seen in figure 39. The essence is that we have access to tons of IVS data and hopefully GRADE for low-flows soon. These two data sources could offer great possibilities for low-flow risk assessments and include the effects of climate change in these risk assessments.

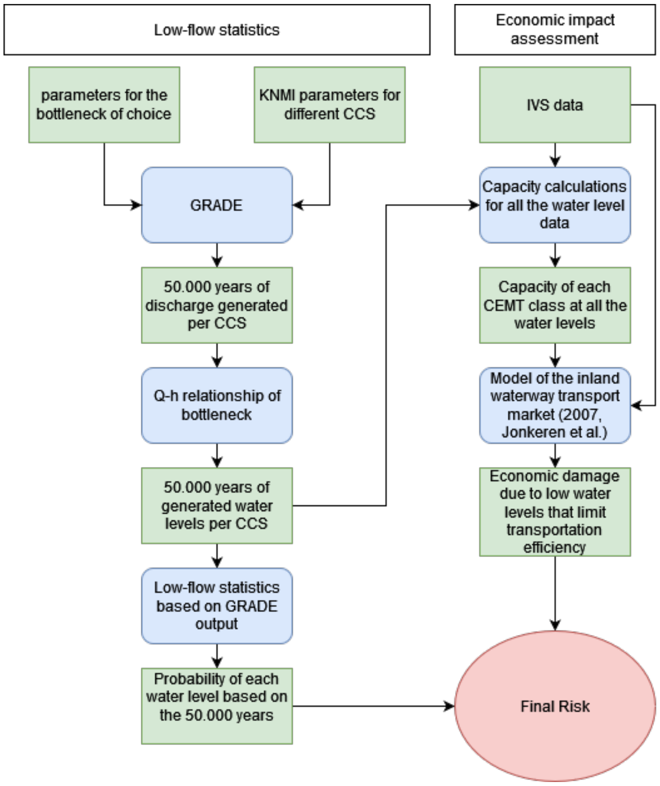


Figure 39: Framework of my advise on how to get a realistic risk assessment of low-flow periods on the Rhine

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