Climate change and Waal Canalization

'Study on the extent and effect of river canalization'

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TU Delft

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By

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Preface

This report is the result of research to the effects of climate change and Waal canalization on inland shipping for my master thesis at Delft University of Technology. The subject is special to me because I have been grown up with inland shipping. In addition, climate change is experienced more often by people and the impact becomes larger. Therefore, the combination of climate change and inland shipping is very interesting to me. I have worked with pleasure on this research and I am grateful for all support.

I would like to thank the members of my graduation committee H.J. Verheij, W.F. Molenaar, J.C.M. van Dorsser and T. Vellinga, for their guidance. Finally, I would thank my family and boyfriend for their support and help during this research. In particular, I would like to thank my parents for their support during my study Civil Engineering.

This report is the end of my master Hydraulic Engineering and therefore the end of my study period in Delft. I have learned a lot during this years and my motto ‘never give up’ gave me the power on the long road to this graduation. I look forward to new opportunities, challenges and experiences in the work field of Hydraulic Engineering.

S. Taekema

Delft, August 2017

Summary

The River Waal is one of the most important shipping routes in the Netherlands. The river fulfills several functions whereof inland shipping is one with high economic value. To maintain the functions of the river, but also to protect the river area, human interventions such as river training structures are applied to regulate the river. Climate change may lead to other circumstances and river characteristics which could have a negative impact on the functions of the river. River canalization is an example of a major regulating measure, that is often applied to create sufficient and more constant water levels which is favorable for inland shipping. However, river canalization has a lot of 'side' effects that can have major impact. Therefore, the consequences of canalization must be investigated carefully.

This research is about the effects by climate change on the inland shipping sector of low discharges in the River Waal. Two different situations are investigated, one without any measure and one with canalization of the river. These two situations are compared with a zero variant where no navigation restrictions occur and therefore a so-called reference situation is also investigated. The focus is on the direct costs for the inland shipping sector due to navigation restrictions caused by insufficient water depth and canalization. Besides, the more integral picture is taken into account by the total costs due to canalization, which consist of the shipping costs due to canalization and the weir- and lock complex costs (from now on referred to as WLC costs). Other external effects, such as the reliability of inland shipping and modal split to other transport modes are not considered in this comparison study.

Canalization is defined as a plausible measure for improving the navigability of the River Waal when the shipping costs in case of canalization are lower than the shipping costs due to climate change without any measure. However, the more integral picture shows whether canalization is a feasible measure. When the total costs due to canalization are lower than the shipping costs due to climate change without measure, canalization can be marked as feasible.

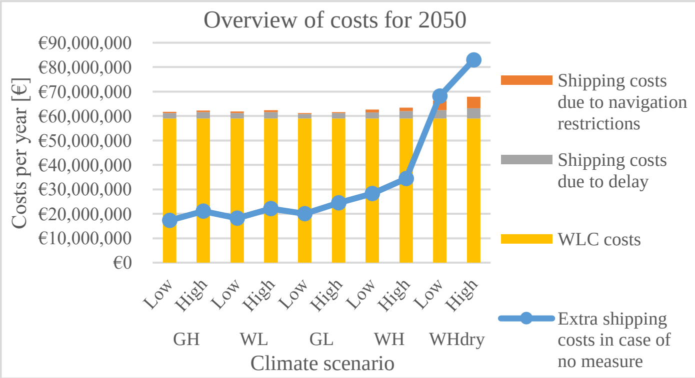
The geographical area that is taken into account is the physical river system from the German border (rkm 860) to the port of Rotterdam (rkm 1000). The fixed layer at Nijmegen (rkm 883 – rkm 885) is the most critical point of the River Waal regarding the navigable depth. The important developments for this research are climate change, economic growth and the future fleet composition. Various possible future situations are considered by taking different scenarios into account. For climate, these are the $W_{H,dry}$, W_H, G_H, G_L and W_L scenarios. For economic growth, the WLO scenarios are used. For the characteristics of the future fleet only scaling is considered and the composition is equal to the current fleet. The consequences for inland shipping are investigated for two time horizons, namely at the years 2050 and 2085.

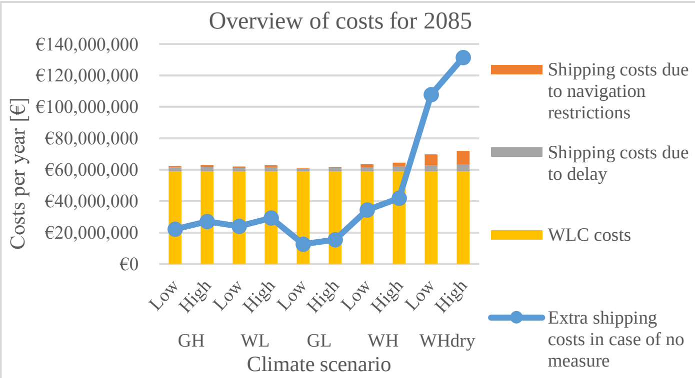
For studying the effects of the different developments on the inland shipping sector an effect model is developed, validated and used. This model requires the following inputs: the normative depth each day during a year, the characteristics of the normative vessel and the total freight transported by inland shipping. Using this information, the model is calculating the load factor for each day and this results in the required number of loaded trips per year for transporting the amount of cargo. Subsequently, the total shipping costs in case of navigation restrictions can be calculated and is given as output of the model. Comparing these shipping costs with the total shipping costs of the reference situation, the extra shipping (or damage) costs due to navigation restrictions can be computed.

The shipping costs in case of canalization are determined for the most optimal option of canalization, which is defined as the option with the lowest total costs due to canalization. The optimization of the canalization is fully determined by the number and the dimensions of the WLC. The relation between the shipping costs and the water level difference over the weir (head) in combination with the relation between the WLC costs and the water level difference affect the optimal option. Applying a lower head leads to increasing shipping cost due to more navigation restrictions and decreasing WLC costs due to lower forces on the structure. For each scenario, there is a different optimum and therefore only for one (representative) situation the optimal option of canalization is investigated. Subsequently, this optimal option is used for investigating the consequences of several scenarios. The representative situation is the annual discharge distribution from 2003 in combination with the high economic scenario and the normative vessel for 2050, because it is expected that the discharge distribution from 2003 will occur annually around 2050.

However, the shipping costs are determined for a specific year, while the WLC costs are total costs. To be able to compare both costs with each other, the WLC costs are translated into annual WLC costs by using the equivalent annual cost method. The equivalent annual costs are the annual rental payments sufficient to cover the present value of all costs of owning and operating. Because the shipping costs are determined for one specific year, it is more convenient to use this equivalent annual cost method than doing a common net present value calculation.

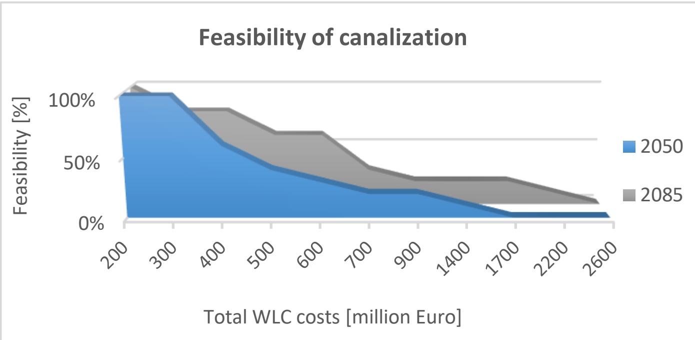
Based on the total head over the entire route it is determined that the area of interest, relating to the number of WLCs, is from one to three WLCs. For this area of interest the most optimal option for Waal canalization is investigated. Taking the total cost into account, it is found that it is more attractive to permit some navigation restrictions by applying a smaller water level difference over the weir. Furthermore, one WLC with a head of 8.0 meter is determined as the most optimal option for canalization of the River Waal. For this situation, the shipping costs are lowered from about 60 million Euro to about 7.5 million Euro. Looking at the integral picture, the total costs of canalization are lower in case of canalization and therefore canalization is an attractive measure to improve the navigability of the fairway.





The consequences in case of several scenarios for this canalization option are investigated to get insight in the range of possible outcomes. The scenario analysis shows that the shipping costs for all scenario combinations are lower in case of canalization than in case without any measure. Looking to the more integral picture, the total costs due to canalization are only in case of the most extreme climate scenario lower than the shipping costs in case without any measure. For all other scenarios, the total costs due to canalization are much higher. The results of all scenario combinations are included in the figures alongside to here.

It has been noted that the WLC costs are the biggest part of the total costs due to canalization. Therefore, the WLC costs have a much greater effect than the shipping costs on the total costs of canalization and therefore on the feasibility of canalization. In addition, the total WLC costs are about €1200 million and this might be a bit high for one WLC. Therefore, it is desirable to improve the accuracy of the WLC costs to obtain more reliable outcomes and insight in the feasibility of canalization. However, no conceptual design is available and therefore it is hard to improve the WLC costs and to quantify the feasibility of canalization. To give an indication of the expected feasibility, the sensitivity of the WLC costs is investigated.



During the sensitivity analysis, the total costs due to canalization for various WLC costs are investigated. The result is shown in the figure alongside to here. For total WLC costs below 400 million Euro the feasibility of Waal canalization is quite high, which means that for many scenario combinations the costs due to canalization are lower than the costs in case without measure. However, for WLC costs between 400 million Euro and 900 million Euro the feasibility decreases to 20%.

Summarizing: canalization can be marked as a plausible measure to improve the navigability of the River Waal for inland shipping, because the shipping costs in case of canalization are lower than in case without any measure. Taking the more integral picture inclusive construction, maintenance and operational costs of a WLC into account, it is hard to indicate whether canalization is also a feasible measure because the WLC costs are very uncertain and these have a major effect. Therefore, an indication of the expected feasibility for various WLC costs is given. For WLC costs up to 600 million Euro the feasibility is more than 50% in 2085. For higher values of the WLC costs, the feasibility decreases to 20% and finally to 0%. It is expected that 1000 million Euro is quite large for one complex and therefore it is assumed that a feasibility of at least 20% is reached.

This research has shown the impact of climate change and Waal canalization on the navigability and therefore on the direct costs for inland shipping. Because the River Waal is the main shipping route between Rotterdam and Germany and a lot of freight is transported by inland navigation, the economic importance is high. A worse navigability can also have impact on other transport modes if modal shift takes place. Therefore, the impact of a worse river navigability can be large and, therefore, it is useful to investigate this. When the overall effects of a worse navigability are known, an appropriate solution can be found and policy implications can be made. At this stage, it is too early to conclude whether canalization is that suitable measure. However, it can be concluded that inland shipping experience such restrictions that a measure must most likely be taken. Therefore, it is recommended to investigate several possible measures that avoid navigation restrictions. In combination with research to the overall effects of a worse river navigability, more reliable policy implications can be made.

Content

Appendices

1 Introduction

1.1 Problem description

The River Waal is one of the most important inland water transport systems in the Netherlands. This river is located in the south of the Netherlands and is orientated in west- east direction. Therefore, it is the most attractive route for inland shipping to transport freight from the port of Rotterdam to Europe and vice versa. The River Waal is part of the River Rhine, which is one of the main important inland waterways of Western Europe. The River Rhine and their Branches are shown in Figure 1.

The port of Rotterdam is ideally located near the North Sea and at the mouth of the River Rhine and is the largest one of Europe with a cargo throughput of 466.4 million metric tons and a container throughput of 12,235,000 TEU in 2015. Every year, about 30,000 sea- going vessels and 110,000 inland vessels call on the port of Rotterdam. Thereby is inland shipping responsible for around 50% of incoming and outgoing cargo between the port of Rotterdam and destinations in Europe. (Port of Rotterdam, n.d.[a]) This is a large amount of freight that is transported by many ships over the River Waal.

"Rhine river's low water levels causing ships to run aground"

The River Rhine, a major shipping waterway through western Germany, is experiencing worryingly low water levels, causing problems for vessels along the major shipping route.

The River Rhine's water level between Bonn and Duisburg, North Rhine-Westphalia, measured this week at 2.14 meters – less than half of its normal depth of 4.33 meters.

The low water levels make the waterway narrower, which in turn means river vessels have less space. Some end up inadvertently navigating too far and getting stuck, according to police.

The Local
13 October 2016

Source: The Local (October 2016, translated)

Since many years, the world is very occupied with climate change and the effects. As can be read in the articles about climate change alongside to here, this also affects the inland water (transport) system. Namely, low discharges and water levels will occur for a longer period and more frequent.

According to the 5th assessment report of the International Panel on Climate Change (IPCC) all global climate models agree on an increase in mean global temperature by 0.3 to 4.8 degrees Celsius over the 21st century (IPCC, 2014). The main consequences of this increasing global temperature are changing weather conditions and sea level rise. The changing weather conditions have an impact on the inland water (transport) systems and therefore it is important to know the consequences.

The effect of climate change on the performance of the West European IWT system has been assessed by a number of studies including: Timmermans (1995), Nomden (1996, 1997), Van Geenhuizen et al. (1996), Harris (1997), Deursen (1998), Middelkoop (1999), AVV (2000), RIZA (2005), Bosschieter (2005), Jonkeren (2009), Demirel (2011), Turpijn and Weekhout (2011), and Riquelme Solar (2012). There is general agreement along these studies that the most severe impacts on inland shipping are related to the occurrence of extreme low water levels. In addition, the effects of extreme high water levels are also often mentioned, but less research has been conducted on this subject until now. (van Dorsser, 2015)

Research to the "very long term development of the Dutch inland waterway transport system up to the year 2100" indicated that the lower section of the River Rhine (up to Ruhrort) may no longer remain all year round navigable in the most extreme climate scenarios towards the year 2100. In addition, the navigability of the lower part of the Rhine may also be very much affected (van Dorsser, 2015).

"Water level rivers low for over a hundred days"

ARNHEM – The water level in the rivers are low for over a hundred days compared to other years. Rijkswaterstaat gave a warning for the low water levels. They expect no improvement until the end of next week.

The Netherlands is experiencing the longest continuous dry period of the past forty years. Since mid-August there was no precipitation in the watershed of the River Rhine in Germany that had any sense of contribution.

Telegraaf
30 October 2015

Source: Telegraaf (October 2016, translated)

Van Dorsser (2015) has included the characteristics of changing weather conditions and the adverse effects on inland shipping. Climate change leads to more extreme weather conditions and this is characterized by:

- Very low precipitation levels in combination with high evaporation levels resulting in exceptionally low river discharge volumes and water levels;
- Very high precipitation levels resulting in exceptionally high river discharge volumes and water levels;
- Very strong winds that restrict barge operations and raises sea water level if they are directed onshore.
- Extreme cold weather conditions related to ice and snow.

The River Waal has a worse navigability in case of extreme climate scenarios. However as said earlier inland shipping is important for the throughput of freight between Rotterdam and Europe. Therefore, the inland shipping sector experience a lot of pressure. The extreme discharges do not lead only to navigation restrictions but also less reliability, image damage and higher prices can occur. These ‘external’ effects might have a big impact on the whole inland shipping sector.

> *“Low water levels in rivers”*
>
> Novum – The water level of the Rhine near Lobith is 7.89 meter above NAP on Wednesday and this is quite low. Rijkswaterstaat says that this is due to the relative less precipitation during the last months in Germany and Switzerland. These low water levels on the river leads to less freight that can be transported by inland shipping. Normally, at this time of the year the water level is 10.80 meter above NAP.

Source: Trouw (October 2016, translated)

To meet the expectations arising from the port of Rotterdam, the country itself and Europe, the River Waal deserves much attention when it comes to the navigability of the river. Therefore, research to deal with the effects of climate change is important.

Possible measures for improving the navigability of the River Waal under climate change need to be properly investigated, because they may affect many aspects. Canalization of the Waal between Rotterdam and Lobith is a possible measure to deal with the conditions that are the result of climate change. This canalization can be achieved with several weirs and locks. However, such a major intervention has many consequences and this should be carefully investigated to see if this is a feasible measure.

In this research the focus is on inland shipping. The scope is limited to one possible measure to keep the River Waal navigable, namely canalization of the Waal between Rotterdam and Lobith. The effects of this canalization will be primarily related to inland shipping. For example, the effects with respect to ships travel time and the navigability of the river are investigated.

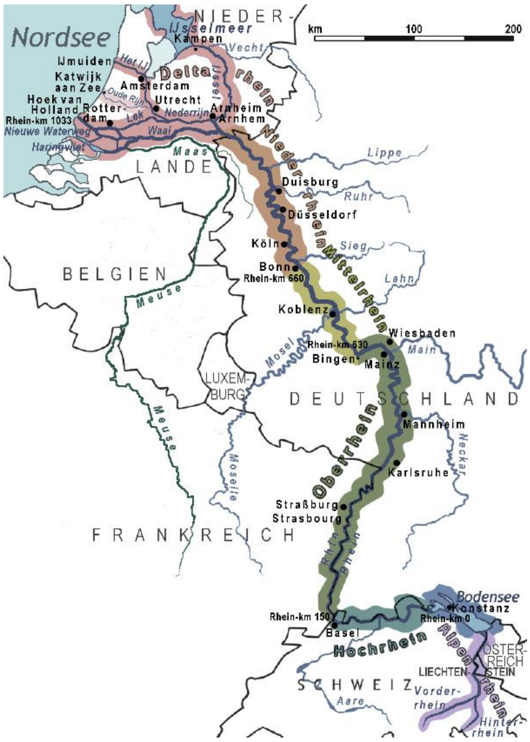


figure 1: Overview of the Rhine basin (Ullrich, 2014)

1.2 Outline of the Thesis

This research report has started with a description of the problem. Now, the rest of the thesis outline will be described.

The second chapter presents the description of the research project about the canalization of the River Waal. The problem will be described followed by the research objective. Subsequently, the main- and sub- research questions are included. At last, the research methodology is described. This contains the various steps that will be taken to answering the research question.

Chapter 3 contains general information about rivers in the Netherlands. The effects on the river system will be discussed and in particular the effect of climate change on the river navigability. The River Waal will be considered and general information about river canalization is included. The effects of canalization will be discussed.

Chapter 4 presents relevant information about inland shipping in the Netherlands. The different shipping routes important for transporting freight are described. Subsequently, the fleet composition is discussed. The various ship types and sizes that occur are included. The shipping costs are presented and the future developments relevant for this study are described in this chapter.

In the fifth chapter, relevant aspects of the River Waal are included. Assumptions and boundary conditions are made, which makes the project tangible.

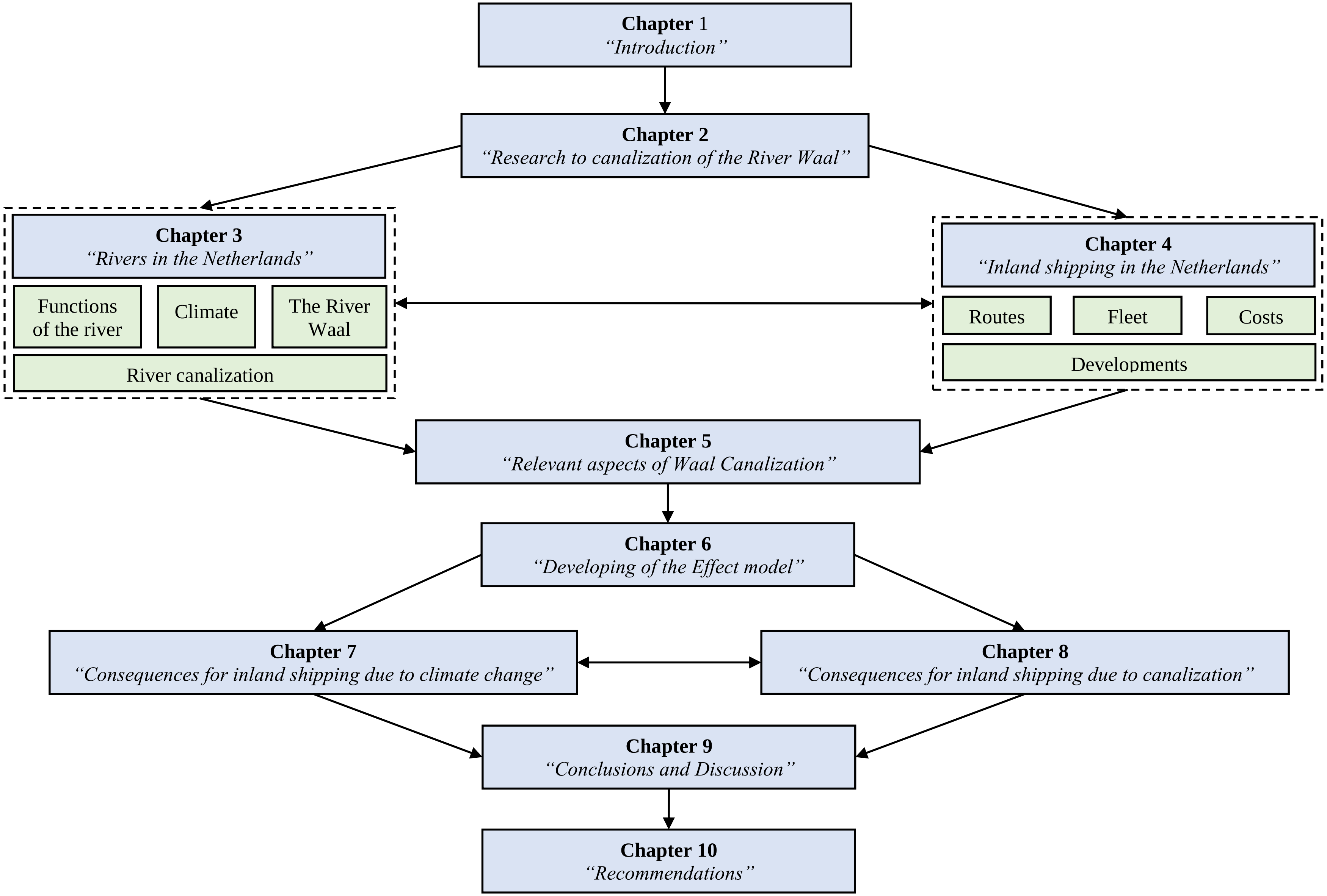
Chapter 6 describes the developing of the effect model. This model is used for answering the research question. The outline of the model, assumptions, calculations and the validation is included.

Chapter 7 presents the used data and results of the analysis to the consequences for inland shipping due to climate change in case without measures. The shipping costs due to climate change and the costs in the situation without any restrictions are both calculated to obtain the extra costs due to navigation restrictions caused by climate change.

The consequences for inland shipping due to canalization are obtained in chapter 8. Therefore, the most optimal way of canalization is determined and the effect of climate scenarios is investigated. The assumptions, calculations and results are presented.

The conclusions and discussion are included in chapter 9. Finally, the recommendations are included in chapter 10

The flow- chart on the next page, shows the relation between the different chapters of this report.



Chapter 1
“Introduction”
Chapter 2
“Research to canalization of the River Waal”
Chapter 3
“Rivers in the Netherlands”
Functions of the river
Climate
The River Waal
River canalization
Chapter 4
“Inland shipping in the Netherlands”
Routes
Fleet
Costs
Developments
Chapter 5
“Relevant aspects of Waal Canalization”
Chapter 6
“Developing of the Effect model”
Chapter 7
“Consequences for inland shipping due to climate change”
Chapter 8
“Consequences for inland shipping due to canalization”
Chapter 9
“Conclusions and Discussion”
Chapter 10
“Recommendations”

2 Research to canalization of the River Waal

2.1 The Problem

Research to the “very long term development of the Dutch inland waterway transport system up to the year 2100” indicated that the River Rhine up to Ruhrort may no longer remain navigable all year round in the most extreme climate scenarios towards the year 2100 (van Dorsser, 2015). So, the Dutch branches of the Rhine involving the River Waal, the Nederrijn/Lek, and the Gelderse IJssel will be affected by climate change. As said earlier the River Waal is one of world’s most intensively used rivers for inland navigation. Therefore, it is important to maintain sufficient water depth for inland shipping. A possible measure to maintain sufficient water depth is canalization of the Waal between Rotterdam and Lobith. This measure, for improving the navigability of the River Waal under climate change, needs to be properly investigated, because it has a large impact on longer travel times for inland vessels, costs of building and cost of maintaining and operating weirs and locks. Therefore, it is important to investigate the costs of the canalization to get insight in the consequences of this measure.

1.1 The Objective

The aim of this research project is to investigate what the consequences of climate change and Waal canalization are on inland shipping, from a financial point of view. Therefore, the impact of river navigability and fairway restrictions on inland shipping are considered. Comparing the situation without measure and the situation with canalization gives insight in the costs and benefits of Waal canalization. Therefore, this research is a comparative study in which the relative costs of canalization will be investigated.

2.2 Research Questions

Waal canalization to improve the navigability of the river under climate change has many impacts for inland shipping. However, in the situation where no measure is taken there are also consequences for inland shipping due to climate change. This research will compare both situations and their effects on the inland shipping sector. As such, the financial consequences for both situations have to be investigated. The starting point is to consider the construction costs and transport costs.

In the situation of canalization there are several options to carry out this canalization. Of course, the most optimal situation where the costs are lowest is preferred. Therefore, different situations, regarding the number of locks and weirs must be investigated.

The output of this study is an overview of the costs due to climate change and due to canalization for several scenarios.

The main question of this research is:

“Could canalization be a plausible measure to improve the navigability of the River Waal under climate change from a financial point of view?”

The following sub-questions have been posed to answer the main research questions:

1. What are the expected developments concerning navigation on the River Waal for the future?
    a. What is the expected amount of cargo transported by inland shipping over the River Waal?
    b. How does the inland waterway fleet develop?
    c. What are the statistics (duration, frequency) of discharges and water levels under climate change?

2. What are the damage costs for inland shipping on the River Waal due to climate change?
    a. What is the effect of climate change on the navigability of the River Waal?
    b. What are the total costs for inland shipping due to climate change?
    c. What are the total costs for inland shipping without any navigation restriction?

3. What are the costs for inland shipping of Waal canalization between Rotterdam and Lobith?
    a. What is the most optimal option to canalize the River Waal? As such, what is the optimal number of weirs and what are the dimensions in that case?
        i. What are the construction-, maintenance- and operational costs of canalization?
        ii. What is the effect on the water level and therefore on the navigability of the river?
        iii. What is the effect on the travel time for ships sailing the River Waal?
        iv. What are the transport costs due to canalization of the River Waal?
    b. What is the effect of the 'optimal' canalization option for the different scenarios?

2.3 The Approach

In this paragraph the approach of the research project will be explained. There are several ways to get the information that is required for answering the main question: (1) literature research; (2) analysing existing trends and future developments and (3) models to obtain insights in future developments. The various steps that have been taken for answering the research question are listed here.

Step 1: *Scoping the project*
- Background information;
- Research objective
- Research questions
- Assumptions

Step 2: *Identifying the problem*
- Trends and developments

Step 3: *Model developing*
- Assumptions;
- Validating and improving the model

Step 4: *Investigating the most optimal way of canalization*
- Research to the number and dimensions of the weir- and lock complexes.
- First and second analysis

Step 5: *Scenario analysis*
- Consequences for inland shipping in 2050 and 2085
    - Reference situation;
    - Situation without any measure;
    - Situation with canalization.
- Sensitivity analysis
    - Feasibility of Waal canalization

Step 6: *Conclusions, discussion and recommendations*

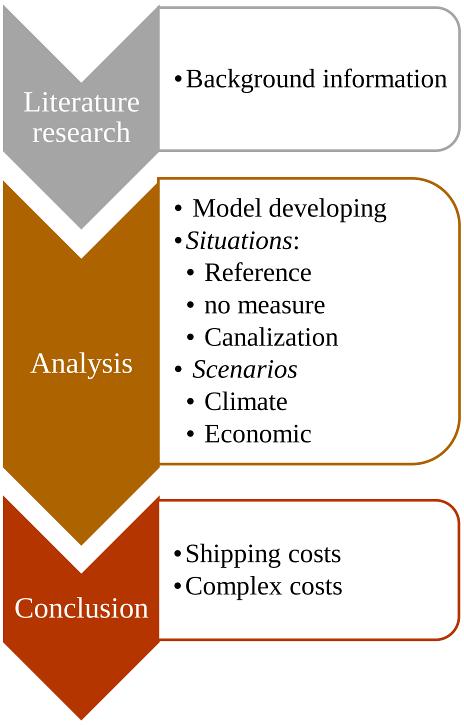


figure 2: Structure of the research method

The research will start with a literature study to make use of existent information, research projects and data. Background information necessary for the next steps will be obtained.

Thereafter, the analysis takes place. There are three different situations: one situation without navigation restrictions and two with navigation restrictions consisting of one without any measure and one with canalization. For these situations, the effects on the inland shipping sector will be researched. There are several scenarios that will be investigated to gain a complete overview of the possible consequences.

At last, there will be an overview of the costs for the different situations and scenarios. Comparing these results shows whether canalization is a plausible measure for improving the navigability of the River Waal under climate change.

3 Rivers in the Netherlands

3.1 Introduction

This chapter describes general information about the river system in the Netherlands, which is required as background information and imaging of the research subject. First, the origin and formation of the rivers will be discussed, which interacts with the different functions of a river. Thereafter, more information about climate change, river canalization and finally the River Waal is given.

The Netherlands is also called the drain pit of Europe. The rivers transport sand, gravel and other materials from the higher areas in Europe to the Netherlands. In this way, the country has originated and therefore the river system was, and still is, very important for the Netherlands. Centuries ago, rough rivers flowed unimpeded throughout the country. Over hundreds of years, the Dutch rivers have been regulated. (Haring et al., n.d.)

The first regulation structures existed of singular groynes and guide walls to force the flow into a low water bed of limited width. These structures lead to larger flow velocities in the main channel and therefore the formation of sand bars was avoided. A larger navigable depth and width were the effects of these regulation structures. However, the biodiversity was reduced due to these structures and therefore the ecological value diminished.

The Rhine underwent a large number of river training measures in the Netherlands in the 19^{th} and 20^{th} century. Several measures for increased navigability, flood protection and land use are taken. Large scale river training measures to improve the navigability are fixed planforms, non- permeable groynes and use of a single main channel. For protecting a certain area or population, dikes are constructed as main flood defence. (van Vuren, 2005)

Nowadays, the Dutch river system is more limited in size and includes two river basins, the River Rhine and River Meuse. In the Netherlands, the River Rhine splits into three different branches, into the Nederrijn/ Lek, the River IJssel and the River Waal. The location of these rivers is shown in figure 3. The rivers connect the North Sea with areas more inland, but they form also barriers through the land.

Over the years, the river had many different functions. The good connection between the sea and the hinterland has caused the economic value of the waterway for transporting goods. Due to trade at the harbours along the river, these areas developed economically well. Another positive effect was the fertile areas along the rivers due to nutrient rich river deposits. Therefore, this land could be used well for agriculture. However, during high water periods the land had to be protected from flooding. Because the economic value of the areas around the rivers were increased, the protection against the unpredictability of the rivers became more important and the river training structures as described previously were applied. (Haring et al., n.d)

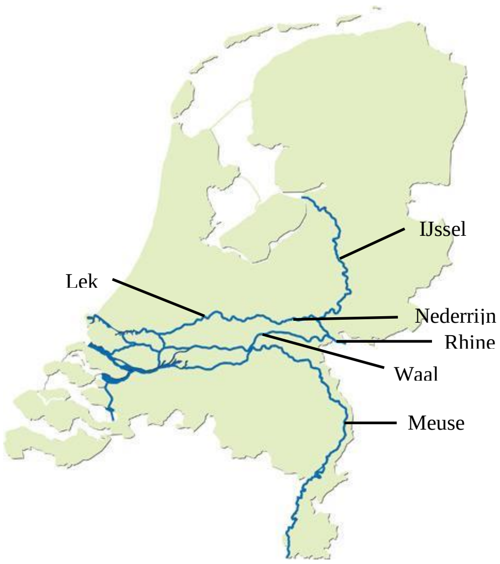


figure 3: Rivers in the Netherlands (retrieved from http://www.rivierennederland.nl/grote-rivieren-nederland/)

However, the Dutch rivers have many more features. The most important functions are listed here.

- Water drainage
- Drinking water
- Energy production
- Material transport
- Agriculture
- Nature
- Industry
- Water recreation
- Inland fishery
- Inland shipping

The river transports fresh water that can be used for multiple purposes. The government extracts water from the river for drinking water. But also, agriculture and the industry use water from the river for respectively irrigation and cooling water. Hydroelectric power stations use the water flow for energy production. In addition, ecology, inland fishery, water recreation and inland shipping are important other functions. (Rijkswaterstaat, December 2015)

Rivers do not only discharge water, but they also transport several materials. These materials are deposit in the river area and therefore it is an important source of minerals. Examples are sand, gravel and clay that is used to produce concrete, limestone and brick. (Haring et al., n.d)

The multiple functions of a river have great influence on each other and sometimes they are conflicting. Therefore, the Dutch government has ranked the several purposes on priority. First the protection of the country against flooding must be guaranteed. Subsequently, the river can be used for various purposes. For example, sufficient fresh water and water quality are ranked high, because these are important for basic needs such as drinking water, agriculture and the environment (nature). Since inland shipping is of high economic value, smooth and safe traffic over water is also important (Rijkswaterstaat, December 2015). Because the function of the river as fairway for inland shipping is most relevant for this study, this subject will be described in more detail in chapter 4.

Not only the interventions by people of human beings affects the rivers, but also external factors such as weather conditions. The two river basins in the Netherlands have originated differently. The River Meuse is a so-called precipitation river, which means that this river is only fed by precipitation. In contrary, the River Rhine is a mixed river and therefore it is feed by precipitation and melting water from the mountains (Geolution, 27 October 2009). Weather conditions affect the amount of water that is flowing through the river and therefore the discharge is not constant over time. In order to regulate these flow fluctuations and fulfil the usage requirements of the river, several measures have been taken during the years. A reference is made to the measures described previously, but also other measures such as river canalization, sand supply and dredging activities are examples.

Because the weather conditions are changing due to climate change, the river system is affecting and therefore river functions could be under pressure. The effects of climate change on the river system are experienced yet. However, it is expected that this impact will grow in the future. In the next paragraph this subject is discussed further.

3.2 Climate

Since many years, climate change was discussed. However, since recent years, the effects of climate change are experienced and therefore this subject becomes more important. Climate change affects the weather conditions and this has impact on the environment. Studies to climate change has resulted into different climate scenarios.

Worldwide climate scenarios have two main uncertainties, namely large scale circulation patterns and global warming. Based on these worldwide scenarios, the Royal Dutch Meterological Institute KNMI has presented four climate scenarios for the Netherlands. (Krekt et al, 2011) The scenarios are the four combinations of two possible values for the global temperature increase, 'Moderate' and 'Warm', and two possible changes in the air circulation pattern, 'Low' and 'High'. Together they span the likely changes in the climate of the Netherlands according to the newest insights (KNMI, 2015). This is schematically shown in figure 4.

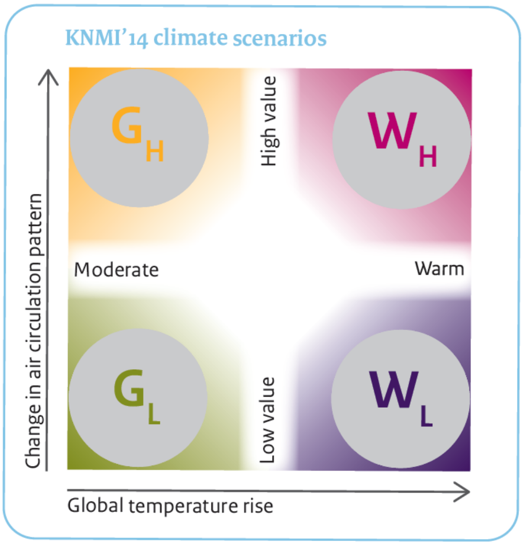


figure 4: Overview of KNMI'14 climate scenarios (KNMI, 2015)

For the Netherlands, the overall changes are a rising temperature, more extreme circumstances such as heavy rains and dry periods and an ongoing rising sea level. These changes do affect the river system. Higher temperatures and longer dry periods result in more evaporation and lower water levels in the rivers. This have many impact on the functions of the river, because less water is available for agriculture, industry, drinking water and nature. Also, the navigability of the river is decreasing during low water periods and this has impact on inland shipping. But, increasing precipitation can lead also to several problems, for example flooding.

Looking at the navigation function of the river, due to climate change the discharges becomes more extreme. The frequency of these extreme circumstances is also increasing. So, high water levels become higher and occur often.

The same is valid for low water levels. This means that the navigability of the River Waal becomes worse and inland shipping can experience navigation restrictions.

Room-for-the-River is a recent project for many rivers in the Netherlands that includes several measures to deal with these more extreme circumstances. It is a collection of measures aimed at increasing the discharge capacity of the country’s main rivers while also enhancing environment and spatial quality. (Royal HaskoningDHV, 2016) The Room-for-the-River measures in the Rhine branches are primarily intended to create a larger cross area flow profile. This leads to lowering of the water level in case of high river discharges. Most of the measures are also effective under normal annual circumstances and not only under extreme conditions. Therefore, these measures affect the flow and sediment transport in the summer bed and thus there is an effect on the morphology of the summer bed throughout the whole year. These effects can be both short and long term. (Sloff et al., 2014)

Because Room for the River is a national flood risk management programme, the measures are mainly against (extreme) high water circumstances. However, also low water periods become more extreme and occur more frequently, which affects the navigability of the rivers in a negative way. Possible measures to improve the navigability of the river are constructing groynes and canalization of the river by constructing weirs. This last measure has been applied in the Nederrijn and Lek, where three weirs are constructed. In the next paragraph canalization of rivers is described in more detail.

3.3 Canalization of rivers

Canalization of the river means that several weirs are constructed in the river to meet the function requirements. A weir is a barrier across the width of a river that affects the flow. Because the river discharges are not constant also the water levels differ over time. The consequence is changing water depths and this could have impact on several functions, such as inland shipping and irrigation. During low discharges, the navigation depth can become insufficient and this leads to navigation restrictions for inland shipping. Water intake for irrigation purposes becomes more difficult at low discharges and pumping systems may have to be used. To create sufficiently high water levels at low discharges, weirs can be constructed in the river. (Vriend et al., February 2011)

A canalized river must not be confused with a canal, which is a fairway completely originated by the intervention of human. Canals are mostly straight fairways, while rivers are meandering and consist of many bends.

Moveable weirs are used for river canalization. These weirs can regulate the water levels by opening or closing such that the desired water depth is realized. There are two main principles of water discharge through the weir, namely by overflow and underflow. Overflow means that the water is flowing over the top or through the weir at a certain distance from the bottom. This is caused by a weir that is moving in upward direction when it is closed. This is schematically shown in figure 6. Underflow means that water is flowing near the bottom through the weir. A sketch of this principle is shown in figure 5. In case of high discharges the weirs are in open position and therefore the water levels will not be raised needlessly. In case of small discharges, the weirs are in closed position. This part depends on the discharge and water level requirements. In principle, the discharge will not be affected by canalization.

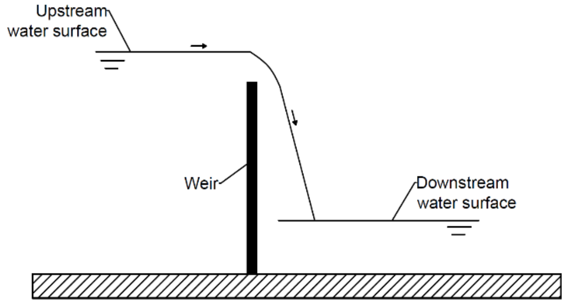


figure 6: Side view of overflow

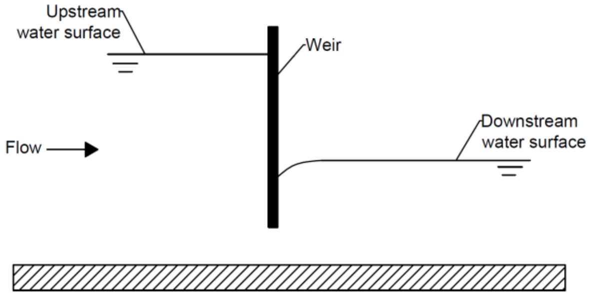


figure 5: Side view of underflow

It depends on the function of the weirs what the requirements on the water level are. If inland shipping is the main objective, sufficiently water depth upstream of the weirs must be created. The discharge at the weir is set on the most critical water depth, which is often just downstream of the upper weir, this is shown in figure 7. Because the longitudinal river slope is not always smooth, shoals can lead to other locations of the critical depth. If waterpower is the main objective, the water differences between both sides of the weir must be as large as possible to obtain maximum power.

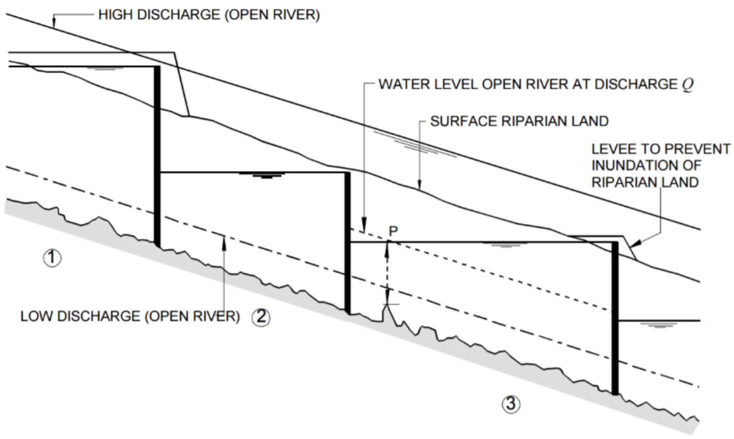


figure 7: The effect of river canalization on the water level (Vriend et al., February 2011)

Canalization is a major measure that has many effects. For instance, there are morphological consequences of canalization. The flow pattern is changing and the obstruction affects the sediment transport. Furthermore, higher upstream water levels have many side effects. For example, ground water levels are increasing and local dike heights could become insufficient. Therefore, river canalization should be investigated in detail to oversee all consequences and make well founded decisions.

Canalization does not only have positive effects for inland shipping. In times of normal or high discharges the weirs are in open position, which means that the River Waal function as a nearly free flowing river and almost unrestricted passage for inland shipping is possible. But in times of low and extreme low discharges the weirs are partly or nearly completely closed to maintain sufficient water depth for inland navigation. In that case, vessels cannot pass the weir and therefore locks have to be constructed in order to provide vessel passage. A top view of a Weir- and lock complex (from now on referred to as WLC costs) is shown in figure 8. In terms of waterway capacity, the resistance of the fairway increases when the weirs are closed. This leads to extra travel time for vessels. The extra time is equal to the lock passing time. A detailed description of the locking cycle is included in Appendix II: Navigation locks.

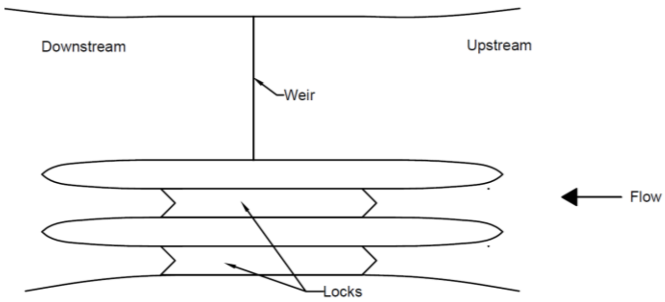


figure 8: Top view of weir- and lock complex

The Nederrijn and Lek are examples of rivers that have been canalized in the past. The weirs have been constructed at Hagestein, Amerongen and Driel. An overview of these locations is shown in figure 9. However, this canalization is not a pure example of water level regulation because also discharge regulation has been attempted. These were the two main objectives of the river canalization. Due to the weir at Driel, the discharge distribution between the River IJssel and the River Nederrijn at the IJsselkop can be regulated. The weirs at Hagestein and Amerongen only have a water level regulation function. At these weirs waterpower is generated by a turbine. However, only about 10% of the theoretically possible profit is in practice realizable, because the primary functions are aimed at navigation and water control. To achieve the main objective a weir program is used. The weir programs of Amerongen and Hagetein are based on the weir program of Driel to meet the navigation requirements. The canalization has resulted in a water depth of the River IJssel and River Nederrijn of at least 2.5 meter. Only in case of floating ice the weir program cannot be used and the weirs are in open position. (Vriend et al., February 2011)

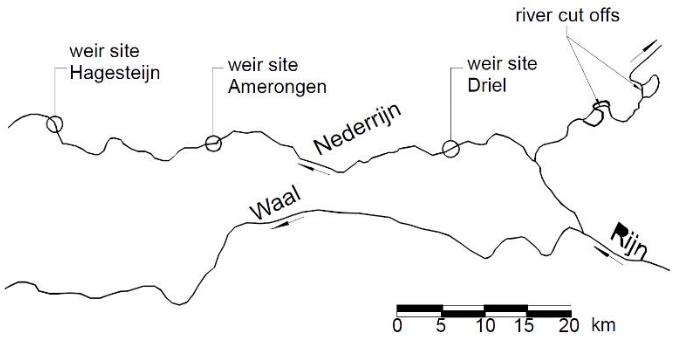


figure 9: location of three weirs in the Nederrijn/ Lek (Vriend et al., February 2011)

3.4 The River Waal

The River Waal is part of the River Rhine. The River Rhine is one of the most important rivers in Western Europe. Its total length is about 1230 km and it has a catchment area of approximately 252,000 km^2. The Rhine rises as a snowmelt- fed river in the Swiss Alps and finally ends as a rain- and snowmelt- fed lowland river in the North Sea.

In the Netherlands, the River Rhine splits into different branches, namely: The River Waal, Pannerdensch Kanaal, River IJssel, Nederrijn and Lek. Two bifurcations take place, one at the Pannerdensche Kop and the other at the IJsselkop. At the Pannerdensche Kop the distribution of the discharge from the Rhine is approximately 66% into the Waal and the remaining 34% flows into the Pannerdensch Kanaal. At the IJsselkop 2/3 is flowing into the Lower- Rhine and 1/3 into the River IJssel. In figure 11 a map of the different bifurcations and branches of the River Rhine in the Netherlands is shown. (Van vuren, 2005)

The River Waal is classified in CEMT category VIc (Rijkswaterstaat, 2016), so units with six pushed barges with a length up to 270 m, a width up to 34.2 m and a depth up to 4.0 m should be able to navigate. In table 1 there are some rough dimensions and characteristics of the River Waal presented.

Characteristic	Value	Unit
Length	83	km
Width main channel[1]	260/ 370	m
Width floodplain	550	m
Bed slope	0.12	m/km
Chézy coefficient main channel	40	$\sqrt{m}/s$
Chézy coefficient floodplain	35	$\sqrt{m}/s$
Grain size of bed material	0.001	m
Mean discharge	1,480	m^3
Agreed low water discharge	818	m^3
Annual sediment load	507,000	m^3/yr

table 1: Dimensions and characteristics of the River Waal (van Vuren, 2005).

[1] width of main channel excluding and including groyne section

In the cross section of the river, several zones can be distinguished, namely: the main channel bed, the groyne section, the flow conveying floodplains and the storage area. These different zones are visualized in figure 10 where the outline of a river in the Netherlands is shown. In general, the bed slope, the floodplain width and the grain size of the bed material decreases in the direction of the North Sea. (van Vuren, 2005)

The width and the depth of the main channel are the most important characteristics for the navigability of the river because these determine the capacity of the fairway. In fact, the least available water depth along the entire shipping route determines the navigability of the river. This means that shipping is restricted to the location of the least water depth. Such locations are called 'nautical bottlenecks' (van Vuren, 2005). Due to these nautical bottlenecks ships are restricted in the amount of freight that they can carry and navigation congestion can occur.

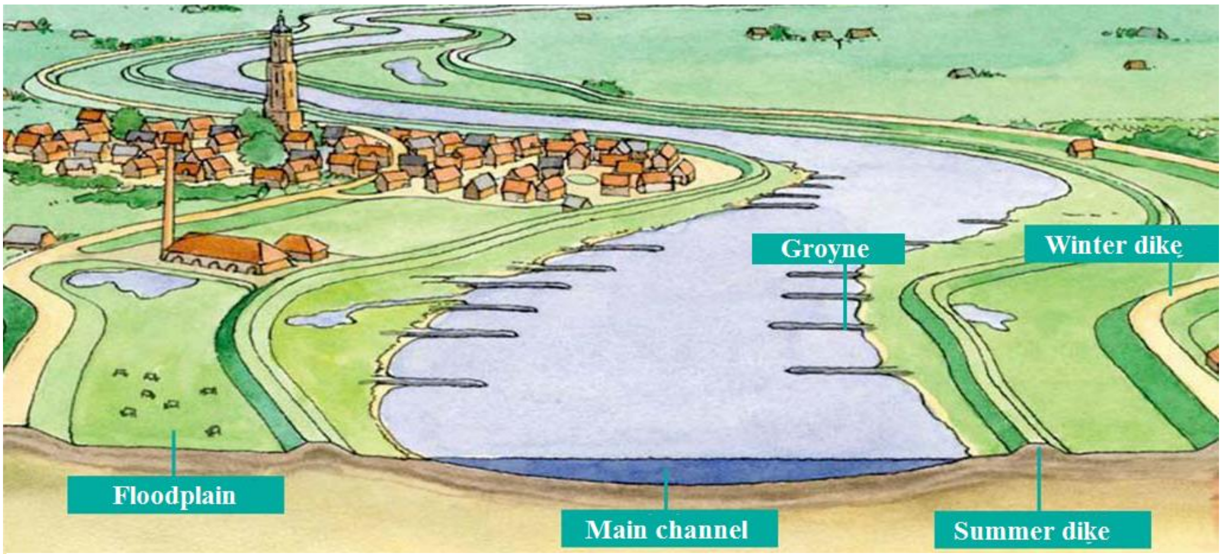


figure 10: Outline of a river in the Netherlands (van Vuren, 2005)

In general, locations with sharp bends and geometrical non- uniformities have a high probability of forming a nautical bottleneck. Looking at the entire length of the River Waal such locations are the bifurcation at Pannerdensche Kop and the sharp bend near Nijmegen. Therefore, these places are most likely to become manifest in the dry season. When the water level drops below 9m +NAP at Nijmegen than this is the critical depth along the complete Waal and therefore ships are restricted in their cargo capacity (van Vuren, 2005). This is mainly induced by the fixed layer at Nijmegen. Because bed subsidence of the River Waal causes shoals at fixed layers since these are not lowering. Therefore, the bed level at Nijmegen is a lot higher which results in a smaller water depth for inland shipping compared to the remaining Waal stretch.

The recent project Room-for-the-River consists of measures in the Rhine branches that are primarily intended to create a larger cross area flow profile. However, the construction of longitudinal dams in the River Waal would be a promising measure to reduce the bed erosion and negative effects for inland shipping. These dams create a smaller main channel of the river and at the same time side channels emerge where water is flowing. As expected this would lead to a higher water level at low discharges and so there would be less problems for inland shipping with loading restrictions. This measure will also have a positive effect on the subsidence of the river bed. (Rijkswaterstaat, 2015) An overview of all the Room-for-the-River projects along the River Waal is included in Appendix I: Room for the river measures.

The Room-for-the-River measures affects the water depth of the fairway and thus it is an important consequence for the navigability of the river. For example, subsidence of the river bed does occur and is about a few centimetres per year. The fixed layer at Nijmegen (rkm 883 – rkm 885) remains the most critical point of the River Waal regarding the navigable depth after implementing of the Room- for-the-River. The depth at the fixed layer near Nijmegen decreases in time as a result of ongoing subsidence of the environment. Also at St. Andries (rkm 925 – rkm 928) a fixed layer is present; however the effect is less because the subsidence at this location is much less compared to Nijmegen. The Room-for-the-River measures reduce the development of subsidence, because relative sedimentation slow down the subsidence. (Sloff et. al., 2014)

3.5 Conclusion

The River Waal is one of the most important shipping routes in the Netherlands. The river fulfills several functions whereof inland shipping is one with high economic value. To maintain the functions of the river, but also to protect the river area, human interventions such as river training structures are applied to regulate the river. Climate change may lead to other circumstances and river characteristics which could have negative impact on the functions. River canalization is an example of a major regulating measure, that is often applied to create sufficient and more constant water levels which is favorable for inland shipping. However, river canalization has a lot of 'side' effects that can have major impact. Therefore, the consequences of canalization must be investigated carefully. The knowledge included in this chapter about river characteristics, river functions and effects of climate change and canalization on the river system will be used for determining the relevant aspects of this research.

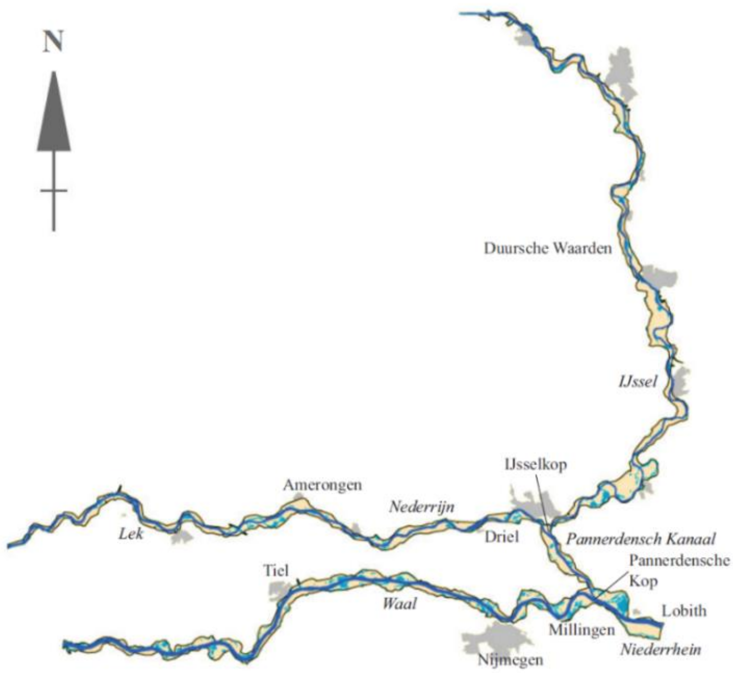


figure 11: Branches of the River Rhine in the Netherlands (Hetzer, 2005)

4 Inland shipping in the Netherlands

4.1 Introduction

International transport by shipping is economically important for the Netherlands. This originates from the advantageous location of the Netherlands in the Rhine Delta, because the inland waterways form a natural access from the sea to the continent of Europe. Inland shipping is responsible for around 50% of incoming and outgoing cargo between the port of Rotterdam and destinations in Europe (Port of Rotterdam, n.d.[a]). The River Rhine is the main shipping connection between the port of Rotterdam and Germany. Therefore, it is one of the most important inland waterways in Europe and safe, efficient and profitable inland shipping is desired. So, reliability of inland shipping is important. This requires an inland waterway with high capacity that is always navigable. Therefore, a deep and wide navigation channel, now and in the future, is required. The European Conference of Ministers of Transport has defined design vessels and their dimensions. European waterways are categorized in different classes, called CEMT- classes. These CEMT- classes determine for which vessels safe navigation can take place. (van Vuren, 2005). In Appendix I: CEMT class characteristics, the different CEMT- classes with their characteristics are shown. Information about the different shipping routes, the shipping fleet and the developments relevant for inland navigation are discussed in this chapter to give insight in the various aspects of inland shipping in the Netherland. This will be used to determine the relevant aspects of climate change and Waal canalization.

4.2 Shipping routes

As has been discussed earlier, the River Waal is an important corridor between Rotterdam and Germany. It is the main connection between the Port of Rotterdam and the hinterland. In 2015 there were 82,000 freight inland vessels that made a call at the port of Rotterdam (Port of Rotterdam, n.d.[a]). Most of these vessels have their route over the River Waal and therefore it is (one of) the main shipping routes in the Netherlands. However, there are also other inland shipping routes where the River Waal is a part of. As can be observed in figure 12, Amsterdam is another big seaport. Inland ships that transport cargo from this place further into Europe also cross the River Waal. First the ships pass the Amsterdam-Rhine Canal before they reach the River Waal nearby Tiel. The Amsterdam- Rhine Canal is a VIb class fairway and therefore maximal units with four pushed barges are allowed to sail on this waterway, while at the River Waal units with six pushed barges are allowed. Now the western ports of the Netherlands are covered, but the northern region should not be forgotten. There are two possible routes to this area, namely via the river IJssel and via the Amsterdam- Rhine Canal and the IJssel lake. The River IJssel is a Va class fairway and therefore maximal one push barge is allowed. On the other hand, the IJssel Lake is a Vb class fairway and this means that bigger ships have to use the route via the Waal, Amsterdam- Rhine Canal and IJssel Lake to reach the Northern part of the Netherlands. In the southern region, there is another VI class fairway near the Volkerak locks. This route connects the Schelde to the River Rhine, but also to Belgium. The River Meuse is part of another important shipping route of Europe. This fairway is classed as Va and therefore only single barges are allowed. (Rijkswaterstaat, 2016)

figure 12: Navigable waterways and ports in the Netherlands, data from 2010 (BVB, 2015)

4.3 Shipping fleet

The diversity of vessels that pass the River Waal is quite big. The range goes from the smallest motor vessels which type is called ‘spits’ (CEMT class I) to the largest push barge formation that is allowed (CEMT class VIc). The composition of this diverse fleet has been developed since the 50s. The ships have become larger and the number of small ships has declined. Due to this development, the average capacity of the vessels is also increased over the years. Figure 13 shows this capacity development for the tanker fleet and dry cargo fleet separately. The figure shows the average vessel size by shipbuilding years. It can be observed that the average vessel size at this time is about 2,800 tonnes, while 600 tonnes was the average size in the sixties. (BVB, 2015)

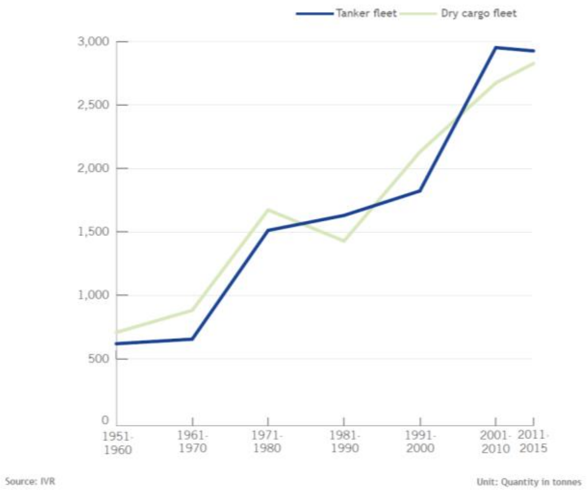


Figure 13: Average growth in tonnage of the Western European fleet (BVB, 2015).

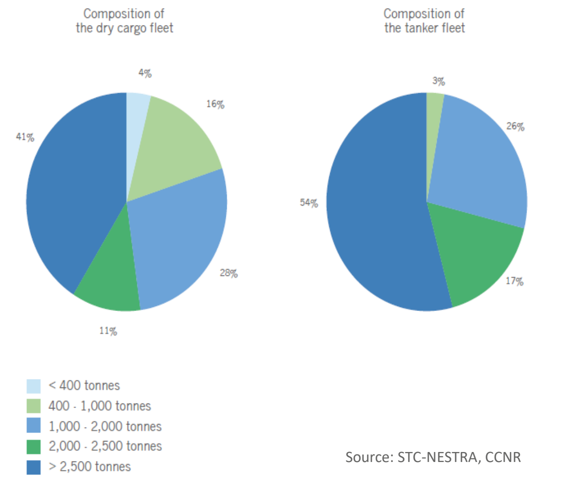


figure 14: Composition of the European inland shipping fleet in 2013 (BVB, 2015).

The composition of the fleet is important for many aspects that has to do with fairway management. Not only the number of ship passages but also the variety in the vessel size has to be taken into account. The composition of the European inland shipping fleet expressed in loading capacity is presented in two diagrams in figure 14. One diagram shows the dry cargo fleet and the other shows the tanker fleet. As can be observed in both diagrams, vessels with a capacity of more than 2,000 tonnes have the biggest share of the fleet. Especially tankers have a big loading capacity, while the dry cargo fleet shows more variety.

It is likely that the composition of the European inland shipping fleet corresponds to the fleet on the River Waal, because a big part of the transport over the River Waal is international transport. In 2013 there was an amount of 252 million tons of freight transported internationally by inland shipping for the Netherlands, while national transport by inland shipping in that year was about 104 million tons. (BVB, 2015). So, international transport by inland shipping was more than twice as large as national transport by inland shipping.

Rijkswaterstaat (2009) has published a lot of data concerning information about the number of vessel passages, vessel types and transported freight at several locations along fairways. For the River Waal, the counting point at Lobith is important, because a lot of ships that pass this counting point will travel further over the Waal. Only a small part will deflect towards the Pannerdensch Canal. This can be observed from table 2, which shows the number of passages measured by radar counting points for different locations along the River Waal. The location Millingen- Waal gives insight in the number of ships that is traveling over the River Waal. However, this counting system does not differentiate between freight transport and recreational. Data for only passages of freight transport by inland shipping is presented in table 3. This data is measured by the primary IVS-90 count point at Lobith. By making a short calculation it can be determined which part of the total passages at Lobith comes from- and goes to the River Waal. Namely, from table 2 the percentage of vessels at Lobith which passes Millingen- Waal as well can be calculated. The results of these calculations are shown in table 4. Taking the average percentages an assumption for the number of passages of only freight transport by inland shipping can be made. The calculation is done for all types of passages shown in table 3 and the results are shown in table 5.

table 2: Number of passages measured by radar count points for different locations along the River Waal.

Location	Direction	Number of passages in 2005	Number of passages in 2008	Development 2005 – 2008 (%)
Lent	E	66,613	60,723	-7,5
	W	78,121	62,723	-20,6
Lobith	E	71,611	62,260	-13,1
	W	97,816	68,558	-29,9
Millingen- Waal	E	65,982	58,810	-10,9
	W	78,105	62,012	-20,6
Oosterhout	E	67,620	65,474	-3,2
	W	84,941	72,707	-14,4

table 3: Number of passages and development to different type of passages at Lobith in 2008 (from Rijkswaterstaat, 2009)

Type of passage	Number of ship passages in 2008	Development 2005 – 2008 (%)
Total freight transport	124,081	74.8
- In East direction	66,402	78,7
- In West direction	58,016	71,9
- Loaded	88,033	-
- Unloaded	36,048	-
Dangerous freight transport	14,682	66,4

table 4: Part of the passages at Lobith that passes Millingen- Waal as well, calculated based on data from Rijkswaterstaat (2009)

	% of passages at Lobith that passes Millingen- Waal as well	
	In East direction	*In West direction*
2005	92,3	79,8
2006	94,9	88,3
2007	95,7	90,4
2008	94,5	90,5
Average	87,3	94,4
	90,9	

table 5: Number of ships passages at Millingen- Waal in 2008, calculated on basis of table 3 and table 4.

Type of passage	Number of ship passages at Millingen- Waal in 2008
Total freight transport	112,736
- In East direction	57,969
- In West directon	54,767
- Loaded	79,984
- Unloaded	32,752
Dangerous freight transport	13,340

The distribution of the ship sizes is shown in table 6. This table is completed by own calculations for the situation at Millingen- Waal and this can be observed in the last two columns.

table 6: Number of passages by cargo transporting ships to loading capacity class at Lobith in 2008 (from Rijkswaterstaat, 2009, completed by own calculations)

Load capacity class	Load capacity (tons)	Number of passages in 2008 at Lobith	Loading capacity (x1,000 tons)	Number of passages in 2008 at Millingen- Waal	Loading capacity (x1,000 tons)
1	21 – 250	225	26	205	24
2	250 - 400	1,057	384	961	349
3	400 – 650	6,325	3,475	5,749	3,159
4	650 – 1,000	12,888	10,551	11,715	9,591
5	1,000 – 1,500	27,861	33,644	25,326	30,582
6	1,500 – 2,000	19,610	31,347	1,783	28,494
7	2,000 – 3,000	27,049	64,388	24,588	58,529
8	3,000 and more	29,031	171,626	26,389	156,008

As has been said before, in 2013 inland shipping was responsible for 104 million ton national transport and 252 million ton international transport. Inland navigation can transport virtually all types of cargo, examples are metal ores, raw minerals, agricultural products and food. figure 15 shows a diagram with the shares of the products that are transported by inland shipping in Europe. This distribution is comparable to the situation in the Netherlands, because the Netherlands carries about two-third of the European tonnage.

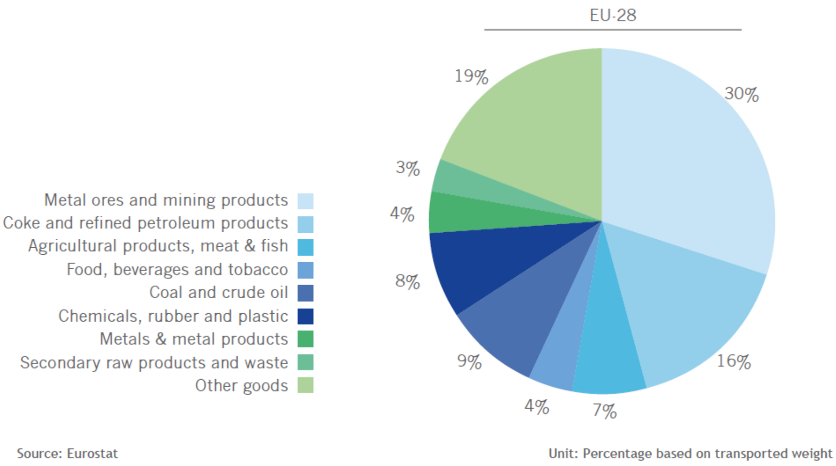


figure 15: Types of goods transported via inland shipping in 2013 (BVB, 2015)

4.4 Shipping costs

The price that has to be paid for transport by inland shipping depends on several factors. First, a distinction is made between the fixed costs and the variable costs for shipping. The fixed costs contain the cost of capital, insurance, loan and maintenance. Variable costs, also called operating costs, are fuel prices, port charges and harbour dues. In addition, the price for inland shipping will also be affected by supply and demand. Globally, it can be said that in periods of strong economic growth the prices are 30% higher and during a recession the prices are 30% lower. (Bureau Voorlichting Binnenvaart, 2016)

The freight rate is the price at which a certain cargo is delivered from one place to another. In this case, the price that has to be paid for inland shipping as discussed above. This price depends mainly on the type of cargo, the weight of the cargo, the distance, fuel prices, cost of capital and supply and demand. The type and weight of the cargo determines mainly what vessel type is needed for the transport and thus what kind of costs are associated with that vessel type. The distance and fuel prices together determine mainly what the cost price is for the vessel during the trip. Therefore, in periods of low fuel prices it is more attractive to transport by inland shipping. It can be observed in figure 16 that transport via inland navigation was more economical in 2014 than in 2013. This was due to a drop in fuel prices and cost of capital, which reduces the cost price of inland shipping. The effect of such fluctuations differs by type of vessel and type of cargo. (BVB, 2015).

figure 16: Cost price development index for inland shipping in the Netherlands (BVB, 2015).

Cost key figures of NEA (2008) give an indication of the costs for inland vessels. Sailing costs with- and without cargo, waiting costs and loading- and unloading costs are included. An overview of these costs figures is shown in Appendix VI: Cost figures 2008.

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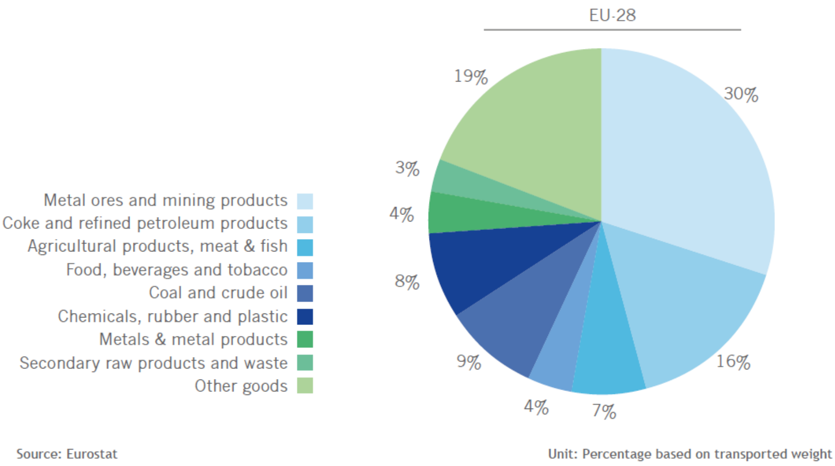

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Cost key figures of NEA (2008) give an indication of the costs for inland vessels. Sailing costs with- and without cargo, waiting costs and loading- and unloading costs are included. An overview of these costs figures is shown in Appendix VI: Cost figures 2008.

4.5 Developments

Since the end of the 20th century inland water container transport was upcoming. It has been developed during the years and in 2016 more than 25% of the total cargo throughput was by container transport. It is expected that the Second Maasvlakte leads to increasing container transport in the coming years. The Rotterdam Port Authority foresees a model split of 45% for inland waterway transport and this is 5% higher than in 2005. (Port of Rotterdam, n.d.[a])

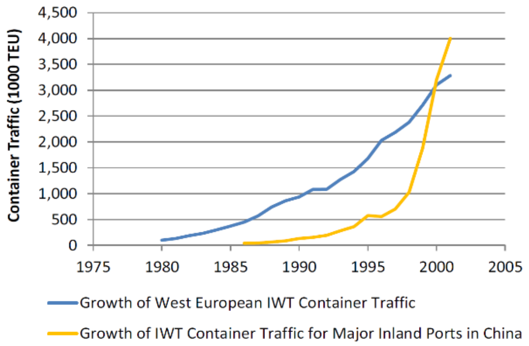


figure 17: IWT Container traffic development (van Dorsser, 2015)

The materials coal and iron ore have great influences on the amount of freight transport because the Port of Rotterdam is the port with the biggest throughput of these materials. Units with six pushed barges can transport 16.000 coal and iron ore daily (Port of Rotterdam, n.d.[b]) The use of these raw materials depends mainly on the economic welfare. However, due to climate change, there is a transition necessary to sustainable energy. Because this transition to sustainable energy is uncertain, also the use and therefore the transport of coal and iron ore is uncertain. A developing in the transport of these materials is expected, but what it exactly will be is doubtful.

Research to the inland fleet development of TNO (2010) shows the changes of the inland shipping fleet over the period 2000 – 2008 and the expected fleet development for the period 2008 – 2020. In table 7 and table 8 are the growth of load capacity for respectively the periods 1970 – 2000 and 2000 – 2008 shown. The average growth per year, expressed in percentages and tonnes, for classes IV, V and VI are shown. As can be observed, the average load capacity is increasing over the past years. For the period 1970 – 2000 this development is about 2,4% and for the period 2000 – 2008 it is about 2,7%. So, it can be concluded that there is scaling of inland vessels; the average loading capacity is increasing over time. However, the growth in loading capacity on fairway classes IV is much less compared to V and VI fairway classes, namely 0,8% per year. This means that there is stagnation of scaling at these fairway classes. This is an opposite trend compared to fairway classes V and VI. For these fairways, the scaling is stronger for the period 2000 – 20008 compared to the period before 2000.

CEMT class	*Average load capacity*		*Average growth per year %*	*Average growth per year [ton]*
	1970	**2000**		
IV	420	751	2,0	41
V	475	1091	2,8	77
VI	760	1597	2,5	105

table 7: Overview development load capcity for the period 1970 – 2000 (translated from TNO, 2010)

CEMT class	*Average load capacity*		*Average growth per year %*	*Average growth per year [ton]*
	2000	**2008**		
IV	751	797	0,8	6
V	1091	1477	3,9	48
VI	1597	2088	3,4	61

table 8: Overview development load capcity for the period 2000 – 2008 (translated from TNO, 2010)

table 7 and table 8 give information for the total inland shipping fleet on the concerned fairway classes. A more detailed overview of the different vessel types is included in Appendix I: Fleet development. Using these data, the following conclusions can be made for the total fleet development:

- There is a strong growth in units with six pushed barges;
- In the category barge combinations, there is a strong growth in class C3I and C4;
- In the category motor vessels, there is a strong development, namely:
  - The number of ships of class M0 to M7 has been decreased
  - The number of ships of class M8 to M10 has been increased

So, especially for motor vessels there is a very high degree of scaling. For the fleet on VI fairway classes, a similar development can be observed.

Based on data of 1970-2008 a trend can be determined concerning the growth of the average loading capacity. This trend can be extrapolated to the year 2020 to obtain an expectation of the fleet development. Two variants have been developed, one has taken into account the year to year development and one is based on the average annual growth of the period 1970 – 2000 that, subsequently, is applied to the period 2008 – 2020. The choice for developing two variants has to do with the relative huge number of new vessels in the period 2000 – 2008 and this might not be representative for the whole period. The development of both variants is shown in figure 18. The first variant leads to a relative high growth and the second one to a lower development. It must be noted that this is only a technical trend analysis whereby no other future developments are taken into account. The expected growth of the average load capacity for fairway class IV, V and VI is included in table 9.

table 9: Expected fleet development to the year 2020 (translated from http://www.informatie.binnenvaart.nl/ algemeen /de-binnenvaart/68-schaalvergroting-binnenvaart, retrieved on 24-01-2017, completed with extra data)

CEMT-class	2020 [ton]	Growth [ton/year]	Lower bound 2020 [%/ year]	Upper bound 2020 [% / year]
IV	1552 – 1857	0 – 10	1,5	3,0
V	1868 – 2271	25 – 45	1,5	3,2
VI	2662 - 3108	30 - 55	1,50	2,9

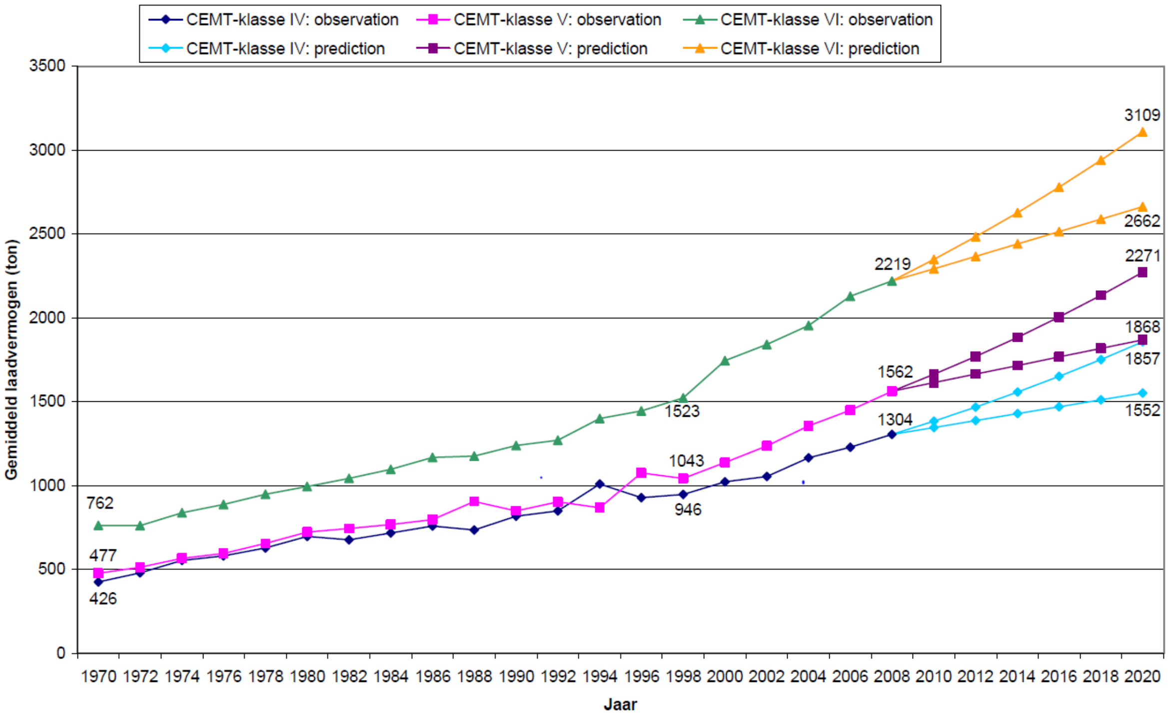


figure 18: Trend analysis of the average loading capacity per fairway class (TNO, 2010)

4.6 Conclusion

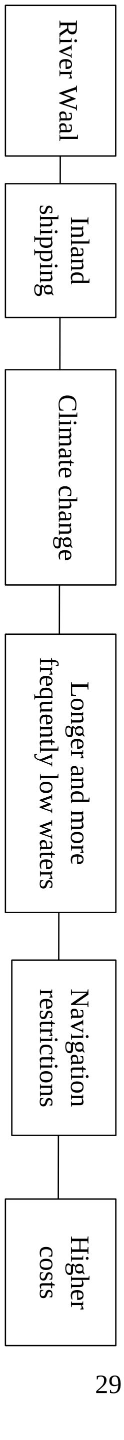
The River Waal is the main connection between the Port of Rotterdam and the hinterland. It is a VIc fairway class which means that units with six pushed barges are allowed. The diversity of the fleet is big, which means that there are a lot of different vessel sizes and types. The fleet has developed during the years and the overall trend is an increase in loading capacity. This so- called scaling of the fleet is still ongoing and therefore it influences the fleet characteristics. IVS-90 counting points are at several locations and give values for the number of vessels that has passed that specific location. This data gives insight in the number of vessels that sail on a certain fairway. It is determined that about 90% of the vessels that sail the River Rhine at Lobith goes into the direction of the River Waal. Furthermore, about 70% of the total vessels is loaded and 30% unloaded. The information included in this chapter will be used for determining the boundary conditions and assumptions of this study. These relevant aspects of climate change and Waal canalization are discussed in the next chapter.

5 Relevant aspects of climate change and Waal Canalization

5.1 Introduction

Each project has effect on, or will be affect by many aspects. It is not possible to take all these aspects into account and therefore assumptions and boundary conditions are made. A good description of the project will be created by distinctive boundary conditions and assumptions. In this chapter the scope of the project will be discussed and thereafter the assumptions are described. A schematic overview of the project description and boundaries are shown in figure 19.

5.2 Project boundaries



The River Waal has a total length of approximately 85 kilometres between Lobith and Woudrichem (Rijkswaterstaat, 2017). The river has many functions and influences on the environment. The main issues are flood protection, water supply and transport by water. As has been said before, climate change is affecting these 'functions' and to fulfil the requirements measures have to be taken.

Because there are many different functions of the River Waal, not all can be considered. In this study the focus is on the transport function and more specific the effects of climate change on inland shipping. It is important to keep in mind that climate change is not only affecting inland shipping, but it can also have a big effect on other functions. From this point on, only aspects that have to do with the effects of climate change on the inland shipping sector will be discussed.

The more extreme weather conditions have influence on the discharge and water levels in the river. Extreme circumstances will occur longer and more frequently and this has a negative effect on the navigability of the River Waal. On one hand, extremely high water levels will occur more frequently and on the other hand extremely low waters will take place for longer periods and more frequently. The problems for the inland shipping sector are much more severe in case of low discharges. Therefore, in this study the focus is on the effects of low discharges and water levels due to climate change.

Longer and more frequent low water periods cause a worse navigability of the river Waal for inland shipping. Consequences of low water levels are restrictions in loading capacity, alternative routes or trips that cannot be executed. To transport the same amount of freight over water more ships are needed. In case of alternative routes, the vessel has a larger travel time compared to the optimal route. Therefore, the cost price per tonnage transported by inland shipping is increasing in periods of low water. These effects make that inland shipping becomes less reliable and potentially unattractive. The change in demand depends partly on the price elasticity. According to Jonkeren et al. (2009) the price elasticity of demand for inland waterway transport is -0.5. This means that the demand on waterway transport is inelastic and the demand remains virtually unchanged in case of a price change. However, the reliability of inland shipping is not considered in this price elasticity. It might be possible that modal shift to other transport modes, such as road and rail, takes place. Then the question arises whether there is sufficient capacity to take over transport from inland shipping. But on the other side, is there enough capacity in the inland shipping sector as more ships are needed for the same amount of freight? It is not easy to answer such a question without doing any well-funded research. This research is a comparison study and in case of canalization there are negative effects for the inland shipping sector. For example, image damage because the resistance increases compared to a free-flowing river and therefore longer travel times of ships. For these reasons, the effects of reliability, price- elasticity, image damage and modal shifts are not considered.

Canalization of the River Waal causes many external effects on the environment. An example is the morphology of the river itself. Due to the construction of locks and weirs the transport of sediment may change. Another consequence of canalization is the increasing water level at several locations, which influences the ground water level. Besides, there are many more external issues that must be considered, such as stakeholders or the ecology of the environment. All these 'external issues' are out of the scope of this project, because only the effect on the inland shipping sector is considered.

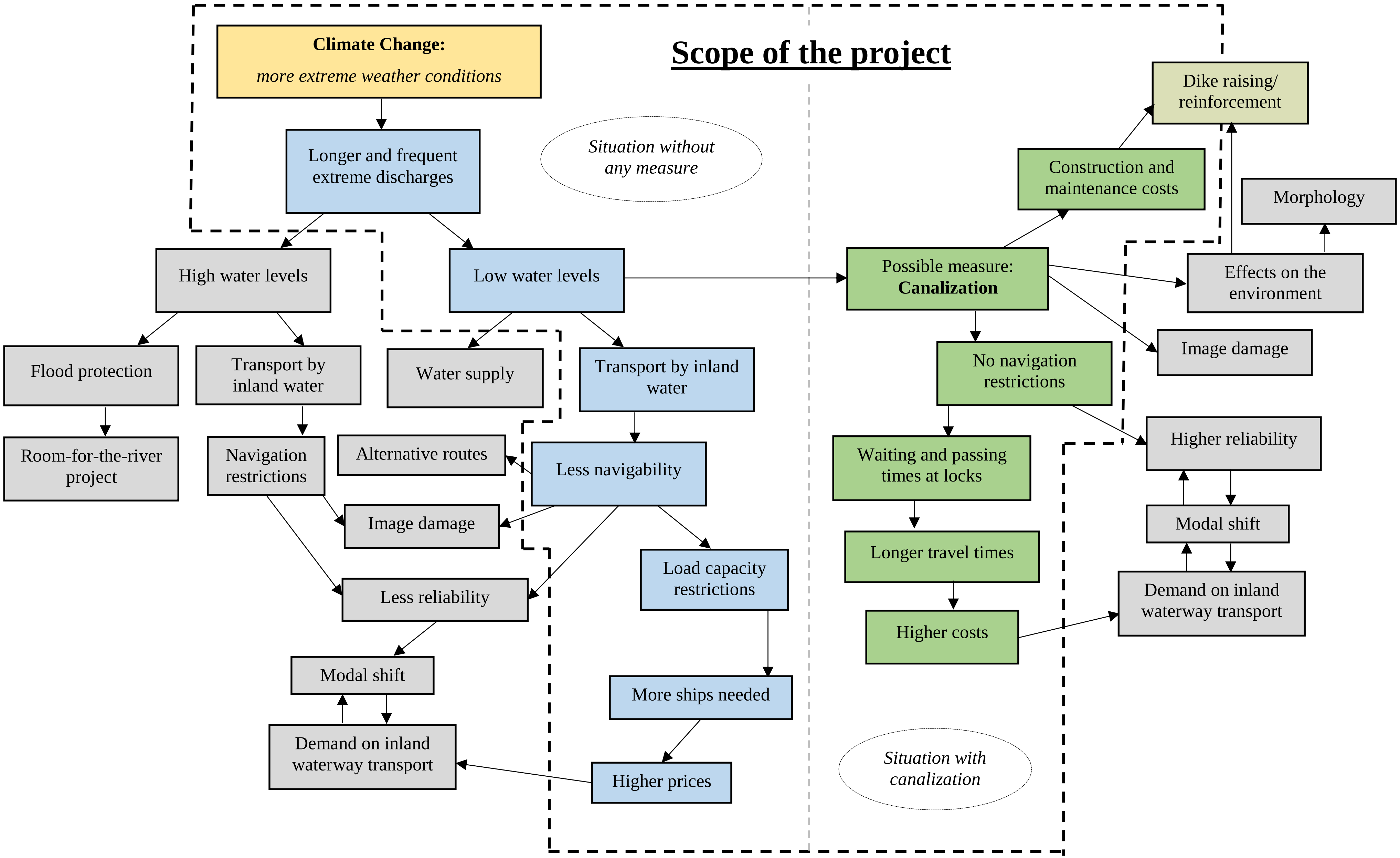


figure 19: Schematic overview of the project boundaries

5.3 Assumptions

Because some aspects in the real world are too complicated, these cannot be taken into account directly and have to be simplified by making some assumptions. The assumptions made for this research project are described in this paragraph.

Inland shipping sector

In this research the effects, expressed in costs, of climate change on the inland shipping sector will be investigated. The whole shipping sector represents all private companies and public organisations that are related to inland shipping, such as shippers of freight, carriers, port operators, freight handling terminals and clients receiving freight. It is not researched in detail what the consequences are for each company and organisation individually, but to the sector as a whole. Because, it is difficult to identify who pays for the extra costs. Therefore, the result of this study is an overview of the costs for the total inland shipping sector.

Geographical area

The focus of this study is on the inland navigation on the River Waal. The River Waal is part of the corridor between the Port of Rotterdam and the hinterland. So, the main traffic route over the Waal is between Rotterdam and Germany. Therefore, the geographical area that is considered is the physical river system from the German border (rkm 860) to the port of Rotterdam (rkm 1000).

Subsidence of the river bed

The bed of the River Waal and the River Rhine has been lowering over the past century. This has to do with the dredging activities and normalisation structures in the river. On average, the bottom subsidence is around one to three centimetres per year. This speed is decreasing, because the authorities take measures to stop the subsidence of the river bed. At places where fixed layers are located the bottom is not lowering and barriers arise in the fairway. These barriers are obstructive for inland shipping (Liefveld & Postma, 2007). In this study, it is assumed that the measures for reducing the subsidence are successful and the bed subsidence stops. Therefore, the data that describes the bottom level of the River Waal (Blom, n.d.) will be used for future situations. So, in this study it is assumed that the bottom of the River Waal has not changed in the past years and will remain the same for this century.

Navigable bottleneck

For the River Waal, there are two normative fixed layers, one at St. Andries and the other at Nijmegen. According to Sloff et. al. (2014) the fixed layer at Nijmegen (rkm 883 – rkm 885) is the most critical point of the River Waal with regards to the navigable depth. However, the River Waal is part of the River Rhine which is the biggest shipping route from Rotterdam to the hinterland. Therefore, this study should look beyond just the River Waal. The Rhine across the border should also be considered when it comes to the normative navigation depth. According to van Dorsser (2015) the critical sections on the Rhine are located near Lobith and near Kaub. For the stretch between Rotterdam and Ruhrort the critical point is near Lobith. For shipments further upstream the Rhine (at the upper Rhine), the critical point is near Kaub (rkm 546). Because, Duisburg is the biggest inland port of Europe (Duits Nederlandse Handelskamer. n.d.), most inland vessels make use of the section between Rotterdam and Duisburg. Furthermore, Kaub is located very far upstream of the River Rhine and therefore a very small part will pass Kaub and make use of the River Waal. Taking these two aspects into account, it can be concluded that the biggest part of the inland vessels that sails over the River Waal experience a navigational bottleneck at Lobith. Therefore, possible critical points across the border are not taken into account but only the navigational bottlenecks at the River Waal are considered.

Developments

The lifetime of a civil structure is about 100 years. Therefore, it is important to gain information about the future situation to make proper calculations, designs and decisions. However, it is not easy to foresee future developments. For this study, three developments are important, namely climate change, economic growth and the future fleet composition. These three variables together tell what the real problem will be when it comes to the navigability of the River Waal. The future fleet composition depends on several developments, for example the transition to sustainable energy, containerization and the use of push barges. These developments are very unsure and hard to quantify. Therefore, the current trend of scaling is the only development that is taken into account for the characteristics of the future fleet and it is assumed that the composition of the fleet will not change in the future.

Climate scenario

The most recent climate scenarios for the Netherlands are the KNMI'14 scenarios G_H, W_H, G_L and W_L. In addition, Deltares has designed scenarios specifically for the Rhine basins that corresponds to the KNMI'14 scenarios to develop discharge rates for the river basin (Sperna Weiand et.al, 2015). Because of the dry KNMI'14 scenario W_H did not appear to be dry enough for the Rhine basin an additional scenario was constructed denoted as $W_{H,dry}$. This scenario is particularly relevant to determine the ranges of change in seasonal mean discharge and in low discharges. The four original discharges are relevant for changes in high discharge.

Because this study is focusses on the effects of low water, the worst scenario in terms of dry periods and thus low discharges must be taken into account. Therefore, the $W_{H,dry}$ scenario that has been developed by Deltares will be used in this study to determine the worst effects on the inland shipping sector. Furthermore, it is valuable to get insight in the consequences for the inland shipping sector in a moderate climate change scenario. Hence, including more than one climate scenario gives a range of possible effects. Therefore, all five climate scenarios $W_{H,dry}$, W_H, G_H, G_L and W_L are considered in this study.

Sea level rise

Near the Dutch coast the sea level is rising and it is expected that this will continue under climate change. Because, the River Waal experiences tide of the North Sea, also the sea level rise may have an influence on the system. Up to the place Zaltbommel the tide influence is experienced. At this location, a tidal range of approximately 10 cm is measured. Due to the higher sea level, the influence of the tide will become larger in the future. Seawater can penetrate further into the river. This has not only an effect on the water level but also on the quality of the water in the river, because salt water intrusion takes place. Because the focus in this research is on the effects on inland shipping such ecological effects are not taken into account. This does not mean that it is not important and the consequences do not have be investigated, but this will not be done within this study. However, sea level rise may have an effect on the water level in the lower part of the River Waal, but it is expected that this does not significantly influence the water level far upstream. Therefore, it is assumed that sea level rise will not influence the water level of the River Waal and thus it is not considered in this study.

Economic scenario

The CPB and PBL (2015a) have designed two reference scenarios (called: WLO scenarios) for the demographic and economic development: High and Low. Scenario High is combining a high economic growth of 2 percent per year with a relative strong population growth. In scenario, Low, there is a moderate economic growth of 1 percent per year and a limited demographic development. The WLO scenarios are policy- neutral completed and therefore they give insight in future bottlenecks and opportunities. To gain a complete range of possible outcomes, both scenarios are taken into account. So WLO High results in the upper bound and WLO Low in the lower bound of possible effects.

Time horizon

Climate is defined as the average weather over a period of 30 years. Therefore, when talking about climate change the effects will be noticeable over a period of 50 to 100 years. In addition, the life time of a civil structure is about 100 years. Climate scenarios are developed until 2085, while the economic (WLO) scenarios do only make a forecast to the year 2050. To gain valuable results, a time horizon has to be stretch to 2085 at least. Therefore, it is decided that the consequences for inland shipping at two time horizons will be investigated, namely around 2050 and around 2085.

5.4 Research methodology

The consequences of two situations are investigated and compared with each other. One situation without any measure and one with canalization. These two situations are compared with a zero variant where no navigation restrictions occur and therefore a so- called reference situation is also investigated.

The scenarios that are used in this study are:

- Climate scenarios
  - $W_{H,dry}$
  - W_H
  - W_L
  - G_H
  - G_L
- Economic scenarios
  - WLO High: Upper bound
  - WLO Low: Lower bound

Combining these scenarios leads to a number of outcomes, which are all investigated. A scheme of the possible combinations is given in figure 20.

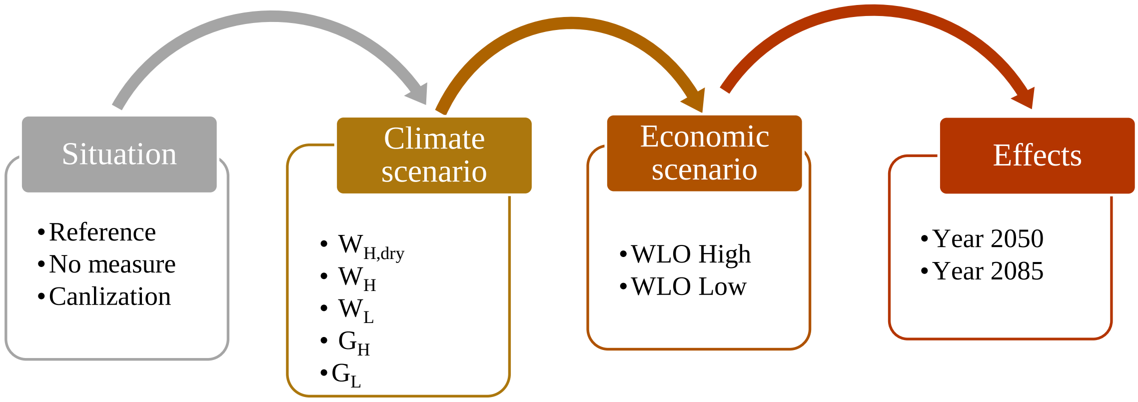


figure 20: All possible combinations of situations and scenarios

Now, a global overview of the different situations and scenarios is given. Using this information, a more detailed approach is given of how the answers on the main- and sub- questions are found. First, the literature research will be discussed shortly, followed by the developing of an effect model and the two considered situations.

Literature research

During the literature study, all information that is needed to analyse the different situations and scenarios are obtained. The first sub question is answered by doing literature research, because there are several studies and data available that can be used. Information that is necessary to get insight in, is summed up below:

- Climate scenarios to determine future weather conditions;
- Statistics of discharges and water levels in 2050 and 2085;
- Expected amount of cargo transported by shipping over the River Waal in 2050 and 2085;
- Characteristics and development of inland waterway fleet;
- Theory on lock capacity, cycle and design;
- Theory on functioning of weirs;
- Data about inland shipping costs prices;
- Information about the model SOBEK

Developing of an 'Effect model'

To investigate the consequences of the several developments (climate, economy and fleet) on the inland shipping sector for the two different situations with navigation limitations, a so called 'effect model' is developed. This model is computing the total shipping costs and extra shipping costs in a defined situation with certain scenarios. Comparing the outcomes of the two different situations gives insight in the relative costs of canalization and therefore canalization as measure to improve the navigability of the River Waal can be rated.

Another possible option for analysing the traffic on the inland waterway network was using BIVAS. The BIVAS model (in Dutch: Binnenvaart Analyse Systeem) is an application to analyse assignments about the inland water transport network. It is developed by Rijkswaterstaat. The model is mainly used to analyse the traffic on the inland waterways network, to analyse the impact of obstructions in the network and to make analyses of long term future scenarios of inland waterway transport. Because the same input is used for comparing two different situations, it is required to understand what the model is doing. BIVAS is a complex model and therefore a sort of black box. In addition, applying this model requires a lot of time. However, this study is a comparison study and therefore it is not necessarily to use an advanced model. So, it is decided not to use this model for this study, but create an effect model that is insightful.

A global description of the effect model is given here. First, the model input is presented, followed by the calculations of the model and finally the output is described shortly. For more details of the model set up a reference is made to chapter 6.

As has been assumed in paragraph 5.3, three developments are considered in this study and therefore these variables must be translated to input for the effect model. To do so, there are three sub models developed that generate the required input. These are the so- called climate model, fleet model and economic model corresponding to the considered developments. The output of these models can be directly used as input for the effect model and these are as follows:

- The normative depth each day during a year;
- The characteristics of a normative vessel;
- Total freight transported by inland shipping.

Using this information, the effect model is calculating the load factor for each day and this results in the required number of loaded trips per year for transporting the amount of cargo. Subsequently, the total shipping costs in case of navigation restrictions can be calculated and is given as output of the model. Comparing these shipping costs with the total shipping costs of the reference situation, the (extra) shipping costs due to navigation restrictions can be computed. An overview of this model is shown in the figure 21

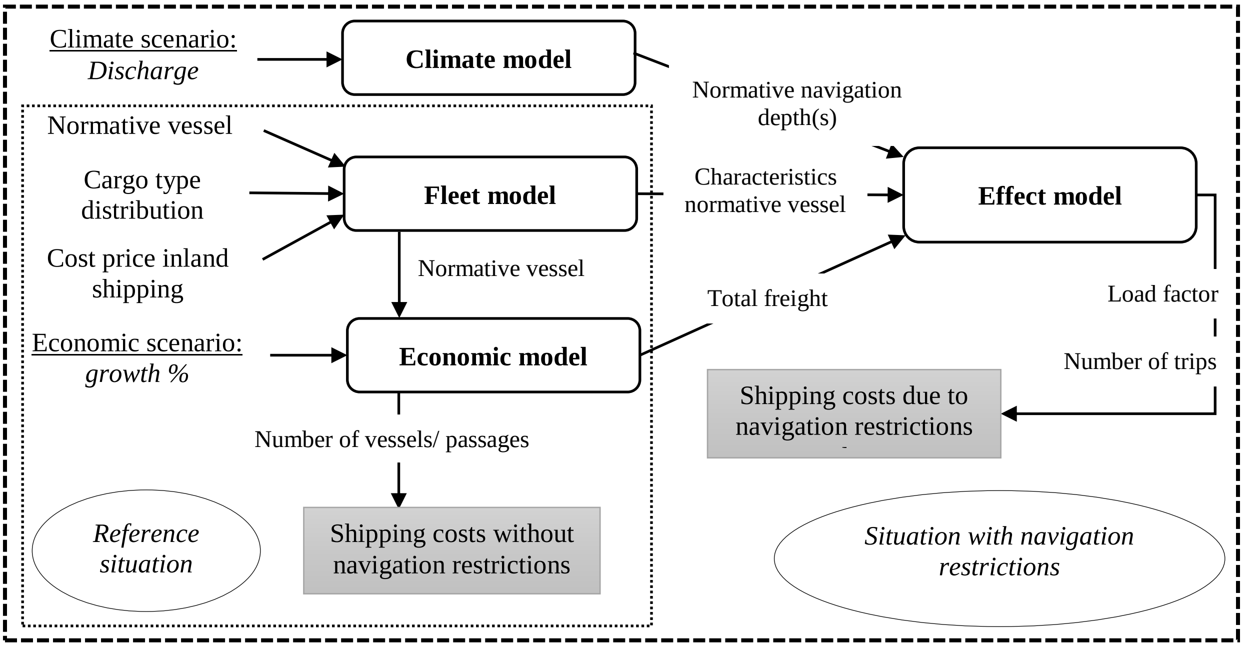


figure 21: Overview of the model systematics

Before using the model to compute results, the reliability of the output of the model has been checked. This is done by using the model to calculate the shipping costs for the year 2003. The year 2003 was a very dry year and data about the damage costs in that year could be found in the literature making it possible to validate the effect model using this information.

Literature (Jonkeren et al., December 2010) has also shown that the yearly discharge distribution of 2003 will be annual around 2050. Therefore, this distribution, in combination with a high economic scenario, is used for a first analysis of the possible effects on the inland shipping sector due to canalization. For this analysis, the effect model is used to compute the shipping costs in the reference situation and in the situation without measure. For the shipping costs in case of canalization, there is more research necessary to obtain these results. The approach for computing the costs in case of canalization will be discussed further under the heading *situation with canalization*.

Now, the three different situations will be described in more detail.

Reference situation

As previously mentioned, the reference situation is the situation where no navigation restrictions occur. This means that the required number of loaded vessels is minimal and therefore also the total shipping costs. The reference situation gives insight in the size of the extra shipping costs due to navigation restrictions. The extra shipping costs can be expressed in the percentage of the total shipping costs without any restriction and this creates a clear view of how large the damage costs really are.

Situation without any measure

The main goal of the situation without any measure is to investigate the costs for inland shipping due to climate change. Therefore, the navigability and thus the water level are important. A lot of information and data that is used in this analysis is gained during the literature research. The five different climate scenarios and two different economic scenarios as have been summed up before are investigated. This gives a complete overview of the possible consequences (costs) for the inland shipping sector in the future situation when no measure is taken.

Several boundary conditions and assumptions have been made for scoping the project. Further, the water levels corresponding to the climate scenarios are computed by using the climate model and the model SOBEK. Besides, a normative vessel is determined, which represents the total shipping fleet. At the end, the shipping costs due to navigation restrictions are computed by the effect model. An overview of the different components is given in table 10.

Situation without any measure		
What to obtain	*How to obtain*	*What do we need*
Normative water depths	Climate model / SOBEK	- Discharge statistics - Measured data about water levels and discharges - Bottlenecks on the shipping route - Characteristics of the River Waal
Normative vessel	Existing research / data / analytical calculations	- Loading capacity - Draught - Cost prices inland shipping
Shipping costs	Effect model	- Navigation criteria

table 10: Important components of the situations without any measure

Situation with canalization

The main goal of this situation is to investigate the shipping costs in case of canalization of the River Waal. This canalization can be executed in many ways. Therefore, an optimal option is investigated, which means that the total costs due to canalization are minimal. This optimal way of canalization is used for the scenario analysis.

The optimization of the canalization is fully determined by the number and the dimensions of the lock- and weir-complexes. Several aspects influence this optimal 'design'; namely the WLC costs, the navigability of the river and the delay time of ships due to the locking process.

The effect of the weirs on the water level in the river is calculated by a backwater curve calculation. Because there is a sudden interruption of the flow, the water level upstream of the weir is not parallel to the bottom but has a more curved shape in upstream direction. This curved shape depends on certain variables, such as the water depth far upstream of the weir, the downstream water depth and the head over the structure. For a detailed description of this backwater curve calculation a reference is made to chapter 8.

Due to the WLCs in the River Waal, the resistance of the waterway is higher compared to the situation of a free-flowing river. This is only the case when the weirs are closed and the vessels have to use the locks in order to pass the complex. Otherwise, the vessels can sail through the weir and there is no additional travel time. The number of weirs, the number of days the weir is closed and the locking time influences the delay time for inland shipping.

To obtain the most optimal option for canalization, the relation between the aspects described above are investigated. In figure 22 a diagram is included to show a qualitative relation between these aspects. The shipping costs in case of canalization are determined by the effect of the head on the navigation depth for a certain number of WLCs.

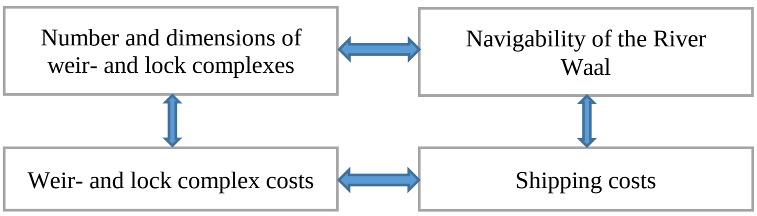


figure 22: Relation between the number and dimensions of complexes and navigability of the River Waal

An overview of the different components that have been discussed above is given in table 11.

Situation with canalization		
What to obtain	*How to obtain*	*What do we need*
Water levels due to the construction weirs	Backwater curve calculation	- Discharge statistics - Characteristics of the River Waal
Delay time	Analytical calculation	*Network* - Number of WLCs - Water level statistics: % per year that weirs are closed *Ships* - Characteristics of the normative vessel: draught and cost prices
WLC costs	- Reference projects - Costs estimate formulas	- Number of WLCs - Dimensions WLCs
Optimal number and dimension(s) of complex(es)	Total costs due to canalization	- Shipping costs: Due to navigation restrictions and due to delay - WLC costs: Construction costs, mitigating costs, operational costs and maintenance costs

table 11: Important components of the situation with canalization

Scenario analysis

In this analysis, the consequences on the inland shipping sector for the years 2050 and 2085 are computed. The scenario analysis uses the effect model that is adapted to give the costs due to the optimal way of canalization. Applying the different climate- and economic scenarios has led to an overview of the possible effects on the inland shipping sector for the two different time horizons. This overview looks like table 12. As can be observed from this table, there are several possible outcomes. In case of canalization, only the most optimal way to canalize the River Waal, which is based on the discharge distribution of 2003 and the high economic scenario for 2050, is used in the analysis to the consequences of the future situation. Therefore, the WLC costs for all different scenarios are the same. All the outcomes together span a range of possibilities and therefore it is a kind of future expectation of what will happen under several circumstances. A lower and upper bound of the expected values will be determined and these form the boundaries of the possible outcomes.

***Time horizon:* [year]**		**No measure**	**Canalization**			
Climate scenario	*Economic scenario*	*Extra shipping costs*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
G_H	Low	€	€	€		€
	High	€	€	€		€
W_L	Low	€	€	€		€
	High	€	€	€		€
$W_{H,dry}$	Low	€	€	€	€	€
	High	€	€	€		€
G_L	Low	€	€	€		€
	High	€	€	€		€
W_H	Low	€	€	€		€
	High	€	€	€		€

table 12: Overview of costs for different scenarios

5.5 Conclusion

This chapter has discussed the relevant aspects of climate change and Waal canalization which has resulted in distinct boundary conditions and assumptions followed by the research methodology. These form the basis of the research to the effect of climate change and Waal canalization on the inland shipping sector. The conclusions that can be drawn are described in this paragraph and will be used during this research.

This research is about the effects on the inland shipping sector of low discharges in the River Waal caused by climate change. Two different situations are investigated, one without any measure and one with canalization of the river. The focus is on the direct costs for the inland shipping sector due to navigation restrictions caused by insufficient water depth and canalization, other external effects are not considered in this comparison study.

The geographical area that is taken into account is the physical river system from the German border (rkm 860) to the port of Rotterdam (rkm 1000). It assumed that the bottom of the River Waal remains the same for this century. The fixed layer at Nijmegen (rkm 883 – rkm 885) is the most critical point of the River Waal with regards to the navigable depth. For the stretch between Rotterdam and Ruhrort the critical point is near Lobith.

The important developments for this research are climate change, economic growth and the future fleet composition. Various possible future situations are considered by taking different scenarios into account. For climate, these are the $W_{H,dry}$, W_H, G_H, G_L and W_L scenarios. For economic growth, the WLO scenarios will be used. For the characteristics of the future fleet only scaling will be considered and the composition is equal to the current fleet. The consequences for inland shipping are investigated for two time horizons, namely at the years 2050 and 2085.

The effect model is used to investigate the consequences of the several climatic- and economic scenarios on the inland shipping sector in case of two different situations, one with canalization and one without measure. Comparing the outcomes of the two different situations, it can be seen whether canalization is a plausible measure to improve the navigability of the River Waal.

6 Developing of the “Effect model”

6.1 Introduction

The effect model gives insight into the consequences for inland shipping under certain circumstances. The model will be used to investigate the consequences for inland shipping due to climate change and due to canalization. The consequences are expressed in costs and this has a major impact on the model operation. All assumptions and conditions are aimed at expressing the results in costs. A detailed description of the development of the Effect model is included in this chapter. At the end of this chapter, the effect model is not a black box anymore, but a distinct model that gives insight in the calculations and therefore in the results. A distinct model is required for making a good analysis of the consequences for the inland shipping sector. To calculate the total shipping costs, several knowledge and data is needed. A general description of this information is given in figure 23 and a more detailed discussion is included in the next paragraphs. At the end of this chapter sub question 1 is answered. Therefore, all information is available to obtain results for the sub questions 2 and 3.

There are several aspects that are characteristic for inland shipping and which are important for this research. First, the shipping fleet and their characteristics must be known. Information about this topic is already given in chapter 4 “*Inland shipping in the Netherlands”*. The shipping fleet is partly dependent on the different cargo types that have to be transported and this in turn affects the cost prices of inland shipping. In addition, the trip duration of a vessel, waiting times and the loading and unloading processes will affect the total costs of freight transport by inland shipping. Using all this information, the ship’s characteristics that are representative for, for example a certain shipping route, can be computed. This so- called normative vessel can be used for calculating the required number of loaded trips for transporting a certain amount of freight. However, in case of navigation restrictions the navigable depth must be known to calculate the amount of freight that can be transported during a trip. Taking all this information into account, the load factor, and therefore the shipping costs can be determined. To reproduce this clearly, figure 23 contains an overview.

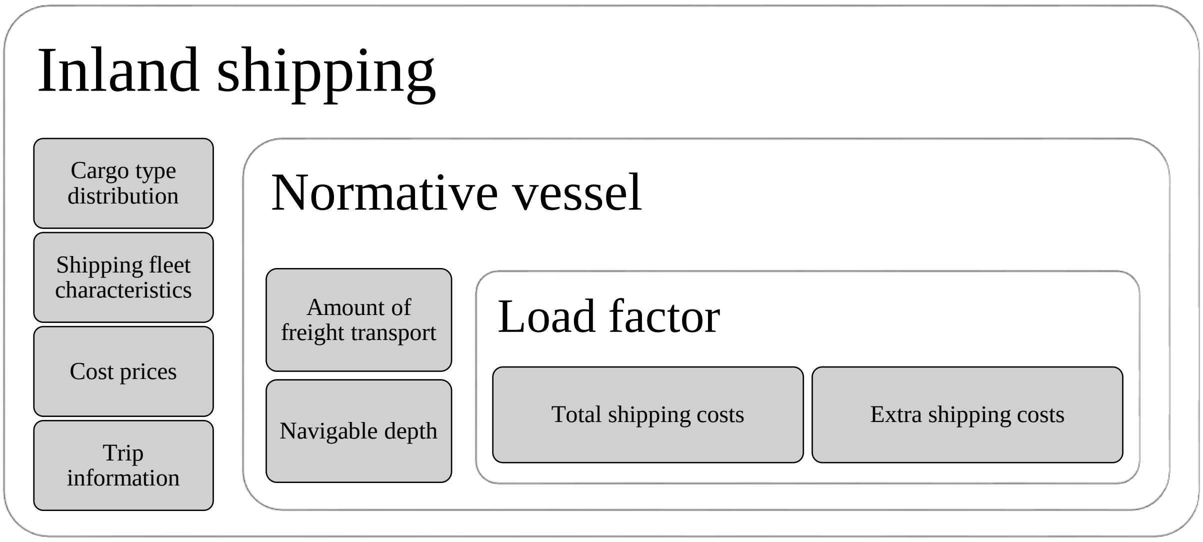


figure 23: Overview of the aspects of inland shipping that are considered for the Effect model

Now, the assumptions made for developing the effect model are described.

6.2 Assumptions

To schematize the real world, several assumptions are made. These assumptions are discussed in this paragraph. The structure used in figure 23 is taken as a starting point for this paragraph. Therefore, the assumptions with respect to inland shipping are described first. Thereafter, the assumptions required for calculating the shipping costs are discussed.

Cost price figures

There are two different sources that give cost price key figures for inland shipping. The first one is a report called "kostenkengetallen binnenvaart 2008" (NEA, 2009). The costs of freight transport by inland shipping are completely described in this report. For each type of inland vessel, according to the classification of DVS[1], an overview of the costs per unit (per ton, per hour or per kilometre) is included. The second source is a tool from Rijkswaterstaat (2014) that gives cost figures for several types of ships and cargo combinations. Both sources are used in this research.

Trip information

According to the information in chapter 4, the main shipping route is from Rotterdam to Duisburg. This is a distance of approximately 220 kilometres. The trip duration depends on the average vessel speed and the resistance of the fairway. According to NEA (2008) the average vessel speed on this route is about 16 km/hr and this leads to an average trip duration of 14 hours. It is possible that certain developments will influence this average speed, such as changing vessel characteristics, change in resistance of the fairway or other external effects. Because there is no information available about the expectation whether this average speed will change due to certain developments, it is assumed that for every time horizon the average trip duration is equal to 14 hours.

In case of canalization, ships experience extra travel time due to the passing of locks. The passing time of locks is estimated on basis of data by Molenaar et al. (2010) and assumed to be 1 hour. This passing time and thus extra travel time is considered by defining this time as waiting time. The cost of waiting time can be calculated easily by the cost price figures.

Loading and unloading processes are not included in the trip duration, but calculated separately. Because vessels are not always immediately start with the loading or unloading of cargo, extra waiting time is considered.

Cargo type distribution

From the information in Appendix VI: Cost figures 2008, it is known that the cost key figures are only given for the following cargo types: liquid bulk, dry bulk and containers. The cargo type distribution that is shown in Appendix VI: Cargo type distribution consists of four types of cargo. These types are liquid bulk, dry bulk, containers and general cargo. Because both sources of cost key figures do only include information about dry bulk, liquid bulk and container transport and in addition, general cargo transport is very small compared to the other types of cargo, it is assumed that all transport by inland shipping consists of liquid bulk-, dry bulk- and container transport. The distribution of the cargo type is assumed as follows.

Liquid bulk – 50%

Dry bulk – 25%

Container – 25%

Shipping fleet characteristics

There are two different time horizons investigated in this research, namely the years 2050 and 2085. In addition, for the validation of the effect model, data of the year 2003 is used. Because there is no reliable data about the (expected) shipping fleet in 2085, only two different shipping fleet characteristics are used in this study. These are an expected fleet for 2050 and the shipping fleet of 2003. For the future shipping fleet characteristics, data of the studies by Rijkswaterstaat from 2007 and 2013 is used. For the shipping fleet of 2003, data of the CBS (in Dutch: Centraal Bureau voor de Statistiek) is used.

It is important to know the rate between the loaded and unloaded vessels. Unloaded vessels do not experience any trouble of smaller water depths, but these vessels must be taken into account for the calculation of the total shipping costs. It is assumed that 70% of all trips are loaded trips and thus 30% are unloaded trips.
Vessels are not always fully loaded due to several reasons, for example due to the weight of the cargo that is transported, supply and demand or navigation limitations. According to Jonkeren et al. (December 2010) the normal (or average loading) factor is about 84% and this value is used in this research.

Because there is a IVS-90 count point at Lobith, a lot of data is available for this location. However, the River Rhine split into the River Waal and the River IJssel and therefore this data cannot be used directly for the River Waal. According to data from Rijkswaterstaat (2009) and further calculations it is determined that about 90% of

[1] In Dutch: Dienst Verkeer en Scheepvaart, "Service traffic and shipping", part of Rijkswaterstaat

vessels passing Lobith are sailing over the River Waal. It is assumed that this value will not change and therefore it is also valid for future time horizons.

Freight transport

The data on freight transport by inland shipping for the year 2003 is obtained by CBS (December 2009) and the total freight transport that have passed Lobith was equal to 136,621,000 ton. However, the River Rhine split into the River Waal and the River IJssel and therefore not all freight transport will take place over the River Waal. This must be taken into account when calculating the amount of freight that is transported over the River Waal.
The data of the WLO scenarios is used for the year 2050. However, this data is on transport by inland shipping in the Netherlands and therefore it cannot be used directly for the route Rotterdam – Duisburg. Looking at the amount of freight that has passed Lobith, an estimate can be made for the part of national transport that takes place over the River Rhine. According to data from 2012 of BVB (2016) and Rijkswaterstaat (2013) 47% of national freight transport has passed Lobith. It is assumed that this distribution will not change and therefore it is also valid for future time horizons.

For the year 2085 there are no economic scenarios developed by the WLO. In addition, it is very hard to make a proper estimate of freight transport on the long term because there are many uncertainties and unknown developments. For this reasons it is decided to freeze the economic scenarios of 2050, so that these scenarios remain the same for the year 2085.

Navigable depth

For the year 2003 measured data of the water level (see Appendix VI: Climate model validation) is used to determine the water depth. The water depth near Nijmegen is assumed to be normative and therefore at this location the navigable water depth is computed. The water depth is computed by subtracting the bottom level from the water level (both with respect to NAP). According to Blom (n.d.) the bottom level at Nijmegen is assumed to be +2.5 m NAP. The navigable depth is defined as the water depth minus a certain safety margin, which is set at 0.3 m.

Research by Deltares (2015) has resulted in discharge projections for the River Rhine. These projections are based on the KNMI'14 scenarios and the CMIP5. Data from the period 1951 – 2006 is used to simulate the discharge projections in 2050 and 2085 for the different climate scenarios. These discharge projections are considered to determine the water depth in the River Waal and subsequently the navigability of the River Waal under certain climate conditions.

Load factor

It is assumed that the relation between the water depth and the load factor is linear. Taking into account the unloaded draught of the vessel, a schematic overview of this relation is shown in figure 24.

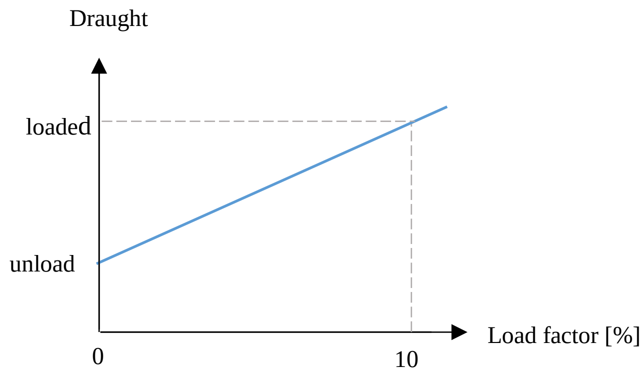


figure 24: Relation between the load factor and draught of a vessel

The load factor can be calculated by the following formula:

$$Load\ factor\ [\%] = \frac{navigable\ depth\ [m] - unloaded\ draught\ [m]}{loaded\ draught\ [m] - unloaded\ draught\ [m]}$$

The draught of the vessel is equal to the navigable depth.

The relation between the draught and the loading capacity is assumed to be linear based on research by van Dorsser (2015). This means that also the relation between the load factor and the loading capacity is linear, because the relation between the draught and the load factor is linear.

Because vessels can transport less cargo in case of navigation restrictions, it could be cheaper to use smaller vessels. Smaller vessels often have lower fixed and variable costs. For example, the insurance, mortgage, requirements on manpower and fuel costs are lower compared to a larger vessel. This translates directly into lower cost prices and therefore it is more attractive to deploy smaller ship sizes when less loading capacity can be achieved due to navigation restrictions. Subsequently, the question arises whether there is a sufficient number of smaller vessels available to fulfil the demand. If the demand will be higher and the supply is the same, the price of inland shipping will rise and therefore, smaller ships will become also more expensive. Because there is not enough data available which can describe and quantify this process and it takes too much time to investigate it, it is not considered during this research.

It is assumed that the number of required loaded trips is equal to the total amount of freight that have to be transported divided by the average loading capacity.

6.3 Shipping costs

The shipping costs are based on cost key figures for inland shipping and several assumptions as described in the previous paragraph. The steps that must be considered to calculate the total shipping costs with- and without navigation restrictions, are listed here:

1. Costs per hour depending on load factor
2. Average costs per hour (cargo type distribution included)
3. Costs per ton
4. Extra costs due to navigation restrictions
5. Total shipping costs

These steps are discussed in more detail in the following paragraphs.

1. Costs per hour

When a vessel is not fully loaded, the costs for fuel will decrease. This results in less costs per hour. However, the amount of freight that is transported is also less and the fixed costs such as maintenance and labor will be the same. Therefore, the costs per ton will increase.

For calculating the costs per hour in case of a load factor that is less than 100%, the assumption is made that there is a linear relation between the costs per hour for a loaded and unloaded vessel. This is schematically shown in figure 25. This means that the costs per hour, depending on the load factor, can be calculated as follows:

$$Costs\ [€/hr.] = costs\ unloaded\ [€/hr.] + load\ factor\ [\%] * (costs\ loaded\ [€/hr.] - costs\ unloaded\ [€/hr.])$$

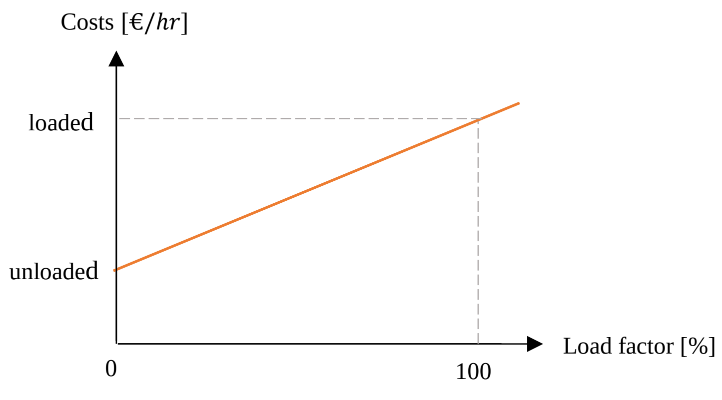


figure 25: Relation between the load factor and shipping costs per hour

2. Average costs per hour

For a known cargo type distribution, the costs/ hr for each vessel according to the DVS classification can be determined. The share of each cargo type must be multiplied by the costs per hour for that specific cargo. Subsequently the different parts have to be added to gain the 'average' costs per hour for a certain vessel type. In formula, this looks like:

$$\text{Average } costs\ [€/hr.] = \%\,liquid\ bulk * costs/\,hr + \%\,dry\ bulk * costs/\,hr + \%\,container * costs/\,hr$$

3. Costs per ton

Depending on the trip duration and the load factor the costs per ton can be determined. The total costs can be calculated by multiplying the costs / hr. and the travel time. Now, the costs per trip are known and these costs must be divided by the amount of cargo that is transported during the trip to obtain the costs per ton. In formula, this looks like:

$$Costs\ [€/ton] = \frac{trip\ duration\ [hrs.] * average\ costs\ [€/hr] + costs for\ loading\ incl. waiting\ [€] + costs\ for\ unloading\ incl.\ waiting [€]}{average\ loading\ capacity\ [ton]}$$

4. Extra costs due to navigation restrictions

In case there are navigable restrictions due to limited water depth, the costs per ton will be higher than in case of no limitations. The extra costs due to this restricted navigable depth can be determined by comparing the costs per ton in both situations.

In case of no restrictions it is assumed that the vessel is not completely fully loaded, because according to Jonkeren et al. (December 2010) the normal (= average) load factor for loaded vessels is about 84%. This means that the costs per ton for a loaded trip without any restriction will be calculated at a load factor of 84%. For that same trip in case of a restricted navigable depth, the maximum load factor must be determined. Using this load factor, the costs per hour, the costs for loading and unloading inclusive waiting time, and the loading capacity (so the amount of freight that can be transported), the costs per ton can be determined. When the maximum load factor is smaller than the normal load factor, the costs per ton will be higher than in the case with no navigation restrictions. Now, the costs per ton without restriction and the costs per ton for a restricted navigable depth are determined. Comparing both costs per ton for the same trip, the extra costs per ton due to a certain navigation restriction can be determined.

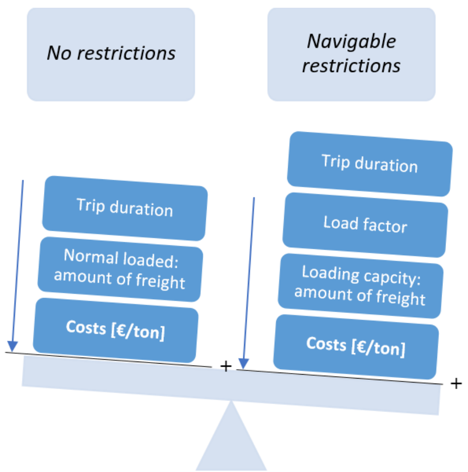


figure 26: Schematically overview of the effect of navigability restrictions on the costs per ton

$$Extra\ shipping\ costs\ [€/ton] = Costs_{restriction}\ [€/ton] - Costs_{normal\ loaded}\ [€/ton]$$

5. Total shipping costs

The total extra shipping costs per year depends on the number of days with a certain navigation restriction. To count the number of days with a certain water depth, the water depth will be divided into certain ranges with an average water depth. Corresponding to these average water depths the load factor and thus the (extra) costs per ton can be calculated. The formula below shows the complete calculation for the total (extra) shipping costs.

$$\textit{Total (extra) shipping costs} = \sum_{Depth} \textit{Number of days} * \textit{(extra) shipping costs } [€/ton] * \textit{amount of freight transport } [ton]$$

Where:

$$\textit{Amount of freight transport} = \textit{Number of vessels per } X^{*} \textit{ days} * \textit{average loading capacity} * \textit{laod factor}$$

*X is the number of days used in the previous formula.

The amount of freight that is transported by inland shipping depends on the average loading capacity of the vessels, the load factor for each type of vessel and the number of passages for each vessel type. Multiplying the average loading capacity by the load factor and the number of passages leads to the amount of freight that is transported by a certain vessel type. Adding the amount of freight of all different vessel types results in the total amount of freight that is transported by inland shipping. In formula:

$$\textit{Total freight } [tons] = \sum_{vessel\ type} \textit{average loading capacity } [tons] * \textit{load factor } [\%] * \textit{number of loaded trips}$$

When the total amount of freight transported by inland shipping is known, the required number of trips can be calculated. Therefore, the previous formula can be reconstructed in the following one to determine the number of required loaded trips.

$$\textit{Number of required loaded trips} = \frac{\textit{Total freight } [ton]}{\textit{average loading capacity } [tons] * \textit{load factor } [\%]}$$

It is assumed that the distribution of loaded and unloaded vessels is respectively 70% and 30% of the total number of vessels. Therefore, the total number of ‘required’ trips is equal to:

$$\textit{Total number of 'required' trips} = \frac{\textit{Number of required loaded trips}}{0.7}$$

6.4 Climate model

To translate climate conditions into daily water depths, a climate model is set up. A schematic overview of this model is shown in figure 27. The input of the model consists of daily river discharges. The model is a Q/H- relation and the output is the normative water depth per day.

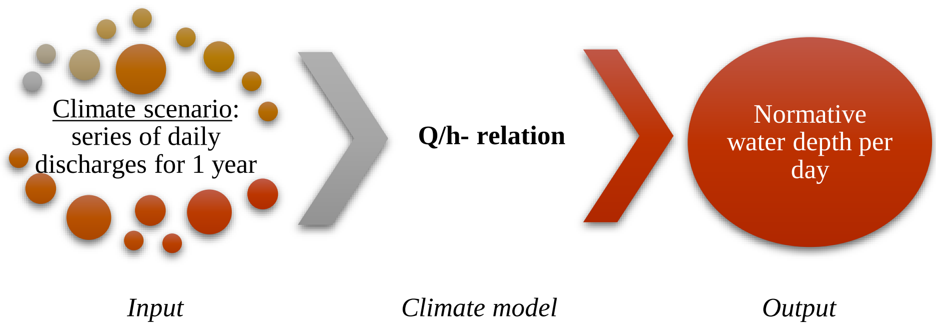


figure 27: Schematic overview of the climate model

The water depth at Nijmegen is assumed normative for the entire route between Duisburg and Rotterdam. Therefore, a relation between the discharge and water depth at this location will be used for determining the water depth corresponding to a certain discharge. Data of 5 years, from 2001 to 2005, is used to compute the relation between the discharge at Lobith and the water level at Nijmegen Haven. The graph in figure 28 shows these measured data and Q/H relation. In Appendix VI: QH- relation at Nijmegen a detailed description of the QH -relation set up is given.

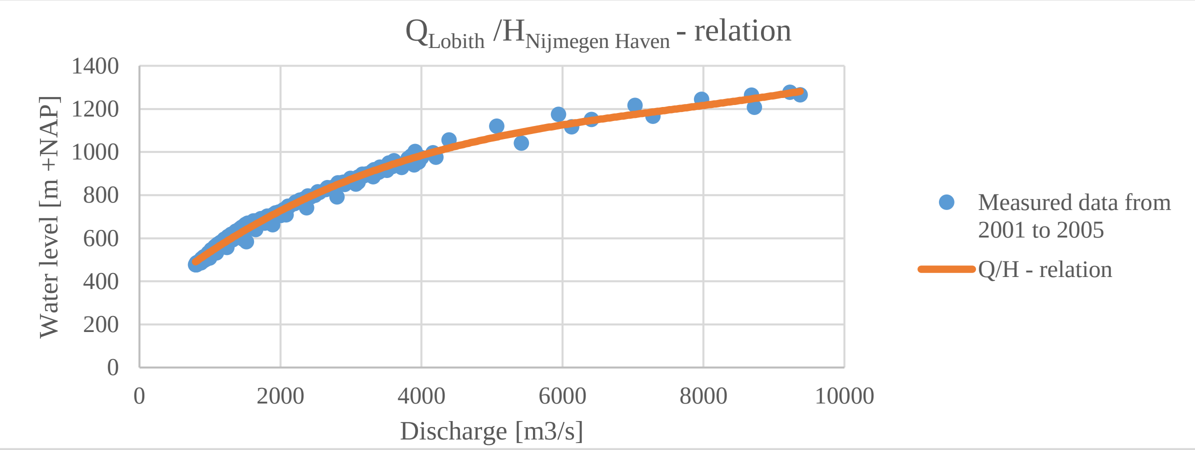


figure 28: Q/H relation at Nijmegen

The Q/H relation that corresponds to the discharge at Lobith and the water level at Nijmgen Haven is as follows:

$$Water\ level\ [cm + NAP]\ \ at\ Nijmegen\ Haven = \frac{0.0000000009 * Q_{Lobith}^3 - 0.00002 * Q_{Lobith}^2 + 0.2407 * Q_{Lobith} + 327.53 + 328.58 * LN(Q_{Lobith}) - 1761.1}{2}$$

Now, the water depth corresponding to a certain discharge can be computed with the following formula.

$$Water\ depth\ [m]\ at\ Nijmegen\ haven = \frac{water\ level\ [cm + NAP]}{100} - 2.50\ [m]$$

With these formulas, the water levels and water depths can be computed for several discharge series.

6.5 Economic model

The economic model is set up to determine the total freight that is transported by inland shipping between Rotterdam and Duisburg. There are two economic scenarios, WLO high and WLO low which represents an economic growth of 1% and 2% respectively. In Appendix IV the WLO scenarios are described in more detail. However, these WLO scenarios describe the national freight transport by inland shipping and therefore these must be corrected for the route Rotterdam – Germany. In addition, the cargo type distribution determines the fleet composition of different vessel types and therefore these must be applied too. A schematic overview of the model is shown in figure 29. The model transforms the scenarios based on assumptions to the amount of freight that will transported by inland shipping on the River Waal.

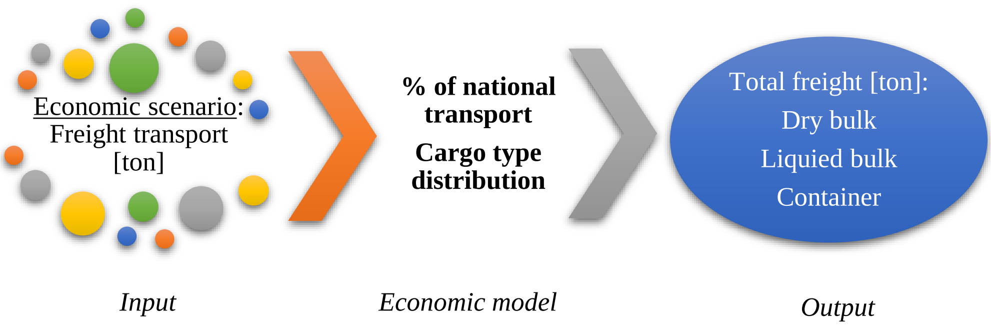


figure 29: Overview of the economic model

6.6 Fleet model

The size and composition of the fleet is decisive for the effects of climate change on the inland shipping sector. Therefore, this shipping fleet is important input for the effect model and so finally for the shipping costs. However, the current shipping fleet might not be the same as the future fleet. Therefore, using the fleet model, a vessel that represents a certain shipping fleet is computed. Looking at the different vessel types according to the CEMT and/or RWS Classes (see Appendix I) the ships with quite similar loading capacity will be used for determining the normative vessel. The characteristics for the normative vessel are determined by taking the average of these equivalent vessels. A schematic overview of the fleet model is shown in figure 30. Appendix VI: Normative vessel includes a complete description of the fleet model regarding the data and calculations.

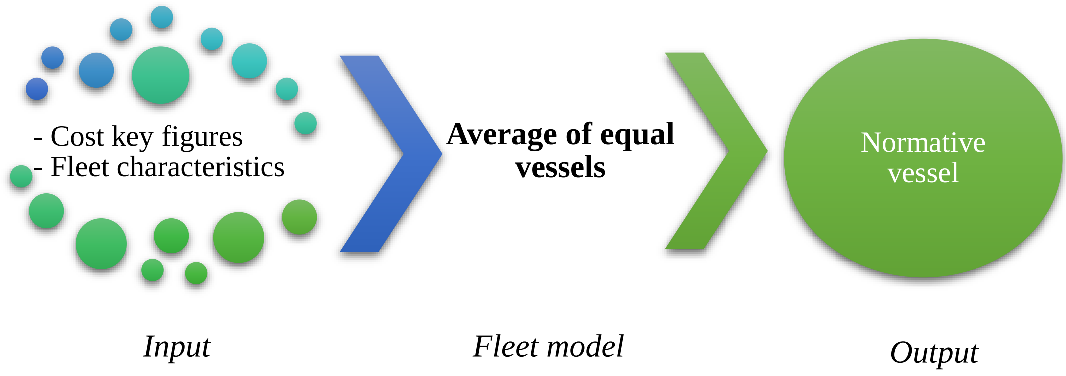


figure 30: Overview of the fleet model

6.7 Effect model

The effect model calculates the load factor using the input values of the normative depth and normative vessel (with their characteristics). In addition, the required number of trips can be calculated using the total amount of freight that must be transported and the average loading capacity. Subsequently, the costs per ton and the total shipping costs can be calculated. The output of the model are total costs of inland shipping transport depended on the input variables. An overview of this model is shown in figure 31.

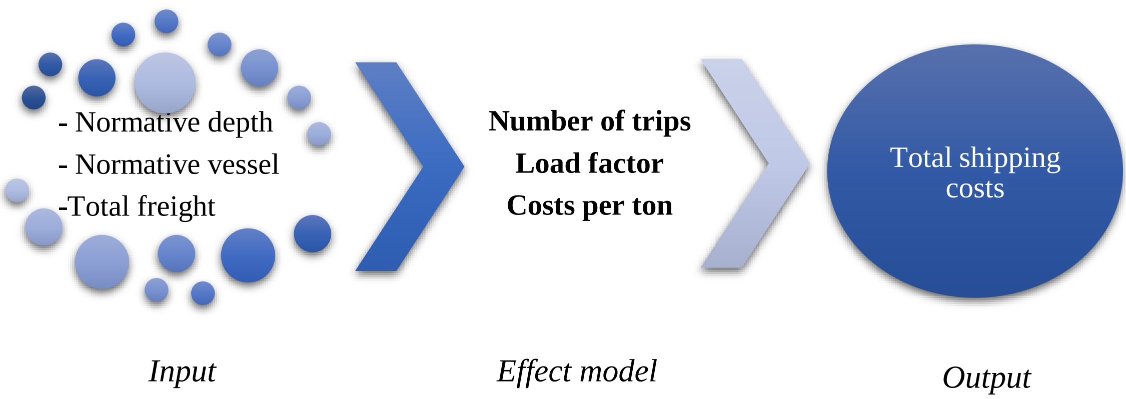


figure 31: Overview of the effect model

The calculations about the shipping costs described in chapter 6.3 are completely covered by the models that are shown here. Therefore, the effect model and the 'sub' models are clear and insightful. However, the reliability of the outcomes has not been proved yet. Therefore, the model is validated to get insight in the reliability of the results. The next chapter includes this model validation.

6.8 Model validation

Before the model is used for computing results, the reliability of the output is checked. This is done by generating output for the year 2003. The year 2003 was a very dry year and it is obtained from literature data how high the damage costs were that specific year.

First, the climate model is validated by checking the results of the climate model with measured data and data obtained with the model SOBEK. The results are shown in Appendix VI: Climate model validation. The average differences between the three methods are included in table 13. It can be observed that the climate model has an average standard deviation of 6 cm with the measured data.

Differences [m]	Measured	QH- relation	SOBEK
Measured	**0**	**0.12**	**0.16**
QH- relation		**0**	**0.22**
SOBEK			**0**

table 13: Average differences [m] between measured data, climate model results and SOBEK results

RIZA et al. (2005) have studied the effects of low water levels on inland waterway transport. They have made an estimate of the 'damage' costs in the year 2003 (when there was a very dry summer period) for domestic inland waterway transport in the Netherlands. These costs are based on assumptions about additional costs of low water levels and concern the increase in number of trips, handling costs and costs due to longer waiting times at locks (Jonkeren et al., 2007). The 'extra' costs or 'damage' are relative to an average year (which is defined as 1:2 year). For the year 2003 these costs amounted €111 million. The total annual costs for transport by inland shipping is about €2,100 million. This means that the costs were 5% higher in 2003 compared to an average year. It must be noted that the average discharge over 2003 was quite normal and therefore the 'damage' over the entire year was somewhat less than expected.

The results of the effect model for the year 2003 are included in Appendix VI: Reference situation. Comparing the results of the study by RIZA and the results of the effect model that is developed for this research, it can be noticed that the total shipping costs and 'damage' costs are approximately a factor 2 smaller. However, the ratio between the extra shipping costs and the total annual shipping costs is approximately equal to that of the study by RIZA, namely the total costs are about 5% higher compared to the situation without restrictions.
The difference between the two models could be explained by the fact that RIZA has studied the situation for domestic inland waterway transport in the Netherlands and this is not the case for the model in this research. Because, in this research the only shipping route is between Rotterdam and Duisburg and the bottleneck is assumed at Nijmegen. Therefore, the navigation restrictions on the River IJssel are not considered, but might have an effect on the inland shipping transport costs. In the dry period of 2003 there was only one-way traffic allowed on the River IJssel and therefore a lot of vessels had to sail an alternative route, which leads to extra shipping costs. Also, the extra costs for the locking process are not included in this model, because there are no locks on the River Waal (and it was assumed that all vessels are sailing on this route).

The total amount of freight transport in the Netherlands was in 2012 about 350 million ton (BVB, 2016). Thereof 163 ton passed the River Rhine at Lobith (Rijkswaterstaat, 2013) and this is approximately equal to 47%. Using this information, it is assumed that 47% of total transport by inland shipping is passing Lobith. Now a rough assumption is made that 42% (90% * 47%) of the extra shipping costs is a result of shipping transport over the River Waal. The national extra shipping costs can be calculated and an overview of these costs are shown in table 14.

Costs	**River Waal - 42%**	**National - 100%**
Total shipping costs	**€ 845,549,379**	**€ 2,013,212,807**
Shipping costs without restriction	**€ 802,033,514**	**€ 1,909,603,605**
Extra shipping costs	**€ 43,515,865**	**€ 103,609,202**

table 14: Average differences [m] between measured data, climate model results and SOBEK results

6.9 Conclusion

In this chapter the developing of the Effect model is described followed by the model validation to give insight in the interpretation and reliability of the results. Because the effect model does not consider all aspects and assumptions are made, the model has some limitations. The following important assumptions are relevant for the outcome and interpretation of the calculations:

- All trips have the route Rotterdam – Duisburg, so other routes are not considered;
- Alternative shipping routes to avoid loading limitations are not considered;
- Waiting time to increase the loading capacity is not considered (so, waiting on periods with higher water levels);
- The deployment of other ship sizes in case of navigation restrictions are not considered.

Of course, not all trips have the same route, some trips are longer and some trips are shorter than the route that is assumed. However, the route Rotterdam – Duisburg seems to be a good assumption for all vessel trips. Also, the alternative routes lead to higher shipping costs. Maybe a little less than in case with navigation restrictions, but there are extra costs when using alternative routes. Therefore, the costs are already somewhat compensated for the assumption of no alternative shipping routes. The same reasoning can be applied to the assumption of extra waiting time to avoid or minimizing the navigation restrictions. Because waiting time leads to higher shipping costs, the gab in total shipping costs is already compensated for not considering these waiting costs.

Because it is expected that in case of navigation restrictions smaller ships will become more expensive due to a higher demand, the question arises how long smaller ships are much cheaper than bigger ships. Therefore, it does not mean directly that not considered the deployment of other sizes will lead to much higher total shipping costs than in the situation when it is considered.

Based on the results of the validation and the discussion above it can be concluded that the effect model gives reliable results under the assumptions that have been made. Therefore, the model is used in this research to study the effects of climate change on the inland shipping sector in the situation without any measure and in the situation of canalizing the River Waal. This means that sub question 1 has been answered and enough basis is created to go on with sub questions 2 and 3. In the next chapters the consequences for inland shipping are determined by using the effect model.

7 Consequences for inland shipping without any measure

7.1 Introduction

This chapter contains the part of research that investigates the consequences for inland shipping without any measure. The results will be compared with the consequences due to Waal canalization to give a well-funded answer on the research question. Therefore, this chapter is answering sub- question two. The effect of climate change on the navigability of the River Waal and consequences for inland shipping are investigated. To obtain the extra shipping costs due to climate change, the reference situation is also considered to compare the situation with and without navigation restrictions with each other. Using the effect model that have been described in chapter 6, the shipping costs per scenario can be determined. First, the data that is used will be discussed and subsequently results of the calculations are shown.

7.2 Data

The data that is used for this situation depends on the different time horizons 2050 and 2085. The required input for the effect model are the characteristics of the normative vessel, the amount of freight and the navigation depth. The normative vessel and economic scenarios for 2050 are used for both time horizons. The characteristics of this vessel are included in table 15. The total freight transport by inland shipping is based on the WLO scenarios for 2050, which are shown in table 16, and the assumption that 47% of national freight transport passes Lobith. An overview of the total freight transport across the border and the number of required trips is shown in table 17. The number of trips are determined by the assumption that 90% of the vessels that passes Lobith are sailing over the River Waal.

Type	Average loading capacity [ton]	Length [m]	Width [m]	Draught [m]
Normative vessel	3500	110	11,4	3.7

table 15: Normative vessel characteristics

Year	Scenario High	Scenario Low
2050	457	375

table 16: Weight of transported goods [in millions] by inland shipping

Year	2050/2085	
Economic scenario	*High*	*Low*
Total freight transport [ton]	214761800	176297000
Average loading capacity [ton]	3500	3500
Number of required trips	65743	53968
Total number of required trips	93919	77098

table 17: Data about freight, vessel loading capacity and number of trips

During the research, it was found that the cost figures of NEA (2008) are not very realistic. The costs for inland shipping are assumed too high and it is expected that this influences the results. Therefore, it must be checked whether the results will change a lot when using other cost figures. A new cost tool for inland shipping of Rijkswaterstaat (2014) gives more realistic values for the cost indication. Both costs figures are used for calculating the shipping costs and thus both outcomes will be presented in this chapter. The shipping costs based on the costs key figures from 2008 and from 2014 that corresponds to the normative vessel are included in table 18.

Characteristics			***Costs***				
Cost key figure	Average loading capacity [ton]	Draught [m]	Average waiting costs/hr	Average loaded costs/hr	Average unloaded costs/hr	Average costs for loading + waiting time	Average costs for unloading + waiting time
2008	3500	3.7	€ 174.79	€ 371.73	€ 258.94	€ 2,750	€ 3,121
2014			€113.67	€219.09	€182.03	€1,786	€2,027

table 18: Cost prices for the normative vessel

The discharge projections developed by Deltares (2015) are used to determine the water depth in the River Waal and subsequently the navigability of the River Waal under certain climate conditions. The water depth for each day in this period is calculated with the Q/H-relation for Nijmegen. All simulated discharge projections are used for counting the number of days with a certain water depth. Subsequently, the average number of days per year corresponding to a certain water depth is determined. An overview of the results is included in Appendix VIII.

7.3 Results

The data described in the previous paragraph are used as input for the effect model. The calculations described in chapter 6 are elaborated by this model and the outcomes are the shipping costs for each scenario combination. Because it is expected that the year 2003 will be an average year in 2050 when it comes to the annual discharge distribution, also this 'scenario' is investigated.

The results based on the costs figures from 2008 are shown in table 19 and table 20 for the year 2050 and 2085 respectively. In table 21, the results based on the discharge distribution of 2003 are included. Subsequently, in table 22 and table 23, the results based on the costs figures from 2014 are shown for the year 2050 and 2085 respectively and the results based on the discharge distribution of 2003 are included in table 24.

Using the cost figures of 2008, for the year 2050 the extra shipping costs in case of the most extreme climate scenario are more than 100 million Euro. For the other scenarios, the extra costs vary between 25 million Euro and 52 million Euro. For the year 2085, the highest extra shipping costs are almost 200 million Euro. This is in case of the $W_{H,dry}$ climate scenario in case with the high economic scenario. In case of the other climate scenarios the extra costs are significantly lower because they vary between 19 million Euro and 62 million Euro.

Using the 'new' cost figures from 2014, the extra shipping costs are lower. Now, in case of the scenario $W_{H,dry}$ the highest costs are maximal 83 million Euro for 2050 and 132 million Euro for 2085. The other scenarios lead to extra costs between 17 million Euro and 35 million Euro for the year 2050 and between 12 million Euro and 42 million Euro for 2085.

7.4 Conclusion

In this chapter the consequences due to climate change for inland shipping in the situation without any measure are investigated. It can be concluded that the extra shipping costs in case of the $W_{H,dry}$ scenario are significantly higher than in case of all other scenarios. There is also influence of the economic scenario on the absolute value of the extra shipping costs, but the percentage damage costs are the same. However, the differences in extra shipping costs are mainly determined by the climate scenarios. Now, sub question two is answered and the results of this part will be used to compare the consequences for inland shipping without measure with the consequences in case of canalization. The consequences in case of canalization will be investigate in the next chapter.

Time horizon	2050									
Climate scenario	***Whdy***		***G_H***		***W_L***		***G_L***		***W_H***	
Economic scenario	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Total shipping costs	€ 769,637,050	€ 937,557,861	€ 693,698,042	€ 845,050,342	€ 695,070,525	€ 846,722,276	€ 697,838,483	€ 850,094,151	€ 710,020,210	€ 864,933,710
Extra shipping costs	€ 101,704,975	€ 123,895,152	€ 25,765,967	€ 31,387,632	€ 27,138,450	€ 33,059,566	€ 29,906,407	€ 36,431,442	€ 42,088,135	€ 51,271,000
Shipping costs without restriction	€ 667,932,075	€ 813,662,710	€ 667,932,075	€ 813,662,710	€ 667,932,075	€ 813,662,710	€ 667,932,075	€ 813,662,710	€ 667,932,075	€ 813,662,710
% damage costs	13.21%	13.21%	3.71%	3.71%	3.90%	3.90%	4.29%	4.29%	5.93%	5.93%

table 19: Shipping costs for various scenarios for 2050 based on cost figures from 2008

Time horizon	2085									
Climate scenario	***Whdy***		***G_H***		***W_L***		***G_L***		***W_H***	
Economic scenario	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Total shipping costs	€ 829,021,939	€ 1,009,899,453	€ 701,074,823	€ 854,036,603	€ 703,688,720	€ 857,220,804	€ 686,832,283	€ 836,686,599	€ 719,158,195	€ 876,065,437
Extra shipping costs	€ 161,089,864	€ 196,236,743	€ 33,142,748	€ 40,373,893	€ 35,756,645	€ 43,558,095	€ 18,900,208	€ 23,023,889	€ 51,226,120	€ 62,402,728
Shipping costs without restriction	€ 667,932,075	€ 813,662,710	€ 667,932,075	€ 813,662,710	€ 667,932,075	€ 813,662,710	€ 667,932,075	€ 813,662,710	€ 667,932,075	€ 813,662,710
% damage costs	19.43%	19.43%	4.73%	4.73%	5.08%	5.08%	2.75%	2.75%	7.12%	7.12%

table 20: Shipping costs for various scenarios for 2085 based on cost figures from 2008

Time horizon	2050	
Climate scenario	***2003***	
Economic scenario	*Low*	*High*
Total shipping costs	€ 743,232,094	€ 905,391,824
Extra shipping costs	€ 75,300,019	€ 91,729,114
Shipping costs without restriction	€ 667,932,075	€ 813,662,710
% damage costs	10.13%	10.13%

table 21: Shipping costs caused by the discharge distribution from 2003, based on the cost figures from 2008

8 Consequences for inland shipping due to canalization

8.1 Introduction

River canalization is a possible measure to deal with conditions that are the result of climate change. This canalization can be achieved with a certain number of WLCs. But what number are most favourable for inland shipping with regards to the costs of transport? And what does this mean for the WLC costs?
The water level difference (or head) per weir depends on the total number of weirs and the criteria for navigation depth. A head that is large enough to guarantee the minimum required navigation depth leads to higher WLC costs than in the situation where a smaller water depth, and thus a smaller head, is allowed. However, a navigation depth that is smaller than the required depth for no restrictions leads to extra shipping costs. This research is about canalization in the most optimal way, which means that the total costs due to canalization are minimal. Therefore, it must be investigated what the effect is of the head per weir on the shipping costs and WLC costs to obtain the most optimal solution. This chapter shows the investigation to the most optimal way of canalization and subsequently the consequences of this canalization are determined for several climatic- and economic scenarios. Therefore, sub question three will be answered in this chapter. Comparing the results of this part with the consequences due to climate change without measure, it can be investigated whether canalization is a plausible measure to improve the navigability of the River Waal and therefore the research question can be answered too.

First, the boundary conditions are investigated. The most important conditions are total water level difference over- and length of the shipping route. The navigational bottleneck between Rotterdam and Duisburg is in the Netherlands, therefore the design of the canalization considers the stretch between Rotterdam and the German border. In addition to this reason, considering the area across the border, canalization may lead to policy issues. So, the boundary of the area of interest at the German border avoid this. A schematic view of the different stretches is shown in figure 32 and a summary of the characteristics is given in table 25.

Section	*i* [-]	L [km]	H_{tot} [m]
Rotterdam - Duisburg	0.00012	220	26.4
Rotterdam - Germany		140	16.8
Woudrichem - Duisburg		171	20.52
Woudrichem - Germany		92	11.04

table 25: Different stretches and their characteristics

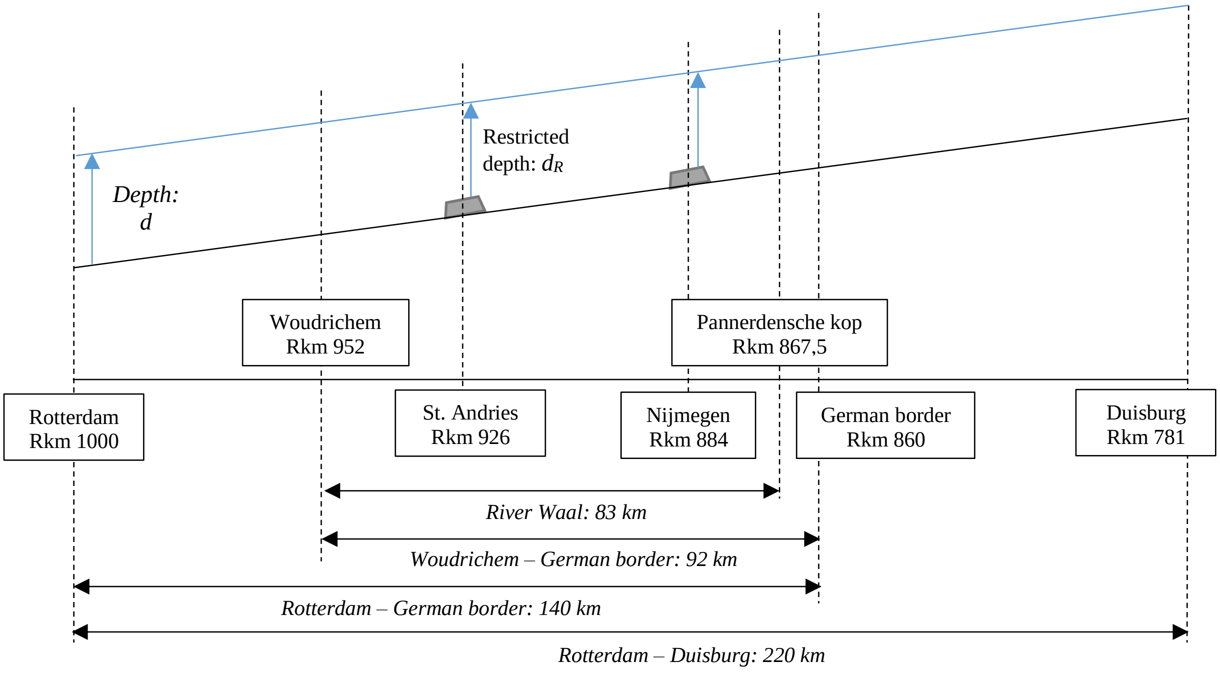


figure 32: Schematic overview of the different stretches between Rotterdam and Duisburg

Research to the WLC costs and shipping costs is included in the next chapters and based on this information and the area of interest the analysis to the most optimal way of canalization is described.

8.2 Weir- and lock complex costs

Introduction

In this research, there is no design of the weir- and lock complexes available and therefore only a rough estimate for the WLC costs can be made. The WLC costs consist of the construction costs, mitigating costs, maintenance costs and operational costs. In this paragraph, two methods are used that estimates these WLC costs. The first method is the index number method and is based on reference projects of weirs and locks in the Netherlands. The second method is the formula method that is based on the relation between the variable construction costs and the head over the structure. Both methods are detailly described in Appendix V and only the relevant aspects and results are shown here.

Index number method

Based on the cost estimation for a canalized River Rhine (Waal) by Ad van der Toorn (2010) a first cost overview for the canalization of the River Waal is made. Van der Toorn has used several reference projects to determine a so-called index number. The index number for the weir is based on the relation between the cost of a weir and the dimensions of the width, the retaining height and the head over the weir. For the lock a kind similar relation is valid; the index number depends on the length, width and head of the lock.

The computed index numbers are as follows:

Lock – 5.000 €/m³
Weir – 30.000 €/m³
Dikes – 6 Million €/km grass dike

The total costs depend on the number of WLCs. An average head of 5 meters leads to the number of WLCs and costs that is shown in table 26. The construction costs ($C_{construction}$) are the summation of the costs for the WLCs (=C_{weir} + C_{locks}) and the costs for mitigating measures (= C_{dikes}). However, these costs do not determine the total WLC costs. The maintenance costs and operational costs must also be added to the construction costs to obtain the total costs for the exploitation of the WLCs.

Length [km]	140
Total head [m]	16.8
Number of required WLCs [-]	3
Costs Lock [€]	€ 840,000,000
Costs Weir [€]	€ 1,350,000,000
Costs Dikes [€]	€ 84,000,000
Total construction costs [€]	€ 2,274,000,000
Maintenance costs [€]	€ 505,333,333
Operational costs [€]	€ 68,666,667
Total WLC costs [€]	€ 2,848,000,000
Total annual WLC costs [€/year]	€ 172,476,986

table 26: Overview of stretch characteristics and WLC costs

Formula method

The formula method is based on the relation between the head over the structure and the construction costs. A general reference is made to Molenaar et al. (2011) who has described this relation. Below, the different relations are shown.

The construction costs of n weirs for the full length of the river amounts to:

$$C_{constr,n} = n * c_{weir} = nC_1 + nC_2\left(H^2 d + \frac{1}{3}H^3 + Hd^2\right)$$

Where: $C_1 = fixed\ costs$ [Euro]
$C_2 = constant\ [Euro/m^2]$
H = $water\ head\ (average\ in\ time)$
$d = downstream\ water\ depth\ relative\ to\ the\ foundation$

This relation is shown in figure 33.

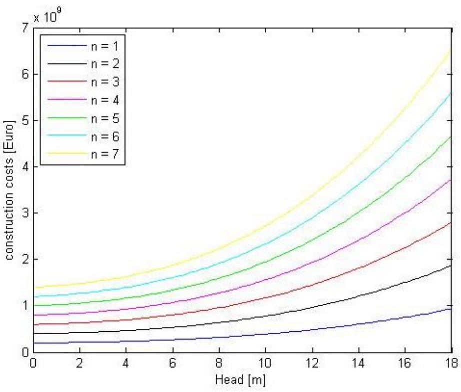


figure 33: Relation between construction

The mitigating costs are costs required for dike raising, dike enforcement and bed protection. The mitigating costs amounts to:

$$C_{mit,n} = C_4 * \frac{H_{tot}^2}{n^2} + C_5 * \frac{H_{tot}}{n} \qquad [Euro * m/km]$$

Where:
C_4 = [Euro/m/km]
C_5 = [Euro/m^2/km]
H_{tot} = Total water head
n = number of weirs

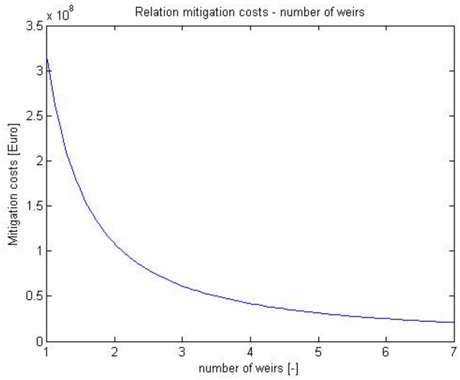


figure 34: relation between the number of weirs and Mitigating costs

A first estimate of the parameters C4 and C5 is made, the values are respectively 50,000 and 500.000. The relation between the costs for mitigating measures and the number of weirs is shown in figure 34.

However, the question arises whether this approach is quite reliable. The relation shown above is clear and logic, but it is not valid for each case. Looking at the River Waal there are a lot of dikes and structures protecting the environment against flooding. The requirements set on these flood protections are quite high and this means that there is a certain over height of the dikes along the River Waal. In addition, the weirs will be constructed for the situation where the discharge and water level is quite small. In that case the remaining dike 'over' height is even higher and this can be used in case of weirs in the River Waal. Therefore, the construction and/or reinforcement of the dikes is not so large as expected by the relation shown above. According to van der Toorn it is assumed that 10% of the total dike length should be heightened by 1 meter.

Using the relations for the constructions- and mitigating costs, a first calculation can be made. It is assumed that the total head is 16.8 meter and the locations of the weirs/locks are determined by equal space between the WLCs. The following parameters are used:

C1 = 100 Mln Euro;
C2 = 100,000 Euro/m^2;
C4 = 50,000 Euro/m/km;
C5 = 500,000 Euro/m^2/km.

n	1	2	3	4
H [m]	8.4	5.6	4.2	8.4
Cmit [mln Euro]	22.51	7.73	4.37	2.98
Cmit,tot [mln Euro]	315.17	108.19	61.15	**41.75**
Cvar [mln Euro]	310.5	65.6	29.7	**17.8**
Ccon [mln Euro]	821.0	**662.5**	778.2	942.6
Ctot [mln Euro]	1136.1	**770.7**	839.3	984.3
Cmaintain [mln Euro]	227.2	**154.1**	167.9	196.9
Coperational [mln Euro]	**20.0**	40.0	60.0	80.0
Total Costs[mln Euro]	1383.4	**964.9**	1067.2	1261.2

table 27: Over view of canalization costs for various number of WLCs

The results are shown in table 27 and figure 35 it can be observed that the lowest costs will be obtained by 2 WLCs.

The values of the parameters used in the table and graph shown above are quite uncertain. Therefore, a further analysis has been done to obtain insight in the sensitivity of these parameters and the outcomes. This analysis is included in Appendix V. The modifications and outcomes of this analysis are as follows:

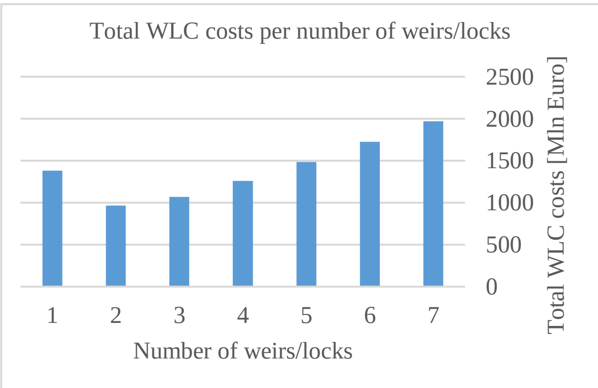


figure 35: Total complex costs for various number of weirs

<u>Relative high fixed construction costs</u>
In case of relative higher fixed costs compared to the variable construction costs a fewer number of complexed becomes cheaper. This was expected beforehand, because the fixed costs will be multiplied by the number of WLCs, so twice more WLCs mean twice as high construction costs.

<u>Relative high variable costs</u>
In case of high variable costs the number of WLCs will increase to obtain the lowest construction costs. A reduced head will have a greater effect in a situation with relative low fixed costs compared to a case with relative high fixed costs.

More or less mitigation cost

The parameter C4 does not affect a lot the number of WLCs that leads the minimum costs, because the distribution of the costs over the different numbers of WLCs remains more or less the same. Of course, in case of a larger value for the parameters C4 and C5 the total costs will increase and a smaller value leads to less total costs, but this is self- evident.

Conclusion

It can be concluded that the parameters C1 and C2 are important for the choice between the number of WLCs that is most favourable with regards to the total costs of the WLCs. The parameters C4 and C5 do contribute on the total costs, but this is only relevant at the level of costs.

From the figures included in Appendix V, it can be observed that the minimum WLC costs will be obtained in case of one, two or three WLCs depending on the total head. Only in case of relative very high variable costs this amount can be increase to 4 WLCs when the total head is about 20 meters. A total head of 20 meters is quite large and will not be relevant because as has been said earlier, the stretch between Rotterdam and Germany will have a maximum height difference of 17 meters. Therefore, it can be concluded that the area of interest, relating the number of WLCs, is from one to three WLCs. For this area of interest, the shipping costs will be determined in the next chapter.

8.3 Shipping costs

Introduction

For inland shipping, there are two aspects important that contribute to the total shipping costs. These are the extra travel time caused by passing a lock and the vessels loading capacity depended on the navigation depth. It might be clear that the extra travel time is increasing by an increasing number of locks. The navigation depth depends on the climate scenarios and the created water depth by the weir(s). Both aspects are discussed in this chapter and therefore, sub question 3a is answered after this chapter. First the assumptions for calculating the shipping costs are discussed. Subsequently the methodology is described followed by the results and conclusions.

Assumptions

According to the conclusion of the previous paragraph about the number of WLCs, it is assumed that one, two and three WLCs are relevant for studying the effects on inland shipping. Therefore, only this number of WLCs is taken into account from now on. Furthermore, the location of the downstream weir is set at Woudrichem. This is because just downstream of Woudrichem the River Waal splits into the Boven Merwede and the Nieuwe Merwede and therefore the river characteristics are changing. In addition, according the measured water levels from 2003 to 2006, the minimum observed depth just upstream of Woudrichem was 4.85 meters corresponding to a discharge of 612 m^3/s on the River Waal. Looking at the discharge projection for the various climate scenarios, which are included in Appendix VIII: Occurrence of discharge ranges for the River Waal, it is observed that the minimum Waal discharge for the considered time horizons is about 400 m^3/s. Using the QH- relation for the location at Vuren, which is included in Appendix VIII: Q/H- relation of the River Waal at Vuren, the corresponding water depth is equal to 4.4 meter and therefore it is expected that the water level downstream of Woudrichem is sufficient for inland navigation. Because only at Vuren data was available for computing a QH- relation and therefore this location is used. Vuren is located just upstream of Woudrichem.

A first calculation to determine the effects for the year 2050 is done. Therefore, a normative vessel for 2050 that represents the future shipping fleet, is used. Because the discharge distribution of 2003 will be annual around 2050, this distribution is taken in this calculation to analyse the possible effects on the inland shipping sector. For the amount of freight that is transported in 2050, the economic scenario WLO High is considered.

Because the River Rhine splits at Pannerdensch kop into the River Waal and the Pannerdensch Canal, the stretch that is considered consist of different characteristics. The upper part of the stretch, between Lobith and Pannerdensch Kop, has characteristics of the River Rhine and downstream of Pannerdench Kop the characteristics are of the River Waal. Because the stretch between Lobith and Pannerdensch Kop is very small compared to River Waal, it is assumed that the River Waal will continue upstream of Pannerdensch Kop to the German Border.

The discharge distribution at Pannerdensch Kop depends on the weir schedule of the weir at Driel in the Nederijn. From literature research, it was found that 2/3 of the discharge is flowing into the River Waal. However, from calculations it was found that about 3/4 of the Rhine discharge is flowing into the River Waal. Therefore, it is assumed that the discharge in the River Waal is about ¾ of the discharge at Lobith.

Because this is a first calculation, a linear bottom slope between the location of the downstream weir and the location of the upstream weir is assumed. This means that the actual bottom profile is not taken into account and the water depth can be calculated without corrections.

It is assumed that the location at Nijmegen is normative as it comes to the navigation depth. Therefore, the depth that corresponds to the normative situation is determined at Nijmegen and is equal to 2.3 meter.

Methodology

The shipping costs in case of canalization can be determined by calculating the effect of the head on the navigation depth for a certain number of WLCs. Namely, the navigation depth can be related on load factor and therefore on the shipping costs. The upstream influence of a certain number of WLCs in the River Waal can be investigated by a backwater curve calculation. The theory of backwater curves is described in Appendix II: Backwater curve Theory. This backwater curve theory is used to determine the required head that disappear the water depth restrictions for inland navigation. Thereafter, the effect of a smaller head on the shipping- and WLC costs is investigated to optimize the river canalization. The combination of number of WLCs and head that results in the lowest total costs can be marked as the most optimal option for canalization of the River Waal. The methodology for calculating the shipping costs is schematically shown in figure 36.

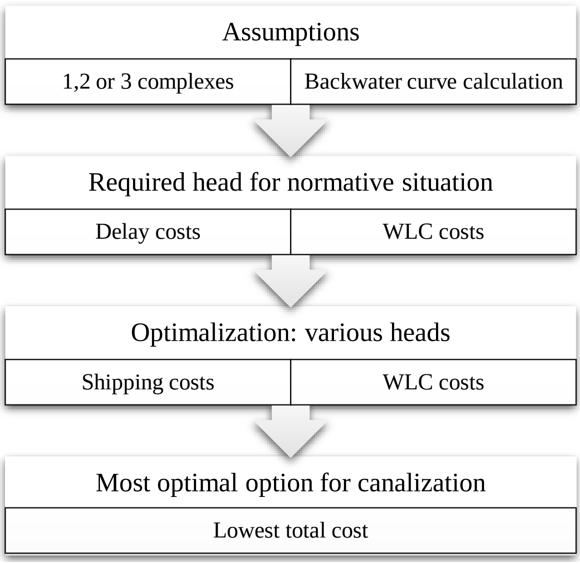


figure 36: Methodology of shipping costs calculation

The Characteristics used in the backwater curve calculation are as follows:

Water depth at distance x:* $h(x) = he + (h_0 - h_e) * 2^{-\left(\frac{x}{L_{1/2}}\right)}$

*Relative to $x_0 = 0$

Half- length:* $L_{1/2} = 0.24 * \left(\frac{h_e}{i}\right) * \left(\frac{h_0}{h_e}\right)^{4/3} \; [m]$

*The length over which the water depth is halved.

Equilibrium depth: $h_e = \left(\frac{\left(\frac{Q}{B}\right)^2}{C^2 * i}\right)^{\frac{1}{3}} \; [m]$

Now, the required information can be determined and this contains:

- The discharge: Q
- The width of the channel: B
- The Chézy coefficient: C
- The River bottom slope: i
- The water level at the weir: h_0

The discharge is not constant during a year and therefore this variable is changing. This is in contrast to the width of the channel, the Chézy coefficient and the river bottom slope, which are assumed to be constant. These parameters are determined by the characteristics of the River Waal as described in chapter 3. The characteristics of the River Waal are used for the entire stretch between Rotterdam and the German border. However, it must be taken into account that the discharge is divided between the River Waal and the Pannerdensch Canal. The discharge of the River Waal is equal to ¾ of the discharge at Lobith, as has been assumed before.

For investigating the upstream effect of a weir in the river, the upstream navigable water depth must be determined. As can be observed from the backwater curve formulas, the water depth at the weir and the normal water depth are important parameters that influence the water level profile and thus the upstream water depth.
The water level at the weir depends of the weir schedule, which is set on basis of a certain discharge or water depth. In this research a simplification is applied to determine the water depth at the weir. Namely, the water level at the weir is determined by the maximum head over the structure, the normal (or equilibrium) water depth and the bottom level (with respect to NAP). The maximum head is chosen as a variable for which various values can be applied. The normal water depth depends on the discharge.

As starting point, the lowest measured discharge is used to obtain the normative situation. Taking this normative situation into account, the head that is necessary for generating the required water depth for a certain distance upstream of the weir can be calculated. For this head, inland vessels experience no navigation restrictions due to water depth limitations. The total costs consist of delay costs due to the passing time of locks and the WLC costs.

The head over the structure varies by discharge and is determined by the maximum head over the structure and the normal water depth. In case of the normative situation, the total retaining height of the weir (or the water depth at the weir) is determined by adding the normal water depth and the maximum head over the weir. In the situation with a discharge, and therefore a water depth, larger than in the normative situation, the value of the head over the structure is decreasing such that the total retaining height of the weir remains the same. This means that the water level at the weir is not changing within one canalization option. This principle is schematic shown in figure 37. However, in case of a decreasing maximum head, the maximum retaining height of the structure will also decrease and therefore the water depth at the weir. In formula form, the head will be calculated as follows:

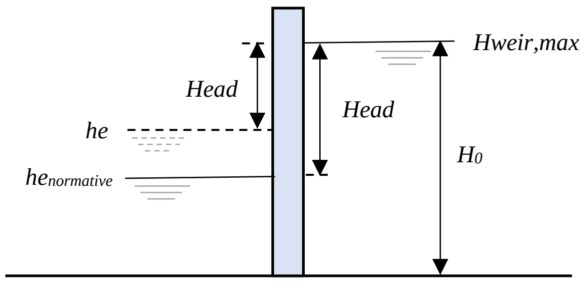


figure 37: Water level at the weir

$$\text{Head} = \begin{cases} \text{Hweir}_{max} - he & if \quad \text{Hweir}_{max} - \text{Head}_{max} < he \\ \text{Head}_{max} & other \end{cases}$$

H_0 = Head + he

For the optimization of the canalization the maximum head is decreased by several steps to investigate the effect on the shipping- and WLC costs. At the end, it can be observed what the effect is of a certain number of weirs in combination with a certain head on the total costs due to canalization. The ‘option’ with the lowest total costs can be marked as the most optimal way of canalizing the River Waal.

To investigate the effect of a certain head on the navigation depth upstream of the weir, the yearly discharge distribution must be taken into account. For determining the shipping costs, the number of days with a certain water depth must be investigated. To do so, the discharge is divided into ranges for which the corresponding average water depth can be calculated. The number of days with a certain discharge range can be counted. This number and the corresponding water depth can be used in the effect model to determine the shipping costs. This approach is schematized in figure 38.

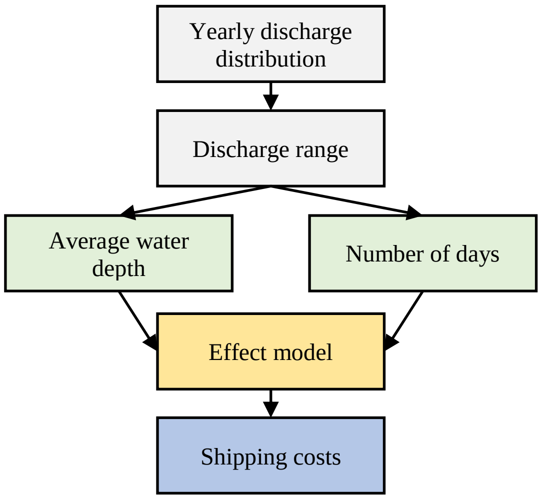


figure 38: Systematic overview of the shipping cost calculation

Costs due to delay

Ships experience extra travel time when they have to pass locks on their route. This extra time is the passing time and is equal to the total additional time that a locking operation required, in comparison to an imaginary situation without a lock, in which the ship can continue traveling at its cruising speed. The total passing time can be divided into waiting time and locking time. The waiting time is the time that ships must wait before they can sail into the lock. The locking time is the time needed for closing the doors, converting the camber, opening the door and sail out of the lock until the cruising speed is reached. (Groenveld et al., 2006)

The total delay time depends on the intensity on the waterway, the capacity of the lock and the number of locks. Because in this stadium of the research there is no global design of the lock a detailed calculation cannot be made. However, using key figures can give a good first estimate of the delay costs.

According to Molenaar et al. (2010) the average locking time is about 30 minutes. The maximum waiting time is set at 30 minutes, because this is also the criteria for the Beatrix locks located in the Amsterdam Rhine Canal. This results in an average passing time of 60 minutes.

In periods when the discharge is large enough to create a sufficient water depth for the vessels without WLCs, the weir will in open position and almost unrestricted passage for inland shipping is possible. According to the normative draught of the vessels the criteria for the minimum required water depth can determined. When the actual depth is smaller than the required depth, the weirs are closed and vessels have to pass the lock. The shipping costs due to delay depends on the number of WLCs and the number of days that the weir is closed and the vessels have to use the locks. Using the Q/H- relation at Nijmegen results in a discharge that must be larger than 1530 in order to create sufficient water depth of 4.0 meter. The number of days per year that the weirs are closed, and thus the shipping traffic have to pass the locks, are about 189. So, more than half of the time the ships experience extra travel time during their trip over the River Waal. The delay costs per year are shown in table 28.

Number of locks	Delay costs
1	€ 8,618,570
2	€ 17,237,141
3	€ 25,855,711

table 28: Delay costs per number of weirs

Costs due to navigation restrictions

On basis of the previous described method and assumptions, the shipping costs due to navigation restrictions for several canalization options are calculated. The characteristics of the River Waal leads to the following values for the parameters used in this first estimate:

$Q_{Waal} = ¾Q_{Lobith}$ (2003) [m^3/s]
$C = 40\ \sqrt{m}/s$
B = 370 m
$i = 0.0012$ [-]

The water depth at the weir is determined by the maximum head and the water depth that corresponds to the discharge. In formula form, it looks like: $H_0 = H + he$

The results are included in table 29 and show the effect of the head on the shipping costs, depending on the number of WLCs. As has been foreseen, the shipping costs are increasing by a decreasing head. By a small change in maximum head the shipping costs due to navigation restrictions rise slowly. If the head is decreasing further, the shipping costs increases by a higher rate. This can be explained by two factors, namely the smaller water depth at the weir and the number of days that navigation restrictions occur.

Canalization 'option'		***2050 - High***
# WLCs	*H [m]*	*Shipping costs per year*
1	7.2	€ 8,931,819
	7.5	€ 3,676,168
	7.8	€ 608,972
	8.1	€ 0
2	4.5	€ 9,988,552
	4.8	€ 3,213,218
	5.1	€ 151,899
	5.4	€ 0
3	3.3	€ 11,430,412
	3.6	€ 5,912,558
	3.9	€ 608,972
	4.2	€ 0

table 29: Shipping costs per canalization based on NEA cost figures (2008)

In case of a lower head, the water depth at the weir is smaller and this influences the water surface profile in upstream direction. The water depth upstream of the weir becomes smaller. In addition, the number of days that the water depth is not sufficient for inland shipping, is increasing fast by a decreasing head. The small discharges occur often than the smallest discharges. For a small decrease in head, this head is no longer sufficient to avoid navigation restrictions in case of the smallest discharges. By a further decrease in head, also the small discharges will not be sufficient for inland navigation. Therefore, the number of days with navigation restrictions due to insufficient water depth is increasing fast when the head is lowering further. The combination of the increasing number of days with the smaller navigation depth leads to an increasing rate of shipping costs for a decrease in head.

Conclusion

The shipping costs are dependent of the number of WLCs and the head over the structure that creates a certain water depth upstream of the WLC. In this chapter, the effect of the head on the water depth upstream of the weirs is investigated, vessels delay time are determined and subsequently the transport costs in case of one, two and three WLCs are calculated. Therefore, all parts of sub question 3a are answered and taking both the shipping costs and WLC costs into account, the most optimal way of canalization can be determined. The next chapter includes the first analysis to the most optimal canalization option.

8.4 First Analysis

Introduction

A first analysis to the financial consequences of climate change and canalization is elaborated to investigate the most optimal way of canalization. The effect of the number of weirs in combination with a certain head on the total costs determines this optimal solution. The shipping costs consist of the costs due to navigation restrictions and the costs due to delay time. The WLC costs consist of the construction-, mitigating-, operational- and maintenance costs. First, the data used in this analysis is described. Thereafter, the results are shown and at the end the conclusion is given.

Data

The data used in this analysis is based on the results of the previous paragraphs 8.2 and 8.3, where respectively the WLC costs and shipping costs are discussed. The shipping costs included in table 29 can be directly used for this analysis. However, the WLC costs must be calculated for the same head as for the shipping costs. This results in 3 (WLCs) times 4 (different heads) which is equal to 12 various WLCs and thus 12 different WLC costs.

The method that is used for estimating the construction costs is the formula method, because the formula method is based on a non-linear relation between the head and the construction costs. This will be more realistic than the index method describes and therefore the formula method will be used in this calculation.

The WLC costs must be expressed in the same price level as the shipping costs to compare it with each other. The shipping costs are based on cost key figures from 2008, because this analysis was done before the new cost figures from 2014 were found to be more reliable. The basis year for the price level is set at 2008 and this means that the WLC cost must be expressed in the price level of 2008. However, the shipping costs are determined for one specific year, while the WLC costs are determined in total. To compare both costs with each other, they must have the same meaning. Therefore, the WLC costs must be translated to annual WLC costs. Using the method of equivalent annual costs, the WLC costs becomes annually. Because the shipping costs will be determined for two specific years, there is no data available of the years in between. Therefore, it is hardly possible to do a net present value calculation and because the equivalent annual costs might be a proper method, this is decided to use. For more information about discounting costs and the equivalent annual cost method, reference is made to Appendix VI.

Because, the total construction costs consist of the fixed and variable construction costs, the order of magnitude of these two costs and the costs relative to each other have impact on the results. As has been said earlier, higher fixed costs lead to lower costs in case of less WLC, but relative high variable costs lead to lower costs in case of more WLCs. Therefore, two situations are investigated: the first one is in case with relative low variable costs and in the second case with relative high variable costs.

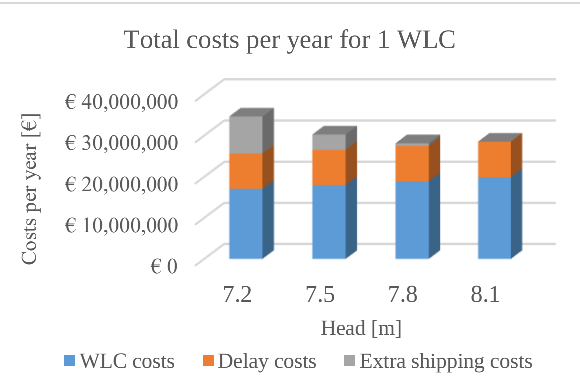
Results

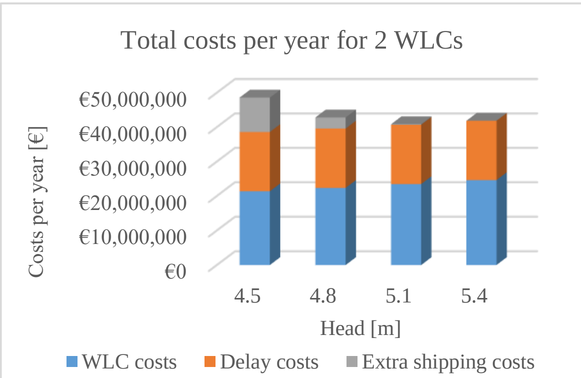
The results of this analysis consist of the costs due to climate change in case without any measure and in case of canalization. Comparing both situations gives insight in the costs or benefits due to canalization. The costs due to canalization are split into the shipping costs due to navigation restrictions, shipping costs due to delay and the WLC costs. The shipping costs due to navigation restrictions and WLC costs depends on the head and number of WLCs, the shipping costs due to delay depends only on the number of WLCs.

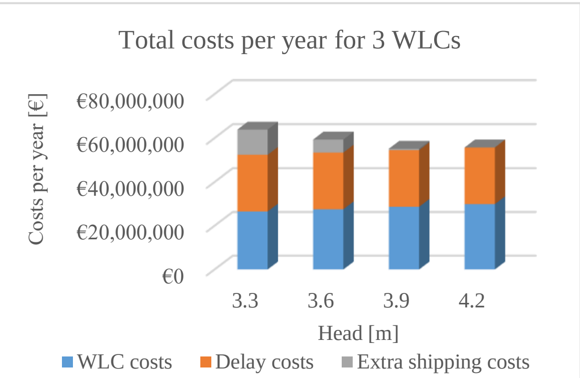
The results for relative low variable construction costs and relative high variable construction costs are included in table 30 and table 31 respectively. For each number of WLCs the effect of the head on the costs are shown in the figures below the table with results.

C1=50mln, C2=250,000		**No measure**	**Canalization**			
# WLCs	*H [m]*	*Extra shipping costs*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
1	7.2	€ 99,964,065	€ 8,618,570	€ 8,931,819	€ 17,048,839	€ 34,599,228
	7.5			€ 3,676,168	€ 17,949,190	€ 30,243,928
	7.8			€ 608,972	€ 18,901,276	€ 28,128,818
	8.1			€ 0	€ 19,906,681	€ 28,525,251
2	4.5	€ 99,964,065	€ 17,237,141	€ 9,988,552	€ 21,357,095	€ 48,582,788
	4.8			€ 3,213,218	€ 22,363,432	€ 42,813,791
	5.1			€ 151,899	€ 23,449,590	€ 40,838,630
	5.4			€ 0	€ 24,618,735	€ 41,855,876
3	3.3	€ 99,964,065	€ 25,855,711	€ 11,430,412	€ 26,507,771	€ 63,793,894
	3.6			€ 5,912,558	€ 27,517,470	€ 59,285,739
	3.9			€ 608,972	€ 28,625,465	€ 55,090,148
	4.2			€ 0	€ 29,836,509	€ 55,692,220

table 30: Overview of costs in both situations for relative low variable construction costs
*all costs are given per year for 2050 – High economic scenario, price level 2008

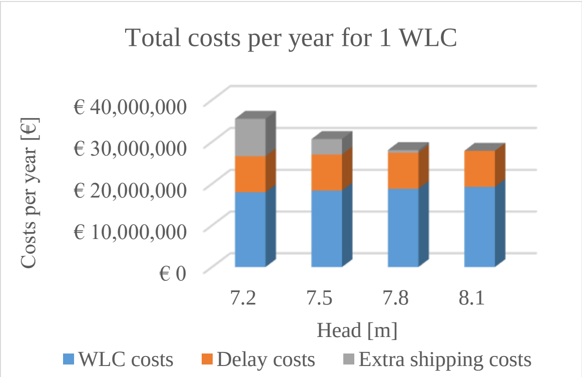


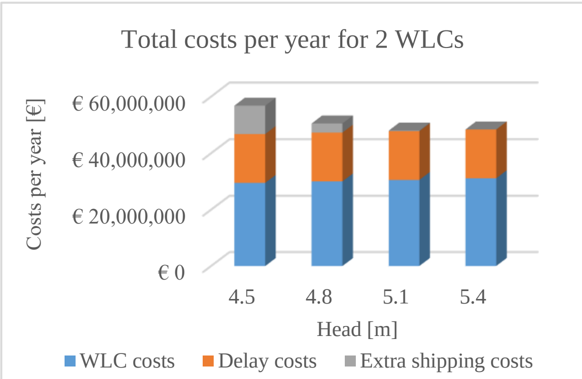


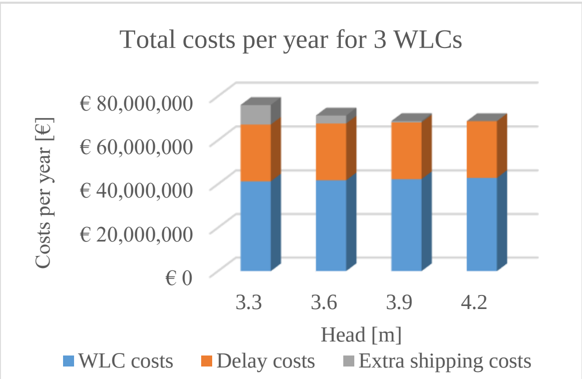


C1=100 mln, C2=100,000		**No measure**	**Canalization**			
# WLCs	*H [m]*	*Extra shipping costs*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
1	7.2	€ 99,964,065	€ 8,618,570	€ 8,931,819	€ 17,956,798	€ 35,507,187
	7.5			€ 3,676,168	€ 18,365,505	€ 30,660,243
	7.8			€ 608,972	€ 18,794,908	€ 28,022,450
	8.1			€ 0	€ 19,245,638	€ 27,864,208
2	4.5	€ 99,964,065	€ 17,237,141	€ 9,988,552	€ 29,542,459	€ 56,768,152
	4.8			€ 3,213,218	€ 30,038,729	€ 50,489,088
	5.1			€ 151,899	€ 30,569,843	€ 47,958,883
	5.4			€ 0	€ 31,137,064	€ 48,374,205
3	3.3	€ 99,964,065	€ 25,855,711	€ 11,430,412	€ 41,228,564	€ 78,514,687
	3.6			€ 5,912,558	€ 41,714,523	€ 73,482,792
	3.9			€ 608,972	€ 42,242,715	€ 68,707,398
	4.2			€ 0	€ 42,815,040	€ 68,670,751

table 31: Overview of costs in both situations for relative high variable construction costs
*all costs are given per year for 2050 – High economic scenario, price level 2008







Conclusion

For both parameters (relative high and low variable costs) the situations with the lowest costs are included in table 32 and table 33. It can be observed that for all number of WLCs it is attractive to lower the head somewhat. However, the shipping costs will rise quite fast by accepting a smaller head than required for no navigation restrictions and therefore this will not compensate the lower WLC costs by a big lowering of the head over the WLC. In addition, it can be observed that the difference in yearly WLC costs for the different parameters will increase by increasing number of WLCs. However, the parameters are quite rough so the absolute costs do not have an accurate value. This does not mean that it gives unusual information, on the contrary, it can be used very well for comparing the different situations and options (number of WLCs and total head).

C1=100 mln, C2=100,000		No measure	Canalization			
# WLCs	H [m]	Extra shipping costs 2050	Delay costs	shipping costs	WLC costs	Total
n=1	8.1	€ 99,964,065	€ 8,618,570	€ 0	€ 19,245,638	€ 27,864,208
n=2	5.1		€ 17,237,141	€ 151,899	€ 30,569,843	€ 47,958,883
n=3	4.2		€ 25,855,711	€ 0	€ 42,815,040	€ 68,670,751

table 32: Most optimal canalization options for relative low variable construction costs

C1=50 mln, C2=250,000		No measure	Canalization			
# WLCs	H [m]	Extra shipping costs 2050	Delay costs	shipping costs	WLC costs	Total
n=1	7.8	€ 99,964,065	€ 8,618,570	€ 608,972	€ 18,901,276	€ 28,128,818
n=2	5.1		€ 17,237,141	€ 151,899	€ 23,449,590	€ 40,838,630
n=3	3.9		€ 25,855,711	€ 608,972	€ 28,625,465	€ 55,090,148

table 33: Most optimal canalization options for relative high variable construction costs

Some assumptions made in this first analysis have major influence on these results. For the interpretation of the results it is important to understand the consequences of the assumptions. Therefore, a short discussion on these assumptions is given.

WLC costs
The parameters used for the calculation of the construction costs are quite rough and therefore the absolute value is not very reliable. It can be observed from both tables that these parameters affect the total costs and therefore the most optimal option. To obtain reliable results, more research to the values of these parameters is necessary.

Bottom slope
It is assumed that the longitudinal bottom slope of the river is linear in the backwater curve calculation. This results in a water depth that might be smaller or larger than is calculated, depending on the location of shoals and drops in the bottom. Because it is known that the bottom of the River Waal is not smooth over its entire length, contrary it contains several shoals of which the fixed bottom layer at Nijmegen is normative. Therefore, it is foreseen that the shipping costs will be higher than the values shown in table 30 and table 31. To obtain more accurate results, the real, irregular bottom slope must be applied in the backwater curve calculation.

Cost key figures
Based on the cost figures of NEA (2008), the costs for inland shipping are assumed too high and it is expected that this influences the results. Therefore, it must be checked whether the results will change a lot when using the cost figures of Rijkswaterstaat from 2014.

Dike height
In the calculation of the mitigating costs it is assumed that 10% of the dike length have to be raised by 1 meter in order to compensate the higher water level in the river due to canalization. However, the question arises whether this is a good estimate. The dikes are constructed on basis of a test level that is set up for extreme high discharges and the weirs are constructed for the situation with low discharges. In case of low discharges the dikes have a certain rest height and this height can be used for the increasing water level caused by the weir. It should be investigated whether this height is sufficient or not to make a good estimate for the mitigating costs.

The four aspects that have been described above can improve the reliability of the results. Therefore, these aspects are investigated further. In Appendix VII a detailed analysis to the WLC costs, cost figures, bottom slope and dike height is included. The outcomes and conclusions are applied in the second analysis to the most optimal way of canalization.

8.5 Second Analysis

Introduction

In this second analysis, the improvements that have been described in Appendix VII are considered. The conclusions of the improvements result in data that will be used in this analysis. The results that will be obtained during in this second analysis are more accurate than the results of the first analysis and therefore it is expected that the consequences for inland shipping are more reliable. First, the data used in this analysis is described. Thereafter, the results are shown and at the end the most optimal option of canalization can be determined.

Data

The data used in this analysis is equal to the data used in the first analysis, but with a few adaptations. These adaptations consist the improvements and only these changed data are shown here.

The new cost figures from 2014 are used and the values for the normative vessel in 2050 are included in table 34.

Type of shipping costs	Cost for normative vessel 2050
Loaded [€/hr]	€ 219.09
Unloaded [€/hr]	€ 182.03
Waiting [€/hr]	€ 113.67
Loading incl. waiting time [€]	€1,786
Unloading incl. waiting time [€]	€2,027

table 34: Cost prices for the normative vessel based on cost key figures from 2014

Again, the formula method is used for calculating the construction cost of the weir WLC. The parameters for the fixed and variable costs are adapted to €200 million and €750,000 €/m^3 respectively. In addition, the cost for the lock are equal to €5000*280*40*H.

Because the dike height is sufficient for a total retaining height of the weir equal to 9.8 meter, the part of dike raising in the formula for mitigating costs can be omitted. This results in the following formula:

$$C_{mit,n} = C_5 * \frac{H_{tot}}{n}$$

Because the shipping costs are based on the price level of 2014, this year is set as basis year. Therefore, all other costs must be expressed in price level of 2014.

Taking the real bottom slope into account, the normative water depth is observed at Millingen and Nijmegen, depending on the discharge. For the calculation of the shipping costs, the location with the lowest water depth is used.

Results

For the first calculation, a maximum head of 7.5 meter is taken, because this option was shown as most optimal in the foregoing calculation (see appendix VII). The results of this calculation are shown in table 35.

# WLCs	*H [m]*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
1	7.5	€ 5,596,474	€ 10,300,558	€ 59,652,037	€ 75,549,069

table 35: Shipping costs in case of 1 WLC with a head of 7.5 meter

Comparing the costs in table 35 with the costs in table 85 (appendix VII), it can be observed that the shipping costs due to navigation restrictions are much higher when the ‘real’ longitudinal bottom slope is taken into account and not a linear one. This means that the most optimal option of the foregoing calculation, namely a maximum head of 7.5 meter, might not be the most optimal anymore. It could be even that two WLCs are another option. First, it will be checked whether two WLCs become an option. Subsequently, a new optimum head that results in the lowest total costs will be investigated.

Whether two WLCs become an option depends on the total costs due to canalization. To make a quick analysis, the total costs of two WLCs are compared with the total costs that are calculated above. When the total costs in table 35 are lower than the costs of two WLCs obtained in the calculation when a linear bottom is assumed, it can be concluded that one WLC is most favourite. Of course, two different calculations will be compared, but this can be done safely because the shipping costs in the calculation with a linear bottom assumptions will become higher when the real bottom is taken into account. Therefore, the total costs of two WLCs will increase with respect to the results shown in table 84 (Appendix VII). So, if the total costs for two WLCs are lower than €75,549,069, one WLC is still more optimal than two WLCs. An overview of the costs for two WLCs is shown in table 36.

Head	*Total costs for 2 WLCs*
4.5	€ 90,775,126
4.8	€ 90,144,717
5.1	€ 92,036,877
5.4	€ 95,937,855

table 36: Total costs for 2 WLCs

As can be observed, the total costs of the calculation above are still lower than the costs of two WLCs and therefore two WLCs will not become more attractive than one WLC. Therefore, in further analysis only an optimum head in case of one WLC will be investigated.

As have been observed in the calculation where the 'real' bottom is considered, the shipping costs are higher than in the calculation where a linear bottom was assumed. This could mean that the most optimal solution is changed. Because the shipping costs have grown bigger and looking at the WLC costs, it is expecting that the optimum head is increased. To make a well-funded analysis for the most optimum head, the shipping costs and WLC costs will be calculated for several heads.

First, the head whereby no navigation restrictions occur will be investigated. As has been said earlier, for no draught limitations the minimum water depth is equal to 4.0 meter. For creating a water depth of 4.0 meter at the most critical location a head of 9.3 meter is required.

Now, the range where to look for the most optimum head over the structure is known, namely between 7.5 meter and 9.3 meter. First, the head will be lowered by 0.3 meter for calculating the shipping costs and WLC costs. Thereafter, these steps will be increased to 0.5 meter so that for H = 9.0, H = 8.5, H = 8.0 and H = 7.5 the costs will be calculated.

During this research, it was found that for infrastructure a discount rate of 4.5%[2] should be taken and not 5.0% as previously is assumed. From now on a value of 4.5% for the discount rate will be used to calculate the annual WLC costs.

In table 37 the shipping and WLC costs for the several options are shown. Looking at the total costs due to canalization, a head of 8.0 meter seems to be the most optimal option. For a head of 8.0 meter, the dike heights are still sufficient and therefore it is assumed right that costs for dike raising are not considered.

C1=200 mln, C2=750,000					
# WLCs	*H [m]*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
1	7.5	€ 5,596,474	€ 10,300,558	€ 54,902,771	€ 70,799,803
	8.0		€ 1,873,473	€ 59,040,328	€ 66,510,275
	8.5		€ 17,626	€ 63,412,271	€ 69,026,371
	9.0		€ 0	€ 68,029,978	€ 73,626,452
	9.3		€ 0	€ 70,923,302	€ 76,519,776

table 37: Shipping-, WLC- and total costs for one WLC with various heads

Conclusion

Because there have been applied several improvements after doing the first analysis, it can be said that the results of the second analysis are more accurate and reliable than the first one. It can be concluded that one WLC with a head of 8.0 meter is the most optimal option for canalization of the River Waal and therefore an answer on sub question 3a is found. However, this is based on the annual discharge distribution of 2003 and the high economic scenario for 2050. The consequences for inland shipping in case of other future scenarios for this canalization option must be investigated to get insight in the range of possible outcomes.

[2] Based on "Rapport Werkgroep Discontovoet 2015"

8.6 Scenario analysis

Introduction

In this analysis, the consequences on the inland shipping sector for the years 2050 and 2085 are investigated and therefore sub question 3b is answered. This means that after this chapter all sub questions are answered. Based on these outcomes, the research question can be answered.

The scenario analysis uses the improved effect model to give the costs caused by the optimal way of canalization. Applying the different climate- and economic scenarios lead to an overview of the possible effects on the inland shipping sector. All outcomes together span a range of possible consequences and comparing the results of the situation without any measure and the situation with canalization, it can be determined for which conditions canalization is a plausible measure to improve the river navigability. In addition, the feasibility of canalization depends on the integral effects and can be determined by taking the WLC costs into account.

Data

For one WLC with a maximum head of 8.0 meter, which was the most optimal option for canalization, the consequences in case of a certain climatic- and economic scenario are investigated.

The climate scenarios are computed for the years 2050 and 2085, while the economic scenarios do only describe the year 2050. To investigate the consequences for 2050, the different climate- and economic scenarios that have been computed for that specific year are combined to obtain all possible outcomes. To give some insight in the consequences at the year 2085, the climate scenarios for 2085 are taken and the economic scenarios of 2050 are used. So, the economic situation is frozen, which means that these scenarios remain the same for 2085.

Results

The results of the analysis are included in table 38 and table 39 for 2050 and 2085 respectively. These results are graphically shown in figure 39 and figure 40.

Time horizon: 2050		**No measure**	**Canalization**			
Climate scenario	*Economic scenario*	*Extra shipping costs*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
G_H	Low	€ 17,258,537	€ 2,133,349	€ 562,621	€ 59,040,328	€ 61,736,298
	High	€ 21,024,036	€ 2,598,808	€ 685,374		€ 62,324,510
W_L	Low	€ 18,177,852	€ 2,107,720	€ 669,672		€ 61,817,720
	High	€ 22,143,929	€ 2,567,586	€ 815,782		€ 62,423,696
$W_{H,dry}$	Low	€ 68,123,936	€ 3,390,944	€ 3,901,301		€ 66,332,573
	High	€ 82,987,340	€ 4,130,786	€ 4,752,494		€ 67,923,608
G_L	Low	€ 20,031,883	€ 1,819,711	€ 298,707		€ 61,158,746
	High	€ 24,402,476	€ 2,216,739	€ 363,879		€ 61,620,946
W_H	Low	€ 28,191,437	€ 2,406,154	€ 1,231,320		€ 62,677,802
	High	€ 34,342,296	€ 2,931,133	€ 1,499,971		€ 63,471,432

table 38: Overview of costs in the two considered situations and scenarios for 2050

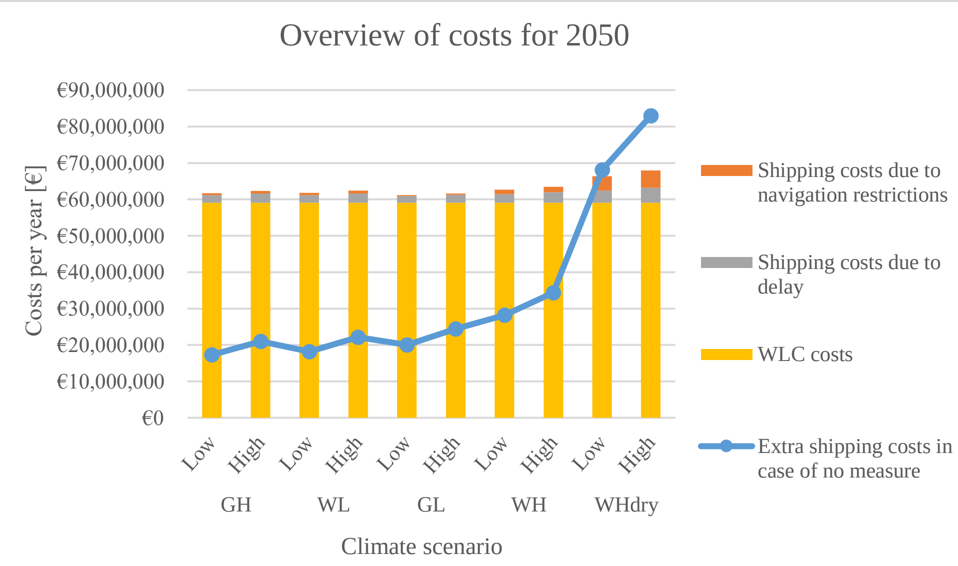


figure 39: Overview of costs in the two considered situations and scenarios for 2050

Time horizon: 2085		**No measure**	**Canalization**			
Climate scenario	*Economic scenario*	*Extra shipping costs*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
G_H	Low	€ 22,199,646	€ 2,343,166	€ 920,605	€ 59,040,328	€ 62,304,099
	High	€ 27,043,205	€ 2,854,402	€ 1,121,464		€ 63,016,194
W_L	Low	€ 23,950,484	€ 2,112,498	€ 941,721		€ 62,094,547
	High	€ 29,176,044	€ 2,573,407	€ 1,147,187		€ 62,760,922
$W_{H,dry}$	Low	€ 107,901,069	€ 3,620,743	€ 7,045,648		€ 69,706,719
	High	€ 131,443,120	€ 4,410,723	€ 8,582,881		€ 72,033,932
G_L	Low	€ 12,659,720	€ 1,793,647	€ 324,258		€ 61,158,233
	High	€ 15,421,841	€ 2,184,988	€ 395,006		€ 61,620,322
W_H	Low	€ 34,312,234	€ 2,537,778	€ 1,845,065		€ 63,423,171
	High	€ 41,798,539	€ 3,091,475	€ 2,247,624		€ 64,379,427

table 39: Overview of costs in the two considered situations and scenarios for 2085

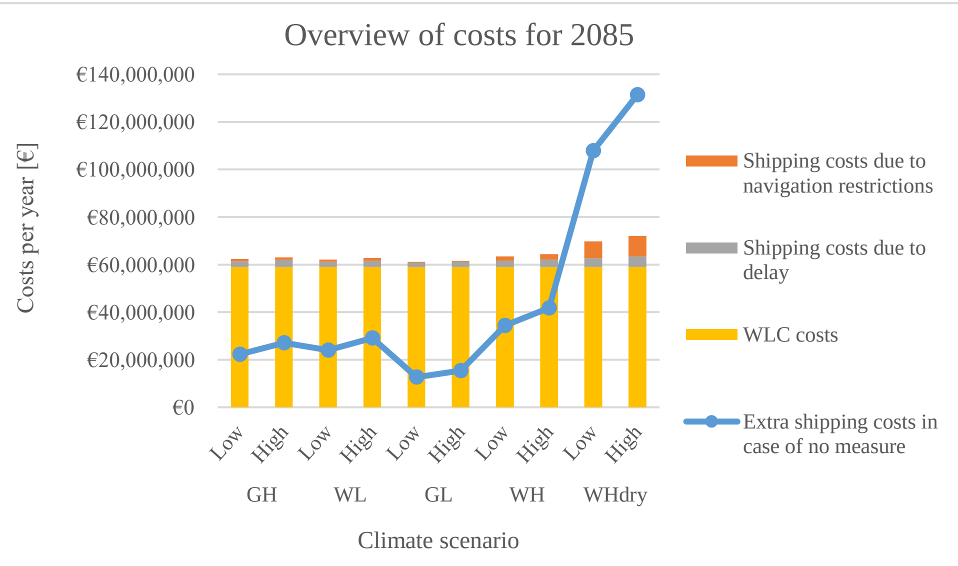


figure 40: Overview of costs in the two considered situations and scenarios for 2085

As can be observed from table 38 and table 39, the total shipping costs in case of canalization are lower than in case without measure for all scenario combinations. Therefore, canalization is a plausible measure for all scenarios to improve the navigability of the River Waal. This results in a plausibility for canalization of 100%. However, taking the total costs due to canalization into account, only in case of the most extreme climate scenario these costs are lower than the shipping costs due to climate change in the situation without measure. Canalization is marked as a feasible measure if the total costs due to canalization are lower than the costs due to climate change without measure. Therefore, it can be said that only in case of the $W_{H,dry}$ scenario the construction of one weir is a feasible measure in order to reduce the navigation restrictions on the River Waal. In case of the other climate scenarios, the shipping costs will reduce a lot, but the costs of the WLC will not be compensated enough by these smaller shipping costs. However, looking to the total costs due to canalization, this results in a feasibility of 20% for canalization as measure to improve the navigability of the River Waal. These results are schematically shown in figure 41.

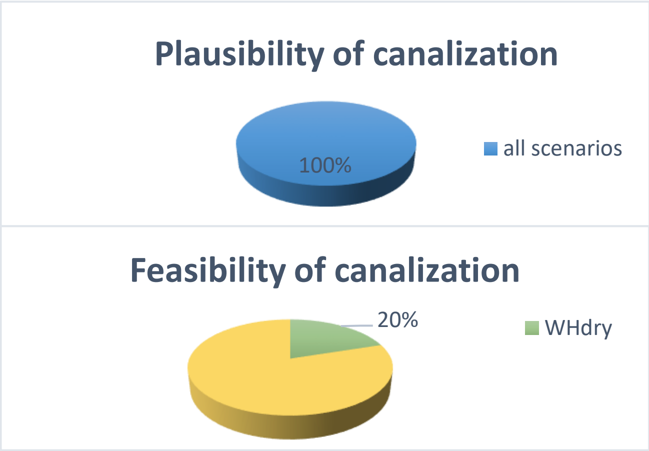


figure 41: Plausibility and Feasibility [%] of Waal canalization as measure to improve the navigability

The results depend on the most optimal solution of the second analysis, which was based on the yearly discharge distribution of 2003 and the high economic scenario for 2050. This does not mean that the costs due to canalization obtained in this paragraph are the lowest possible costs. After all, a WLC with a maximum head of 8.0 meter is unlikely to be optimal for all scenarios. To give more insight in the feasibility of one WLC, the relation between the WLC costs, head and total costs must be further investigated.

In addition, from table 38 and table 39 it can be observed that the annual WLC costs are already higher than the extra shipping costs due to only climate change, except in case of the $W_{H,dry}$ climate scenario. This means that the total costs due to canalization can never be lower than in the situation without measure. Looking to the total WLC costs, these are approximately €1200 million (when H = 8.0 m). This might be a bit large for only one WLC. Because the annual WLC costs do mainly determine the total costs, the feasibility of canalization depends much on these costs. As has been said earlier, the parameters used to determine the construction costs are very rough. Therefore, it is valuable to investigate the effects of various WLC costs on the feasibility of Waal canalization. This will be done by a sensitivity analysis in the next sub- paragraph.

Sensitivity analysis

During the sensitivity analysis, the feasibility of canalization for various WLC costs is investigated. The WLC costs are very uncertain, but have a great influence on the total costs due to canalization and therefore they determine mainly the feasibility of Waal canalization. The sensitivity of the WLC costs gives an indication of the expected feasibility.

To give some insight in the feasibility of one WLC with a certain head for the different scenarios, the relation between the WLC costs and maximum head is computed and shown in figure 42. As can be observed from this graph the WLC costs with a head above 4 meter are higher than the extra shipping costs when no measure is taken. In addition, the extra shipping costs due to navigation restrictions and delay have not yet been considered. It can be foreseen that costs due to navigation restrictions will increase significantly by lowering the head. Therefore, based on these values it is not expect that one WLC could be feasible for the scenarios considered.

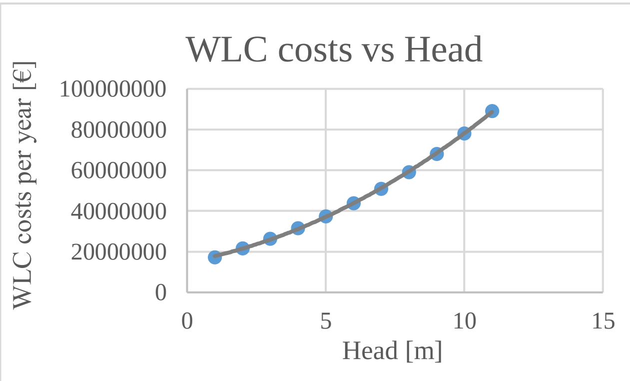


figure 42: Relation between annual complex costs and head

However, the total WLC in the above situation are quite high and therefore the accuracy of these values is questioned. Therefore, the effects of various WLC costs on the feasibility of Waal canalization will be investigated. During this analysis, the WLC costs are 250, 500, 750 and 1000 million Euro to obtain several results. The results are included in Appendix IX. It can be observed that the WLC costs do have a great impact on the total costs. For WLC costs about 250 million Euro, canalization is a feasible measure for all scenario combinations. However, real insight will be obtained by determining the feasibility of canalization dependent on the WLC costs. For various WLC costs, it is investigated whether the total costs due to canalization are lower than the shipping costs due to climate change without measure. This is executed by a positive or zero score for each scenario combination given a certain value for the WLC costs. The tables that show this complete analysis are included in Appendix IX. The outcome of this inventory is shown in table 40 and the corresponding visualization is shown in figure 43.

	Feasibility [%]										
Total WLC costs [mln]	200	300	400	500	600	700	900	1400	1700	2200	2600
2050	100%	100%	60%	40%	30%	20%	20%	10%	0%	0%	0%
2085	100%	80%	80%	60%	60%	30%	20%	20%	20%	10%	0%

table 40: Feasibility of canalization for various WLC cost

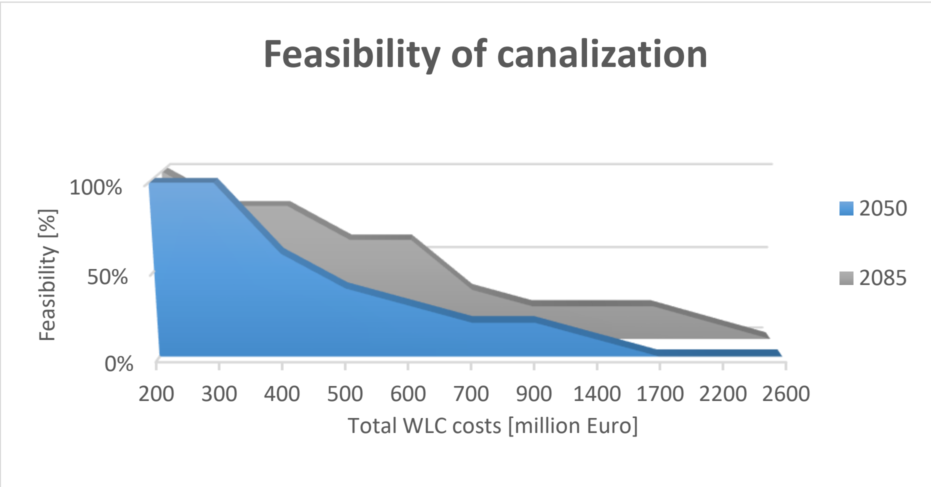


figure 43: Feasibility of canalization for various WLC costs shown graphically.

The inventory of the feasibility of canalization for various WLC costs shows the sensitivity of the WLC costs on this feasibility. For total WLC costs below 400 million Euro the feasibility of Waal canalization is quite high, which means that for many scenario combinations the costs due to canalization are smaller than the costs in case without measure. However, for WLC costs between 400 million Euro and 900 million Euro the feasibility is decreased to 20%, which can be marked as quite low. Thereafter, the feasibility reaches 0% for the year 2050 in case of WLC costs larger than 1700 million Euro. For the year 2085, 0% feasibility is reached when the WLC costs become larger than 2600 million Euro. However, it is expected that that WLC costs with a value much higher than 1000 million Euro are not likely for one WLC. This could mean that at least 20% feasibility will be obtained. However, it is hard to indicate what the exact WLC costs will be without having any conceptual design. Therefore, the feasibility of canalization cannot be quantified by hard values. In addition, there is given an indication of the expected feasibility for various WLC costs.

Conclusion

For all scenario combinations, the total shipping costs in case of canalization are lower than the shipping costs in case without measure. Therefore, canalization is a plausible measure for inland shipping to improve the navigability of the River Waal. However, taking the total costs due to canalization into account, only in case of the most extreme climate scenario these costs are lower than the shipping costs due to climate change in the situation without measure. Therefore, it can be said that only in case of the $W_{H,dry}$ scenario the construction of one weir is a feasible measure in order to reduce the navigation restrictions in the River Waal. This results in a feasibility of 20% for canalization as measure to improve the navigability of the River Waal. However, the WLC costs are very uncertain and have a big effect on the total costs due to canalization. Therefore, the feasibility cannot be given by hard values, but an indication of the expected feasibility for various WLC costs is given.

8.7 Conclusion

This chapter has shown the investigation to the most optimal way of canalization and the consequences of this canalization for several climatic- and economic scenarios. Therefore, sub question 3 is answered by this chapter. These results are compared with the consequences due to climate change without measure, which was questioned in sub question 2 and investigated in chapter 7. From this comparison follows whether canalization is a plausible measure to improve the navigability of the River Waal. So, the research question can be answered after this chapter. In this paragraph, the conclusions that can be drawn from the research to the consequences of Waal canalization, are included.

The costs due to canalization depends on the number of WLCs and the created water depth. On basis of the total head over the entire route it is determined that the area of interest, relating to the number of WLCs, is one to three WLCs. It must be noted that the parameters used in the formula method are quite rough and therefore the absolute values are possibly not very accurate. However, it can be used well for comparing the different combinations of number of WLCs with various heads. The most optimal way of canalization is based on the annual discharge distribution of 2003 and the high economic scenario for 2050.

From the first analysis, it can be concluded that for this area of interest, it is more attractive to permit some navigation restrictions by applying a lower head than is required for no navigation restrictions. However, the assumptions about the construction costs parameters, the cost key figures from 2008 and the linear bottom slope in the backwater curve calculation are not very realistic and therefore these aspects are improved to obtain more reliable results. In the second analysis, the improvements are considered and it is investigated that one WLC with a head of 8.0 meter is the most optimal option for canalization of the River Waal.

During the scenario analysis, the consequences of this optimal way of canalization for various future scenarios is investigated to get insight in the range of possible outcomes. From this analysis, it follows that the shipping costs for all scenario combinations are lower in case of canalization than in case without any measure, which makes canalization a plausible measure to improve the navigability of the River Waal for inland shipping. Looking to the more integral picture, the total costs due to canalization are only in case of the most extreme climate scenario lower than the shipping costs in case without any measure. For all other scenarios, the total costs due to canalization are much higher. Therefore, it can be concluded that only in case of the most extreme climate scenario one WLC might be an attractive measure to reduce the navigation restrictions and corresponding shipping costs. However, the most optimal value for the head over the structure is not necessarily 8.0 meter as has been calculated in the second analysis. In addition, the WLC costs are very uncertain and have a big effect on the total costs due to canalization. Therefore, the sensitivity of the WLC costs on the feasibility of canalization is investigated during the sensitivity analysis to give an indication of the expected feasibility for various WLC costs. For total WLC costs below 400 million Euro the feasibility of Waal canalization is quite high in both time horizons, which means that for many scenario combinations the costs due to canalization are smaller than the costs in case without measure. For the year 2050, the feasibility decreases to 20% if WLC costs are equal to 900 million Euro and reaches 0% for WLC costs larger than 1700 million Euro. In 2085, the feasibility is more than 50% for WLC costs until 600 million Euro. For values of the WLC costs between 600 million Euro and 2100 million Euro, the feasibility decreases to 20% and for values larger than 2600 million Euro 0% is reached.

9 Conclusions and Discussion

9.1 Conclusions

This research describes the effects of low discharges in the River Waal caused by climate change on the inland shipping sector. Two different situations are investigated, one without any measure and one with canalization of the river. These two situations are compared with a zero variant where no navigation restrictions occur and therefore a so- called reference situation is also investigated. The focus is on the direct costs for the inland shipping sector due to navigation restrictions caused by insufficient water depth and canalization. Besides, the more integral picture is taken into account by the total costs due to canalization, which consist of the shipping costs due to canalization and the WLC costs. The research question that is answered in this study is as follows:

"Could canalization be a plausible measure to improve the navigability of the River Waal under climate change from a financial point of view?"

Canalization is defined as a plausible measure for improving the navigability of the River Waal when the shipping costs in case of canalization are lower than the shipping costs due to climate change without any measure. However, the more integral picture shows whether canalization is a feasible measure. When the total costs due to canalization are lower than the shipping costs due to climate change without measure, canalization can be marked as feasible.

For studying the effects of the different developments on the inland shipping sector an effect model is developed, validated and used. This model requires the following inputs: the normative depth each day during a year, the characteristics of the normative vessel and the total freight transported by inland shipping. Using this information, the model is calculating the load factor for each day and this results in the required number of loaded trips per year for transporting the amount of cargo. Subsequently, the total shipping costs in case of navigation restrictions can be calculated and is given as output of the model. Comparing these shipping costs with the total shipping costs of the reference situation, the extra shipping (or damage) costs due to navigation restrictions can be computed.

In the situation without any measure the shipping costs are determined based on two different cost key figures, because during the research it was found that the key figures from 2008 give unrealistic high values and therefore new cost figures from 2014 are applied. Using the cost figures from 2008, the extra shipping costs in case of the most extreme climate scenario are more than 100 million Euro for the year 2050. For the year 2085, the highest extra shipping costs are almost 200 million Euro. Using the cost figures from 2014, the extra shipping costs are lower. In case of the scenario $W_{H,dry}$ the highest costs are up to a maximum of 83 million Euro for 2050 and 132 million Euro for 2085. The other scenarios lead to extra costs between 17 million Euro and 35 million Euro for the year 2050 and between 12 million Euro and 42 million Euro for 2085. So, the extra shipping costs in case of the $W_{H,dry}$ scenario are significantly higher than in case of all other scenarios. There is also influence of the economic scenario on the absolute value of the extra shipping costs, but the percentage additional costs are the same. However, the differences in extra shipping costs are mainly determined by the climate scenarios.

The shipping costs in case of canalization are determined for the most optimal option of canalization, which is defined as the option with the lowest total costs due to canalization. For each scenario, there is a different optimum and therefore only for one (representative) situation the optimal canalization option is investigated. The representative situation is based on the annual discharge distribution of 2003 and the high economic scenario for 2050, because it is expected that the discharge distribution from 2003 occurs yearly around 2050. The optimization of the canalization is fully determined by the number and the dimensions of the WLCs, because the costs due to canalization depend on the number of WLCs and the created water depth.

Based on the total head over the entire route it is determined that the area of interest, relating to the number of WLCs, is from one to three WLCs. It must be noted that the parameters used in the formula method are quite rough and therefore the absolute values are possibly not accurate. However, it can be used well for comparing the different combinations of number of WLCs with various heads.

During a first analysis, the financial consequences of climate change and canalization are elaborated to investigate the most optimal way of canalization. From this analysis, it can be concluded that for the area of interest, it is more attractive to permit some navigation restrictions by applying a smaller water retaining height of the weir than is required for no navigation restrictions. However, the shipping costs will rise quite fast by accepting a smaller head and therefore this will not compensate the smaller WLC costs by a big lowering of the head over the WLC. In addition, some assumptions have a major effect on the results and therefore the reliability of the results was questioned. To create more reliable results, several improvements have been made, such as adapting the WLC costs, considering the real bottom slope, new cost key figures for inland shipping and the required dike height.

During the second analysis, these improvements are applied to investigate the most optimal way of canalization with reliable values. Based on this analysis, it can be concluded that one WLC with a head of 8.0 meter is the most optimal canalization option for the River Waal in the considered situation. The shipping costs are lowered from about 60 million Euro to about 7.5 million Euro and therefore canalization is a plausible measure for improving the navigability for inland shipping. Looking to the more integral consequences, the total costs due to canalization are lower than the total costs due to climate change without measure. Therefore, the benefits of canalization do counteract the shipping costs in case without measure. The consequences of canalization in case of other future scenarios for this canalization option must be investigated to get insight in the range of possible outcomes.

The scenario analysis shows that the shipping costs for all scenario combinations are lower in case of canalization than in case without any measure. Looking to the more integral picture including WLC costs for construction, maintenance and operating, the total costs due to canalization are only in case of the most extreme climate scenario lower than the shipping costs in case without any measure. For all other scenarios, the total costs due to canalization are much higher. However, it has been noted that the WLC costs are the biggest part of the total costs and they are not very reliable. Because no conceptual design is available, it is hard to improve the WLC costs and to quantify a reliable feasibility of canalization. Therefore, the sensitivity of the WLC costs is investigated to give an indication of the expected feasibility.

During the sensitivity analysis, the total costs due to canalization for various WLC costs are determined. For total WLC costs below 400 million Euro the feasibility of Waal canalization is quite high for both time horizons, which means that for many scenario combinations the costs due to canalization are smaller than the costs in case without measure. For the year 2050, the feasibility decreases to 20% if WLC costs are equal to 900 million Euro and reaches 0% for WLC costs larger than 1700 million Euro. In 2085, the feasibility is more than 50% for WLC costs up to 600 million Euro. For values of the WLC costs between 600 million Euro and 2100 million Euro, the feasibility decreases to 20% and for values larger than 2600 million Euro 0% is reached.

Summarizing: The River Waal is the main connection between the Port of Rotterdam and the hinterland and international freight transport by inland shipping is economically important for the Netherlands. Several developments, such as climate change, economic growth and scaling of the fleet affect inland shipping. Scaling of the inland fleet influences the vessel characteristics and climate change affects the river discharges and therefore the navigability of the fairway. Canalization is a possible measure to improve the navigability of the River Waal and can be marked as plausible, because the shipping costs in case of canalization are lower than the shipping costs in case without any measure. Taking the more integral picture inclusive construction, maintenance and operational costs of a WLC into account, it is hard to indicate whether canalization is also a feasible measure because the WLC costs are very uncertain and these have a major effect. Therefore, an indication of the expected feasibility for various WLC costs is given. For WLC costs up to 600 million Euro the feasibility is more than 50% in 2085. For higher values of the WLC costs, the feasibility decreases to 20% and finally to 0%. It is expected that 1000 million Euro is quite large for one WLC and therefore it is assumed that a feasibility of at least 20% is reached.

9.2 Discussion

In this chapter the positioning of the research is described. The relation with other studies and the contribution to the work field are discussed. Furthermore, the interpretation of the results and the limitations of the research are addressed. First, the positioning of the research in relation to existing studies is described.

Research to the “very long term development of the Dutch inland waterway transport system up to the year 2100” indicated that the River Rhine up to Ruhrort may no longer remain all year round navigable in the most extreme climate scenarios towards the year 2100 (van Dorsser, 2015). So, the Dutch branches of the River Rhine involving the River Waal, the Nederrijn/Lek, and the Gelderse IJssel will be affected by climate change.

Before the research of van Dorsser (2015), there have been done several other researches to the effect of climate change on inland shipping. Bosschieter (2005) studied the effects of climate change on the discharge distribution of the River Rhine and what the impacts of these effects are on inland shipping. Several measures to avoid the effects of low water levels and water shortage have been discussed in this research as well. One measure was canalization of the river. However, this was only marked as realistic if the extra waiting costs do outweigh the increasing loading capacity.

Recently, Deltares (2015) has assessed changes in discharges for the River Rhine and River Meuse resulting from the new KNMI'14 climate scenarios and the CMIP5[3]. Discharge distributions for two time horizons of the different climate scenarios are developed. Older studies to the effect of climate change on inland navigation have used the climate scenarios of 2006. There are no recent studies that take the discharge distributions of Deltares (2015) into account. However, these discharge distributions are especially developed for the Rhine basin and therefore more accurate than older modelled distributions.

The possible measure river canalization, to maintain sufficient water depth, need to be properly investigated, because it has a major impact on inland shipping. The newest climate scenarios and corresponding discharge distributions give the most reliable results. Therefore, this research has investigated the effect of climate change on inland shipping and the costs of the canalization. The research is based on the most recent climate scenarios to get reliable insight in the consequences of this measure.

It is important to know the effects of climate change on the navigability of the river and the impact on inland shipping. Therefore, this research contributes to the determination whether and what kind of measure is most favourable for improving the navigability of the River Waal. However, it is also good to think about the impact of a worse navigability of the fairway on other transport modes. If inland shipping becomes less reliable, more expensive and therefore less attractive it is possible that model shift takes place. This in turn may possibly lead to capacity problems for road and rail and again economic impact is foreseen. Therefore, the impact of a worse river navigability can be large, not just for inland shipping. Besides, it may be useful to invent different measures that can improve the navigability of the fairway to oversee the possible options. Because canalization is a possible measure with large impact on inland shipping, it is necessary to investigate this measure and get insight in the consequences due to canalization. This research shows the effects of climate change on the navigability and the effects of canalization. Other side effects of a worse river navigability and canalization are not taken into account. However, these side effects could be important for the integral picture. In addition, assumptions are made to simplify the approach, but these will probably deviate from the reality. Therefore, the interpretation of the results and the limitations of this research are important to know for the implication of this study. In the next paragraphs, important aspects and limitations will be discussed.

The assumptions and calculations in the effect model approaches the reality. For example, it is assumed that the relation between the draught and loading capacity is linear. However, it differs per ship what the corresponding loading capacity and draught are. Another example is the use of a normative vessel. This vessel represents the shipping fleet, but it is not the same. Therefore, the absolute results obtained with the effect model have a certain error. Because the shipping costs in both situations are calculated with the same model, the error is for both situations the same. When the values are compared with each other, the relative values give reliable information and the differences between the two situations can be obtained. However, it must be noted that it is expected that the absolute value of the shipping costs contains an error. Because it is unknown how big this error is, it is advisable to use these values with caution.

The assumption for the number of days that the weirs are closed may not be completely correct. Because the number of days the weirs are closed is assumed to be equal to the number of days that the normal water depth is lower than the required water depth. However, the increase in water level upstream of the weir takes some time and therefore several days before the critical depth is reached, the weir must already be closed. In addition, there was no requirement on the sequence of days. Therefore, it is expected that the shipping costs due to delay are somewhat higher than the costs shown in this research.

If the results about the navigability of the River Waal are compared to the results of the study by van Dorsser (2015), it can be observed that for the most extreme climate scenario the same lowest navigable depth of 1.5 meter occurs. For the other scenarios, the water depths that occur are somewhat smaller in this research than in the research of van Dorsser. However, van Dorsser found these water depths at Lobith and not at Nijmegen and the climate scenarios used are slightly different in both studies. For a water depth of 1.5 meter, the river becomes

[3] Coupled Model Inter- comparison Project

unnavigable for a lot of vessels. This means that it is not logic the vessel will sail during such low water periods. However, in this research it is assumed that trips always take place, so it does not matter how much the reduction in loading capacity is. This is not realistic in case when the navigation depth is so small that only a minimum part of the loading capacity can be used. Because, it is unknown what the effect is of such small water depths, it is not considered. It is possible that the same amount of cargo is transported by another transport mode, but it could also be that the vessels are waiting a few days on higher water levels and so increase their loading capacity.

It is assumed that bed subsidence does not take place due to sufficient measures against bottom erosion. However, Havinga (2012) has indicated that bottom erosion can reduce the available water depth on the Benedenrijn by about 60 centimetres over the next 30 years if insufficient counter measures are taken. This means, that in case of insufficient measures against bottom erosion, the navigability is worse than is shown in this study. Because future policy is uncertain, it is important to know what the possible effects are if bed subsidence takes place. Van Dorsser (2015) found that a water depth of 1 meter can occur at Lobith, then navigation is not possible.

Krekt et al (2011) has studied the effects of canalization on the shipping costs. It was found that the cost reduction due to canalization in case of the W+ climate scenario (2006) is equal to 317 million Euro annually. This is more than 1.5 times higher than in this research is obtained. Different climate and economic scenarios have been used in both studies. The economic scenarios about freight transport are adjusted downwards after the economic crisis of the past year and this might cause the differences. However, it is not clear whether the different scenarios are the (only) reason. It can be noted that approximately the same order of magnitude is obtained in both studies.

There was no information available about the usage of different shipping routes, but it was known that the shipping route between Rotterdam and Duisburg is the most important one. Therefore, this route is assigned to all vessels that sail over the River Waal. Because only the shipping route between Rotterdam and Duisburg is taken into account, other important shipping routes are not considered in this research and it is not known what the effect is on the absolute shipping costs. However, in the situation with- and without measure the same assumption is used and therefore these situations can be compared with each other without any problem.

The effect on vessels that sail over the River Nederrijn and River IJssel is not investigated, while the water levels in the River IJssel are also low during dry periods and therefore the vessels here experience navigation restrictions as well. Of course, the River IJssel is much smaller than the River Waal and less ships use this fairway, therefore the shipping costs due to navigation restrictions will be lower. Also, the effect of Waal canalization on the navigability of the River IJssel is not studied yet, but it is possible that this navigability will also improve due to larger water depths in the River Waal. The discharge distribution at Pannerdensch Kop is possibly changing, but this is out of the scope of this project. Which does not mean that it should not be investigated, because it may also have consequences for the discharge flowing into the River Waal.

The total freight transport by inland shipping is split into three different cargo types, namely liquid bulk, dry bulk and container transport. The distribution of these different cargoes determines the amount of freight expressed in tons for each type. It is assumed that all vessel types experience navigation restrictions. However, container transport is often expressed in TEU and not in tonnage. In addition, during this study it was found that for container vessels the maximum loading capacity in TEU is mostly achieved earlier than the maximum loading capacity in tonnes. Therefore, navigation restrictions for container vessels are not often limited by water depth but by height of bridges or stability reasons of the vessel itself. These vessels experience less limitations of low water levels but just in case of high water levels due to insufficient navigation height. Therefore, the assumption that all vessel types do experience the same hindrance is probably not correct. This has resulted in an error of the absolute extra shipping costs in both situations. It is expected that shipping costs due to navigation restrictions become lower when the actual navigation restrictions by insufficient water depth for container vessels are taken into account. Because this is a comparison study, the relative differences in shipping costs due to navigation restrictions for both situations remain the same. However, the total costs due to canalization consists of two other components as well and therefore it has influence on the total results. When it is assumed that there are no navigation restrictions for container vessels, which seems to be a better assumption, a quick analysis to the effect on the results can be made. Container transport is 25% of the total freight transport by inland shipping and therefore it is responsible for roughly 25% of the shipping costs due to navigation restrictions. This is not completely correct, because the cost prices differ per ship type. The cost prices for container transport are a bit higher than for other cargo types, but it gives a good first indication of the effects on the results. The new shipping costs are 75% of the old costs and this results in the effect that only for the year 2085, the total costs due to canalization are lower than in case without any measure. For all other scenarios, the costs due to canalization are bigger than in case without measure. In order to minimize the error due navigation restrictions of container vessels, a complete calculation must be done.

The most optimal way of canalization is determined for the stretch between Woudrichem and the German border, based on the assumption of equal distance between the WLCs and the normative depth at Nijmegen. Because Nijmegen was assumed to be normative, only at this location the navigation depth is considered. Therefore, the effect of climate change on the navigation depth at other locations in the River Waal is not investigated. Since it is investigated that one WLC is the most optimal option, the question arises whether Woudrichem is the best location. Because Nijmegen is located 68 km upstream of Woudrichem the distance between the weir and the navigational bottleneck is quite large. This research has not considered the most optimal location of the weir WLC. However, a fixed layer is located at St. Andries and therefore this location is also considered to be critical. It is expected that the weir must be located downstream of St. Andries, because otherwise this location will lead to navigation restrictions. St. Andries is located 26 km upstream of Woudrichem, so it is expected that the weir could move maximal this distance upstream. Displacing the weir upstream leads to a smaller required head over the weir, which has a positive effect on the WLC costs. However, this is a hypothesis and there is no well-funded research.

10 Recommendations

In this chapter, several recommendations are given based on the conclusions and discussions previously described. The recommendations can be divided into two categories. The fist category consists of recommendations about the research method, assumptions and possibilities to improve the reliability of the results. The second category is about the more integral picture of the impact of climate change and canalization.

As has been said many times before, the WLC costs cannot be determined accurately and therefore the reliability of these costs is very low. For the integral consequences of canalization, it is important to have more accurate values for the WLC costs. However, this can only be obtained by having a conceptual design. This conceptual design needs information about for example dimensions and material usage. Subsequently a cost estimate on basis of this design can be made. Therefore, it is recommended to make a conceptual design and a cost estimate of the WLC.

The shipping costs are determined for one normative vessel that represents the future shipping fleet. To improve the accuracy of the results, a shipping fleet should be used instead of a normative vessel. Because different vessel types have different characteristics which can be considered and a more detailed analysis can be done. In particular, the distinction between container vessels and other vessel types can be made more easily. Using a shipping fleet, also various developments can be included such as containerization and the transition to sustainable energy which reduces the transport of coal a lot. Therefore, it is recommended to use a future shipping fleet taking into account various possible developments to create more accurate results and insight in the range of possible consequences.

Because the effect of canalization on the water depth is determined by a backwater curve calculation only, it is questioned whether the results of this calculation are accurate enough because in this research they have not been compared with an alternative method. Therefore, it is recommended to do further research on the navigation depth in case of canalization. For example, a hydraulic model such as SOBEK can be used to investigate the effect on the water levels due to the construction of a weir in the River Waal.

The most optimal location for the WLC is not investigated in this study. To obtain this most optimal location, research to the effect of climate change on the navigation depth at other locations in the River Waal is needed. In addition, another location for the weir than Woudrichem affects the WLC costs, because it might be that the optimal head over the structure changes. Therefore, a new analysis must be elaborated to obtain the most optimal retaining height of the weir and the effects on the inland shipping sector. So, a recommendation is given for research to the optimal way of canalization, including the location, the dimensions and the effects on the shipping and WLC costs for the various scenarios.

Because a worse river navigability could also affect other transport modes if modal shift takes place, it is useful to investigate the overall effects and not just the effects on inland shipping. Therefore, research to the impact of climate change on the reliability of inland shipping and the effect on model split must be done. Subsequently, if modal split takes place, the consequences for each transport mode must be investigated, such as capacity and economic impact. In addition, the effect of climate change on the navigability of the Nederrijn and River IJssel do also contribute to the extra shipping costs. How big this contribution on the extra shipping costs will be must be investigated in further research because this was out of the scope of this research.

The effect of Waal canalization on the water level in the River IJssel is not investigated yet, but it could be that the navigability will improve due to larger water depths in the River Waal. In addition, the discharge distribution at Pannerdensch Kop is possibly changing and this might also affect the discharge flowing into the River Waal. It is recommended to investigate the effects of Waal canalization on the discharge distribution at Pannerdensch Kop and subsequently the impact on the discharge in the River Waal and River IJssel.

Based on the results of the shipping costs due to climate change compared to the shipping costs with no restrictions, it can be concluded that inland shipping experience such restrictions that a measure must most likely be taken. Therefore, it is recommended to investigate several other possible measures that avoid navigation restrictions. Because, it is impossible to mark canalization as suitable solution without doing well- funded research to alternative measures.

Policy implications can be made on basis of the researches to the overall effects of climate change and Waal canalization in combination with the alternative solutions. At this stage, there is too less research on this subject that well- funded policy is not possible and therefore recommendations about policy implications cannot be given here.

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List of tables and figures

Figures

Tables

Appendix I

Inland shipping

Overview Dutch fairways

CEMT class characteristics

Fleet development

Room for the river measures

Overview Dutch fairways

figure 44: Map of Dutch fairways (Rijkswaterstaat, 2009)

CEMT class characteristics

Motorvrachtschepen (Motorvessels)								Doorvaart-hoogte incl. 30 cm schrikhoogte
CEMT-klasse	RWS/CBS-klasse	Karakteristieken maatgevend schip*				Classificatie		
		Naam	Breedte	Lengte	Diepgang (geladen)	Laadvermogen	Breedte en lengte	
			m	m	m	t	m	m
0	M0	Overig				1-250	B < = 5,00 of L < = 38,00	
I	M1	Spits	5,05	38,5	2,5	251-400	B = 5,01-5,10 en L > = 38,01	5,25**
II	M2	Kempenaar	6,6	50-55	2,6	401-650	B = 5,11-6,70 en L > = 38,01	6,1
III	M3	Hagenaar	7,2	55-70	2,6	651-800	B = 6,71-7,30 en L > = 38,01	6,4
	M4	Dortmund Eems (L < = 74 m	8,2	67	2,7	801-1050	B = 7,31-8,30 en L = 38,01-74,00	6,6
	M5	Verl. Dortmund (L > 74 m)	8,2	80-85	2,7	1051-1250	B = 7,31-8,30 en L > = 74,01	6,4
IV	M6	Rijn-Herne Schip (L < = 86 m)	9,5	80-85	2,9	1251-1750	B = 8,31-9,60 en L = 38,01-86,00	7,0**
	M7	Verl. Rijn-Herne (L > 86 m)	9,5	105	3,0	1751-2050	B = 8,31-9,60 en L > = 86,01	7,0**
IVb								7,0**
Va	M8	Groot Rijnschip (L < 111 m)	11,4	95-110	3,5		B > 9,60-11,50 en L > = 38,01-<111	9,1**
	M9	Verlengd Groot Rijnschip (L > 111 m)	11,4	135	3,5		B > 9,60-11,50 en L > = 38,01-<111	9,1**
Vb								9,1**
VIa		Rijnmax Schip	17,0	135	4,0		B > 11,51 en L > = 38,01	7,0**

figure 45: CEMT class characteristics for motorvessels (Rijkswaterstaat, 2009)

Duwstellen (Barges)								Doorvaart-hoogte incl. 30 cm schrikhoogte
CEMT-klasse	RWS/CBS-klasse	Karakteristieken maatgevend duwstel*				Classificatie		
		Combinatie	Breedte	Lengte	Diepgang (geladen)	Laadvermogen	Breedte en lengte	
			m	m	m	t	m	m
I	BO1		5,2	55	1,9	0-400	B < = 5,20 en L = alle	5,25**
II	BO2		6,6	60-70	2,6	401-600	B = 5,21-6,70 en L = alle	6,1
III	BO3		7,5	80	2,6	601-800	B = 6,71-7,60 en L = alle	6,4
	BO4		8,2	85	2,7	801-1250	B = 7,61-8,40 en L = alle	6,6
IV	BI	Europa I duwstel	9,5	85-105	3,0	1251-1800	B = 8,41-9,60 en L = alle	7,0**
Va	BII-1	Europa II duwstel	11,4	95-110	3,5	1801-2450	B = 9,61-15,10 en L < = 111,00	9,1**
	BIIa-1	Europa IIa duwstel	11,4	92-110	4,0	2451-3200	B = 9,61-15,10 en L < = 111,00	9,1**
	BIIL-1	Europa II Lang	11,4	125-135	4,0	3201-3950	B = 9,61-15,10 en L = 111,01-146,00	9,1**
Vb	BII-2l	2-baksduwstel lang	11,4	170-190	3,5-4,0	3951-7050	B = 9,61-15,10 en L > = 146,01	9,1**
VIa	BII-2b	2-baksduwstel breed	22,8	95-145	3,5-4,0	3951-7050	B = 15,11-24,00 en L < = 146,00	7,0**
VIb	BII-4	4-baksduwstel (incl. 3-baks lang)	22,8	185-195	3,5-4,0	7051-12000 (7051-9000)	B = 15,11-24,00 en L = 146,01-200	9,1**
VIc	BII-6l	6-baksduwstel lang (incl. 5-baks lang)	22,8	270	3,5-4,0	12001-18000 (12001-15000)	B = 15,11-24,00 en L > = 200,01	9,1**
VIIa	BII-6b	6-baksduwstel breed (incl. 5-baks breed)	34,2	195	3,5-4,0	12001-18000 (12001-15000)	B > = 24,01 en L = alle	9,1**

figure 46: CEMT class characteristics for push barges(Rijkswaterstaat, 2009)

Koppelverbanden (Convoys)								
CEMT-klasse	RWS/CBS-klasse	Karakteristieken maatgevend koppelverband*				Classificatie		Doorvaart-hoogte incl. 30 cm schrikhoogte
		Combinatie	Breedte	Lengte	Diepgang (geladen)	Laadvermogen	Breedte en lengte	
			m	*m*	*m*	*t*	*m*	*m*
I	C1l	2 spitsen lang	5,05	77-80	2,5	< = 900	B < = 5,1 en L = alle	5,25**
	C1b	2 spitsen breed	10,1	38,5	2,5	< = 900	B = 9,61-12,60 en L < = 80,00	5,25**
IVb	C2l	Klasse IV + Europa I lang	9,5	170-185	3,0	901-3350	B = 5,11-9,60 en L = alle	7,0**
Vb	C3l	Klasse Va + Europa II lang	11,4	170-190	3,5-4,0	3351-7250	B = 9,61-12,60 en L > = 80,01	9,1**
VIa	C2b	Klasse IV + Europa I breed	19,0	85-105	3,0	901-3350	B = 12,61-19,10 en L < = 136,00	7,0**
	C3b	Klasse Va + Europa II breed	22,8	95-110	3,5-4,0	3351-7250	B > 19,10 en L < = 136	9,1**
VIb	C4	Klasse Va + 3 Europa II	22,8	185	3,5-4,0	> = 7251	B > 12,60 en L > = 136,01	9,1**

figure 47: CEMT class characteristics for barge combinations (Rijkswaterstaat, 2009)

Fleet development

The following tables give information about the number of passages of different vessel types. table 41 gives data of the total fleet and table 42 of the fleet on fairway classes VI.

table 41: Number of ship passages per vessel type and RWS- class (translated from TNO (2010), completed with own calculations).

Vessel type	*RWS- class*	*2000*	*2008*	*growth %*	*average growth per year %*
Push barges	BII	3302	3769	14,1	***-0,1***
	BII-1	7360	7978	8,4	***1,0***
	BII-2b	3357	2374	-29,3	***-4,5***
	BII-2I	2784	2859	2,7	***-1,4***
	BII-4	6353	4220	-33,6	***-4,5***
	BII-6b	45	986	2091,1	***40,9***
	BII-6I	66	937	1319,7	***34,3***
	BIIL-1	2419	2863	18,4	***-0,4***
	BO1	102	160	56,9	***-2,8***
	BO2	243	508	109,1	***5,5***
	BO3	313	371	18,5	***-1,1***
	BO4	860	912	6,0	***11,3***
barge combinations	C1b	322	298	-7,5	***-0,8***
	C1I	469	551	17,5	***1,4***
	C2b	656	437	-33,4	***-5,7***
	C2I	1285	2063	60,5	***3,6***
	C3b	3061	1595	-47,9	***-7,1***
	C3I	5365	10707	99,6	***6,8***
	C4	476	1248	162,2	***11,2***
Motor vessels	M0	5174	4750	-8,2	***-5,4***
	M1	18593	7826	-57,9	***16,6***
	M2	65892	40350	-38,8	***-5,7***
	M3	55868	40968	-26,7	***-5,7***
	M4	60731	44212	-27,2	***23,4***
	M5	53684	44332	-17,4	***-2,9***
	M6	87092	76438	-12,2	***-1,8***
	M7	31724	27332	-13,8	***-2,6***
	M8	74889	107794	43,9	***2,7***
	M9	875	11144	1173,6	***34,3***

	M10	4556	14772	224,2	***12,6***
Total		*324486*	*499916*	*464754*	***-7,0***

table 42: Number of ship passages per vessel type and RWS- class for fairway CEMT class VI (translated from TNO (2010), completed with own calculations).

Vessel type	*RWS- class*	*2000*	*2008*	*growth %*	*average growth per year %*
Push barges	BII	1713	1697	-0,9	***-0,1***
	BII-1	4458	4890	9,7	***1,0***
	BII-2b	3178	2105	-33,8	***-4,5***
	BII-2I	2014	1771	-12,1	***-1,4***
	BII-4	6350	4176	-34,2	***-4,5***
	BII-6b	45	985	2088,9	***40,9***
	BII-6I	66	937	1319,7	***34,3***
	BIIL-1	1916	1847	-3,6	***-0,4***
	BO1	18	14	-22,2	***-2,8***
	BO2	111	179	61,3	***5,5***
	BO3	102	92	-9,8	***-1,1***
	BO4	130	340	161,5	***11,3***
barge combinations	C1b	274	256	-6,6	***-0,8***
	C1I	412	467	13,3	***1,4***
	C2b	589	346	-41,3	***-5,7***
	C2I	1180	1621	37,4	***3,6***
	C3b	3052	1570	-48,6	***-7,1***
	C3I	5171	9356	80,9	***6,8***
	C4	476	1235	159,5	***11,2***
Motor vessels	M0	2605	1580	-39,3	***-5,4***
	M1	13380	5491	-59,0	***-10,5***
	M2	33205	19656	-40,8	***-5,7***
	M3	33506	19684	-41,3	***-5,7***
	M4	33359	22347	-33,0	***-4,9***
	M5	35606	27318	-23,3	***-2,9***
	M6	55441	47061	-15,1	***-1,8***
	M7	24417	19242	-21,2	***-2,6***
	M8	60042	76576	27,5	***2,7***
	M9	693	9849	1321,2	***34,3***
	M10	3977	11529	189,9	***12,6***
Total		*324486*	*294217*	*-9,3*	***-1,1***

Room for the river measures

#	Description	Measure	Branch	Start - rkm	End – rkm
1	Rijnwaarden		Boven Rhine and Pannerdensch Kanaal	862.5	873.6
2	Millingerwaard	Construction of gullies	Waal	867.6	873
3	Bemmelsche Waarden	Flood plain excavation	Waal	878.2	881.4
4	Lent	Dyke relocation	Waal	881.5	914.7
5	Lowering of groynes Mid-Waal	Lowering of groynes	Waal	886.8	914.7
6	Afferdensche and Deetsche	Construction of gully and flood plain excavation	Waal	898.5	903.2
7	Longitudinal dams Tiel	Construction dams inner bend and lowering of groynes outer bend	Waal	911.5	921.5
8	Lowering of groynes Waal Fort St. Andries	Lowering of groynes	Waal	914.7	934.2
9	Lowering of groynes Waal		Waal	934.3	953.6
10	Munnikenland	Lowering of groynes	Waal	947.6	952.6
11	Avelingen	Construction of gullies and dyke relocation	Boven Merwerde	955.8	957.5
12	Noordwaard	Depoldering	Nieuwe Merwede	963.0	979.7

table 43: Description of measures with end- and begin- river kilometer (translated from: Sloff et al., 2015)

The effects of the Room-for-the-River measures shown above has influence on the water depth of the fairway and thus it is an important consequence for the navigability of the river. Especially the accretion at the beginning of the measure is normative for inland shipping. For the long-term effects, it is important to separate effects of the Room-for-the-River measures from the effects without these measures. For example, subsidence of the river bed does occur and is about a few centimeters per year. (Sloff et. al., 2014)

According to Sloff et. al. (2014) the fixed layer at Nijmegen (rkm 883 – rkm 885) remains after implementing of the Room- for-the-River projects the most critical point of the River Waal with regards to the navigable depth. On the long term, no new bottlenecks will arise and the location at Nijmegen remains normative. The depth at the fixed layer near Nijmegen decreases in time as a result of ongoing subsidence of the environment. Also at St. Andries (rkm 925 – rkm 928) a fixed layer is present; however, the effect is less because the subsidence at this location is much less compared to Nijmegen. The Room-for-the-River measures reduce the development of subsidence, because relative sedimentation slow down the subsidence. Therefore, the navigation depth at Nijmegen decreases slower in time compared to the reference situation where no measures are taken (Sloff et. al., 2015). The development of the minimum depth at low water relative to the agreed low water level (in Dutch: OLR) including the Room-for-the-River measures over the entire Waal is shown in figure 48. This graph shows clearly the development in time and the most critical location around river kilometer 884 which is at Nijmegen.

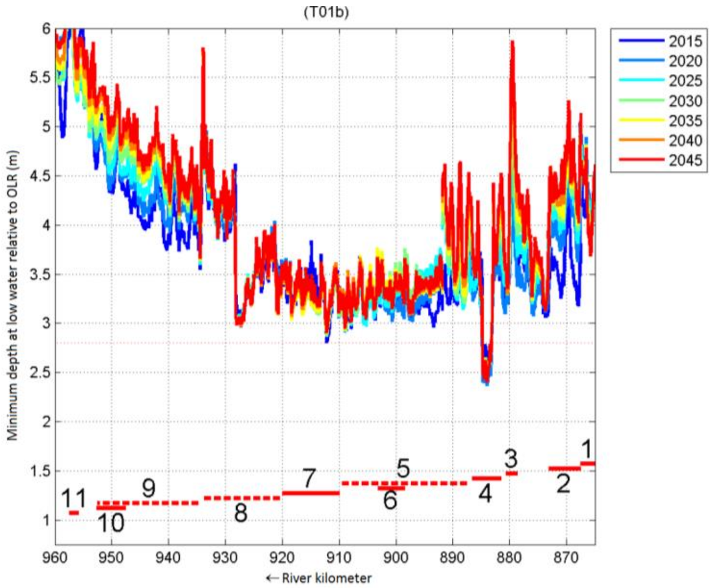


figure 48: Development of the minimum depth relative to low water including room-for-the-River measures (translated from: Sloff et al., 2015)

Appendix II:

River Canalization

Number of weirs- and lock complexes

Navigation locks

Backwater curve Theory

For the information shown under the headings *Number of weirs- and lock complexes* and *Navigation locks* a general reference is made to Molenaar et al (2011).

Number of weirs- and lock complexes

The number of weirs and locks depends on several variables. There are two kind of variables: boundary conditions, such as the area of interest and their characteristics, and situation depended conditions, such as construction costs and costs for inland shipping. Therefore, an iterative process is needed to determine the optimal amount of WLCs. The variables that will take into account in the iterative process to the determine the number of WLCs, are:

- WLC costs, consists of:
    - Construction costs of the weir- and lock- complexes
    - Costs of mitigating measures (raising dikes, bottom protection etc.)
    - Maintenance and operational costs
- Extra costs for inland shipping (due to passing and waiting times at locks)

First, the boundary conditions have to be investigated. The most important conditions are total head over- and length of the shipping route. Therefore, we have to look to the area of interest and this area is the shipping route between Rotterdam and Duisburg.

Navigation locks

There are three main functions of a navigation lock, namely:

1. Water retention;
2. Ship passage;
3. Water quality management.

These functions are important to determine the necessary lock components, but also to prepare the design criteria for the navigation lock or finding the quantitative requirements the lock should suffice to.

Water retaining function – maintaining a water level difference

A lock is part of a water defense system. It is situated in a waterway between two sections with a different water level. The navigation lock must be able to retain water under all circumstances. Due to the different water level at both sides of the lock a groundwater flow under and around the sides of the lock structure will occur. This flow exits the soil at the downstream side, where erosion will occur in case the flow velocity is high enough. This phenomenon is known as seepage or piping and must be taken into account when designing a lock in order to prevent damage to the structure.

Ship passage function – solutions for vertical and horizontal transport of vessels

Navigation locks play an important role in the inland waterway transport network for the transport of goods. For the most common Dutch inland navigation lock the solution for transport of the vessel is to use a lock chamber that can be closed by gates. Within the lock chamber the water level can be adjusted to allow for the vertical transport of the ships. The horizontal transport is taken by the ship's own propulsion.

Water quality management – dependent of the environment of the lock

A lock can be used for water management, for quantitative and qualitative aspects as well. Qualitative water management is generally the separation of water masses with different properties, e.g. clean and polluted water, or salt and fresh water. Quantitative water management has to do with the amount of water, e.g. the discharge of a predefined amount of water within a certain period of time or minimizing the fresh water loss form the upper canal reach.

Discharge through a navigation lock can be achieved in various ways, for example with valves in the gates or a drain system. At times of large river discharges the full cross section of the lock may be needed for discharge. In this situation flow velocities, will be too high for safe navigation and locking is impossible. In case of smaller discharges the locks, drainage system can be used to get rid of a surplus of water.

Generally, there is an imbalance in traffic. This means that there is a different number of ships sailing up than sailing down the river. But also, the imbalance in loaded and unloaded ships have to be mentioned. The main cause of these imbalances is alternative routes for ships.

In Figure 49 the locking cycle and water losses are shown. The amount of water lost per levelling cycle is:

$A * z + W_{up} - W_{down}$

Where:
$A =$ horizontal area lock chamber
$z =$ difference in water level
$W_{up} =$ water displacement by ships going upstream
$W_{down} =$ water displacement by ships going downstream

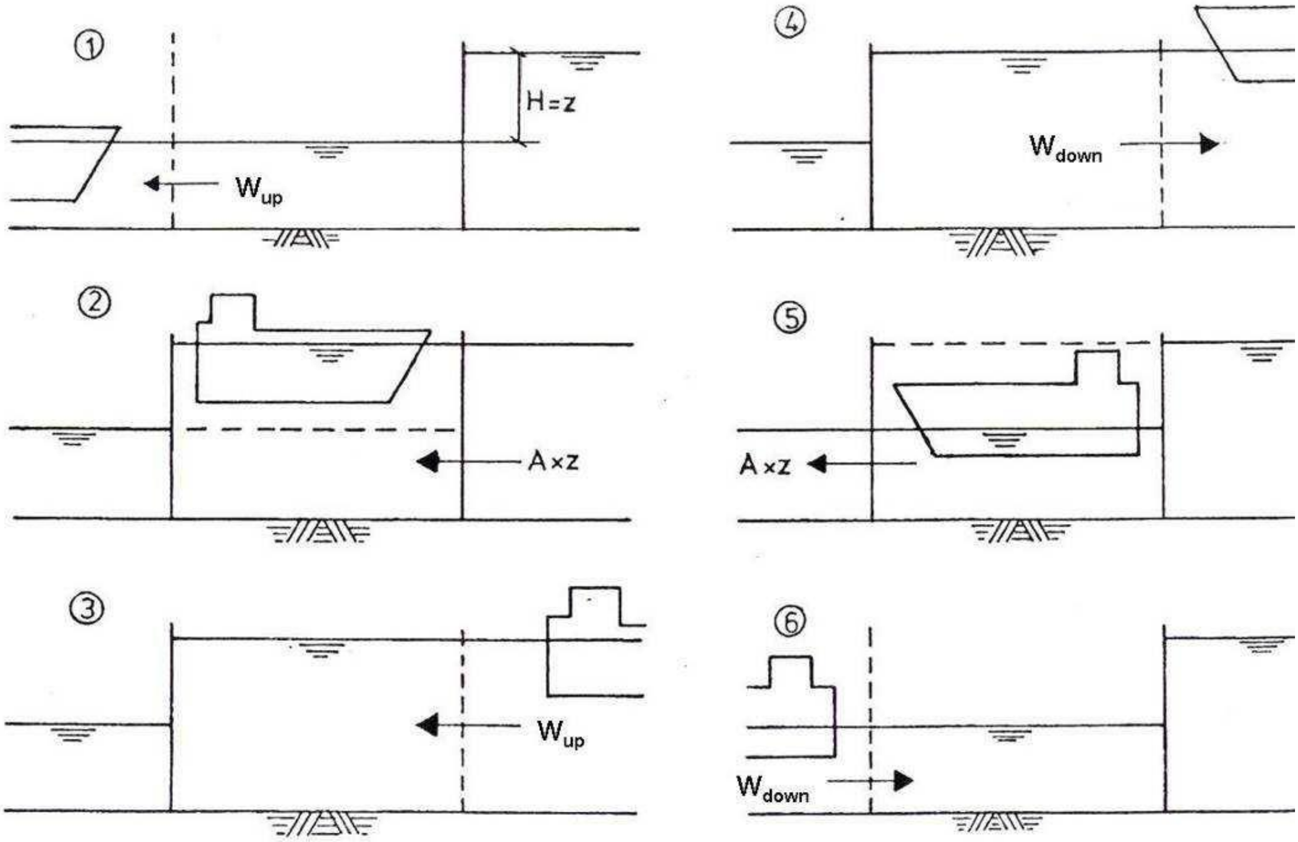


Figure 49: locking cycle and water losses

The function analysis for the typical Dutch lock would result in the following lock components being necessary:
- Gates and housing;
- lock chamber;
- a water levelling solution;
- cut-off screen.

Locking cycle

In figure 50 the factors influencing the lock cycle are shown qualitatively. Below the figure the different point of times and symbols are explained. The combination of the lock capacity and the variation of the traffic gives a certain performance of the system. However, for an accurate research it is necessary to use quantitative results of a traffic simulation model, for example SIVAK.

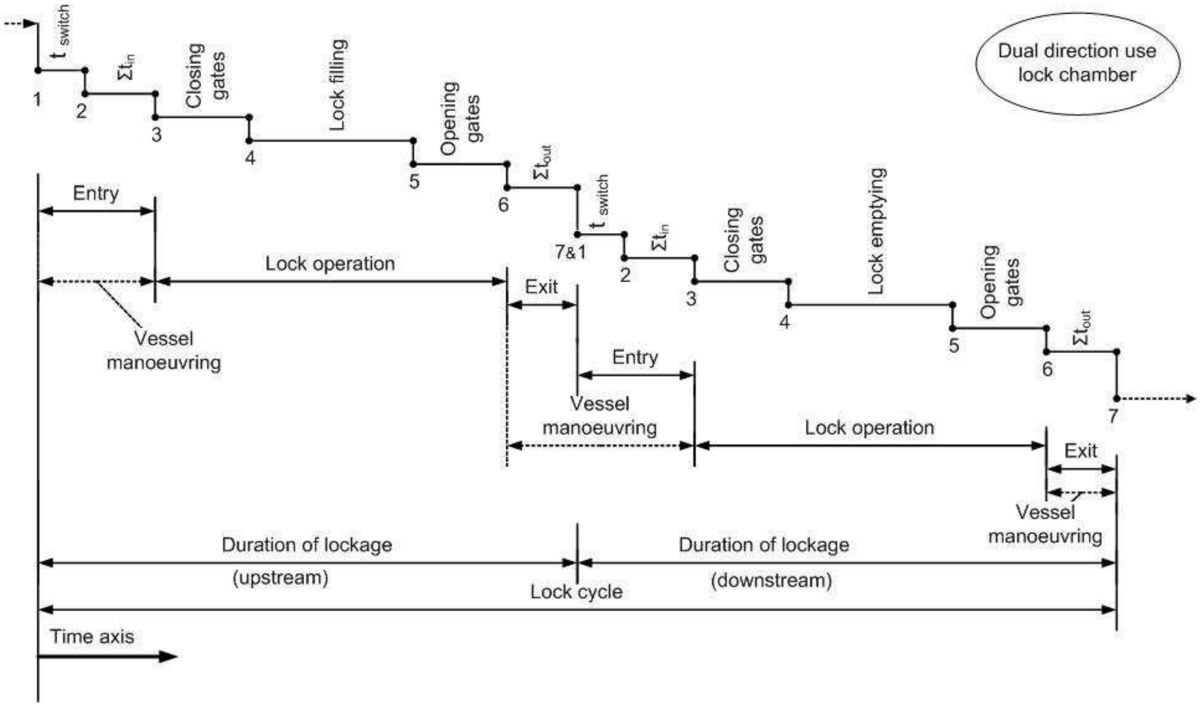


figure 50: lock cycle, indication of duration, distinguishing vessel and lock operations

<u>Point of time:</u>

1. Stern of vessel of previous locking passes gates
2. Stern of first vessel to enter passes gates
3. Stern of last vessel to enter passes gates
4. Entry gates closed
5. Exit gates start opening
6. Exit gates open (first vessel starts leaving)
7. Stern of last vessel leaving passes gates

<u>Symbols:</u>

t_{deb} = time for deberthing and manoeuvring into lock chamber of the first vessel

$\sum t_{in}$ = interval between the first and last vessel (sterns) to enter the lock chamber for locking

$\sum t_{out}$ = interval between completed exist of successive vessels

t_{switch} = interval between exit of last vessel of preceding locking operation and completed entry of first vessel of new locking operation

The following factors influencing the lock cycle:

- Type of vessels and heterogeneity;
- Dangerous cargoes and special transports;
- Size of the lock chamber;
- The types of gates;
- Gate opening and closing time;
- Water level difference (lift height)
- The operating speed of the filling and emptying system;
- Water motion in the lock chamber;
- Water management;
- Manoeuvring and mooring aids in and around the lock;
- Inspection and maintenance activities

Lock design

For the design of a new lock in the waterway the following data are required:

- Seasonal, monthly, weekly or even daily variation of the traffic intensity;
- Types of ships and how they are distributed (mixed);
- Frequency of special transport and vessels with dangerous cargoes;
- (In)balance between upstream or downstream traffic, and even the (in)balance in loaded or unloaded vessels.

Besides the historic data that is needed also a forecast has to be made to be prepared on the future situation.

Traffic intensity can be combined with data on the dimensions or deadweight tonnage of the vessels. Therefore, the traffic intensity can be expressed in deadweight per hour or m^3 per hour. Especially the expression in tonnage per time would be useful for economic evaluation of a lock project. For the technical design of a lock the capacity expressed in m^3 per time unit is needed. Given the required lock capacity the lock cycle requirements for a new lock can be determined.

Costs

The construction costs are depended of the number of weirs and locks. The more WLCs the higher the costs will be. This is also valid for the maintenance and operational costs. However, in case of a larger number of weirs the head per weir will decrease and therefore the forces per weir will reduce which leads to a relative cheaper structure. figure 51 shows this principle. Such a non- linearity will also occur in case of the costs for mitigating measures. A reduced head per weir might lead to less requirements on dike rising and/or reinforcement which results in lower costs. In principle, for inland shipping the fewer number of locks the better. However, in case of navigational restrictions regards the navigation depth it has to be a balance between the extra travel time and reduced loading capacity.

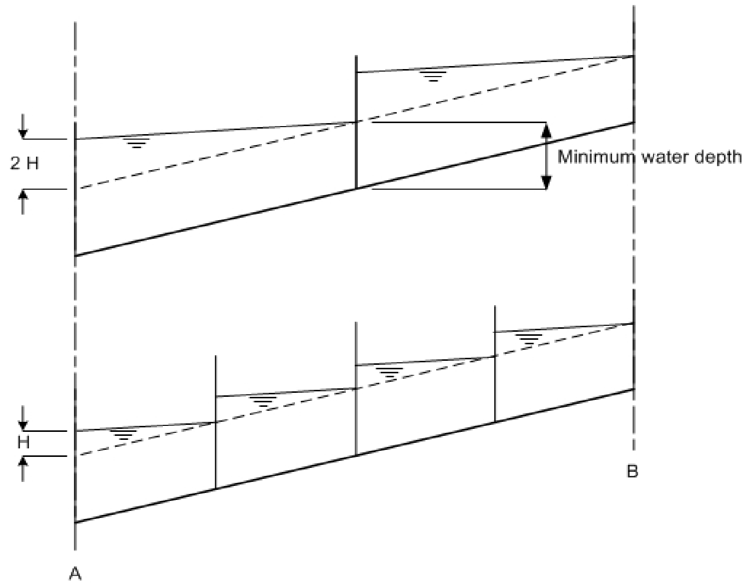


figure 51: Principle of canalization

Backwater curve Theory

The water surface profile is created by the flow depth changes in longitudinal direction of the river. How this water surface looks like, and thus what the water depth is in upstream direction of an obstacle, depends on the relation between the actual water depth, the normal (or equilibrium) depth and the critical depth. The normal water depth is the depth at uniform and steady flow. The critical depth is the depth where energy is at minimum for a particular discharge and the Froude number is equal to 1. Critical depth will occur at critical flow, however critical flow is very unstable and a small fluctuation in energy will a flow change into subcritical- or supercritical flow. Subcritical occurs when the actual water depth is smaller than the critical depth. In this case the Froude number is smaller than 1. Supercritical occurs when the actual depth is less than the critical depth and this is the case when the Froude number is larger than 1.

Supercritical flow does only occur in rivers with steep slopes. This is not the case in the Netherlands, because a delta is characterized by mild and flat slopes. Therefore, the water surface profile that is created by subcritical flow determines the water depth. It depends on the value of the normal depth with respect to equilibrium depth how the water surface profile looks in upstream direction. The possible surface profiles for subcritical flow are shown in figure 52.

In case of a weir in the river, which is schematized in figure 53, the actual depth will be larger than the equilibrium depth. This means that the water surface profile is a M1 backwater curve as can be observed in figure 52.

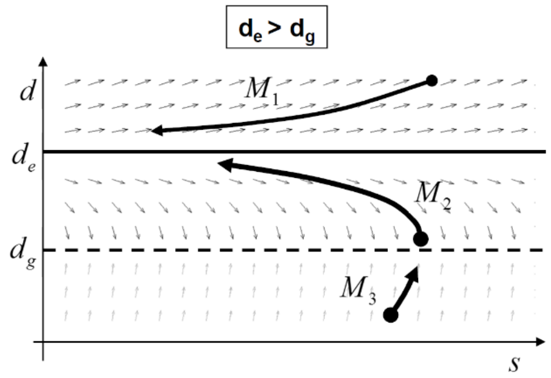


figure 52: surface profile for various backwater curve types (Blom, 2016a)

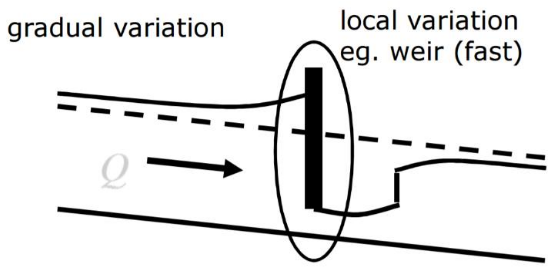


figure 53: Water surface profile at the weir (Blom, 2016a)

To determine the water surface and therefore the water depth upstream of the weir, a first order approximation can be made. The general solution of this approximation is: $\Delta h(s) = \Delta h_0 * \exp\left(\frac{s-s_0}{L}\right)$. Where L is defined as the adaption length, which is a characteristic length scale of adaptation of the flow towards normal flow (Blom, 2016a). In figure 54, a sketch of this approximation is shown. In addition, Bresse has made an analytical solution. However, this solution was too complicated and after an empirical fit, the following solution has been developed:

$$h(s) = h_e * (h_0 - h_e)\left(\frac{s_0 - s_e}{L_{1/2}}\right)$$

where: $L_{1/2} = 0.24 * \left(\frac{h_e}{i}\right) * \left(\frac{h_0}{h_e}\right)^{4/3}$ $[m]$

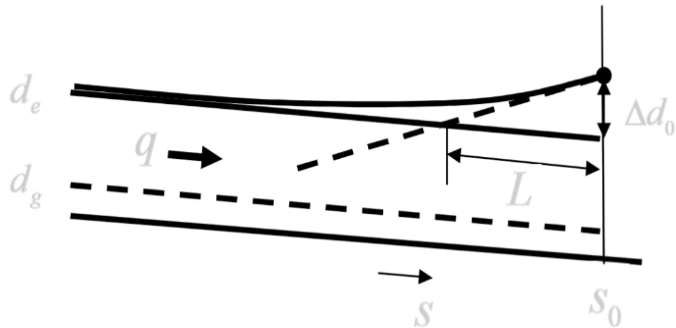


figure 54: Sketch of backwater curve approximation (Blom, 2016a)

For this solution, subcritical flow and a rectangular channel is assumed. The first assumption is valid for the situation in this research, namely the lower stretch of the River Rhine. However, the river profile is not a rectangular channel and therefore there will be some differences between the backwater curve calculation and the real water surface profile. Because the backwater curve method is applied in many river calculations and accepted widely, it is assumed that this method is reliable for the calculation of the water surface profile and therefore the water depth in upstream direction of a weir in the River Waal.

Appendix III

Climate change

Climate scenarios

Climate scenarios

Worldwide climate scenarios have two main uncertainties, namely large scale circulation patterns and global warming. Based on these worldwide scenarios, the Royal Dutch Meterological Institute KNMI has presented 4 climate scenarios for the Netherlands. (Krekt et al, 2011) The scenarios are the four combinations of two possible values for the global temperature increase, 'Moderate' and 'Warm', and two possible changes in the air circulation pattern, 'Low' and 'High'. Together they span the likely changes in the climate of the Netherlands according to the newest insights (KNMI, 2015).

Scenario classification

The IPCC scenarios for future emissions of greenhouse gases and pollutants, in conjunction with land use changes, form the basis for the KNMI'14 scenarios. The KNMI'14 climate scenarios provide a consistent picture of the changes in 12 climate variables, including temperature, precipitation and sea level. The G scenario stands for *Gematigd,* i.e. Dutch for moderate. In this scenario, the global mean termperature increase is 1 °C in 20150 and 1.5 °C in 2085 relative to 1981-2010. The W scenario stands for *Warm*, i.e. Dutch for warm. The temperature increase in this scenario is 2 °C in 2050 and 3.5 °C in 2085 relative to 1981-2010.

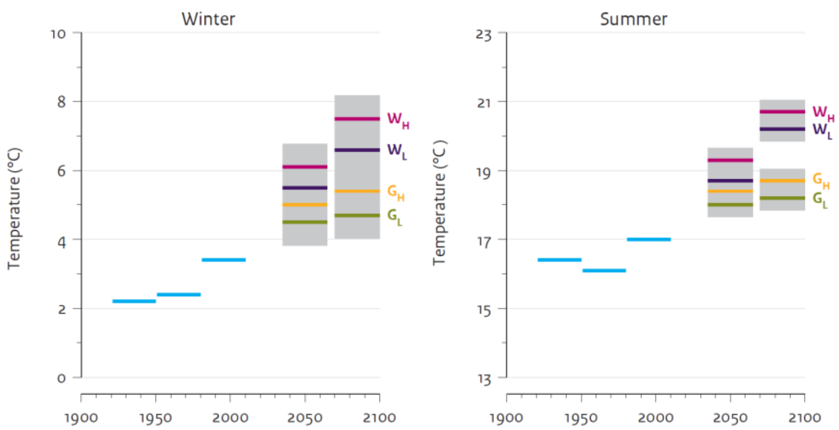
The change in air circulation is taken as the second classification criterion to distinguish the scenarios. In the Low (L) scenarios, G_L and W_L, the influence of circulation change is small, while in the High (H) scenarios, G_H and W_H, the influence of circulation change is large. In the H scenarios, more frequent westerly winds occur in winter, which leads to mild and more humid weather compared to the L scenarios. In the summer, high pressure systems cause more easterly winds, which implies warmer and drier weather compared to the L scenarios.

Temperature

In all scenarios for the Netherlands, the temperature will increase further. The mean temperature increase is largest for winter (December, January, February) and smallest for spring (March, April, May) in 2050. There is a decrease in temperature differences between winters because very cold winters become much less likely. On the other hand, temperature differences between summers increase somewhat because the temperature increase is largest for the warmest summers. The temperature difference between day and night reduces slightly. The increase in maximum temperature is slightly less than the increase in minimum temperature. (KNMI, 2015).

The coldest days in winter and warmest days in summer will warm most. On the other hand, mild days in winter and cool days in summer show relatively modest changes. For winter, this leads to a considerable reduction in the number of frost days with minimum temperature below zero. Record-breaking daily temperatures are still possible under all scenarios, but become much less likely for cold extremes in winter and more likely for warm extremes in summer.

figure 55: Observations (three 30-year averages, in blue) and KNMI'14 scenarios (2050 and 2085, in different colors) of winter and summer temperature in De Bilt. Natural variations are for 30-year averages (in grey) (KNMI, 2015).



Precipitation

The mean precipitation increases in all scenarios, except for summer. This is primarily due to the increase in water vapour in the air in a warming climate. Model calculations disagree about the sign of change in mean precipitation in summer. This is reflected in the different scenarios and can be observed in figure 56 where for both winter and summer the precipitation for the four scenarios is shown.

In all scenarios, precipitation extremes increase throughout the year. This is primarily due to the increase in water vapour in the air in a warming climate. The change in precipitation extremes for a particular summer scenario is quite uncertain. Rain showers are less dependent on changes in air circulation, but more dependent on the processes acting on the local scale. Therefore, a lower and upper value is provided for all scenarios in summer. However, the probability for heavy rain showers increases in all scenarios, albeit with a large uncertainty band.

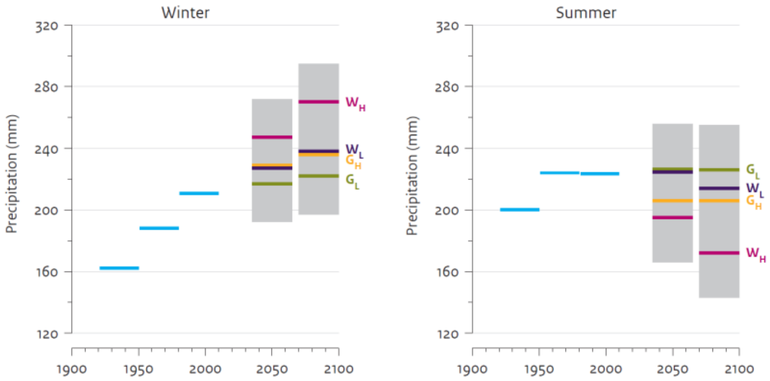


figure 56: Observations and KNMI'14 scenarios for 2050 and 2085 of precipitation climate in the Netherlands (KNMI, 2015).

Sea level

For this variable, there is no distinction between the L and H scenarios because changes in air circulation over Europe have minor impact on long term sea level rise. The potential future sea level rise along the Dutch North Sea coast for all scenarios is shown in figure 57. A lower and upper value for the sea level rise is provided. In each scenario, the rate of sea level rise along the Dutch coast until 2085 is higher than the mean rate of change observed in the past. It must be noted that the effect of land subsidence on the sea level is not included in the scenarios because this varies widely along the Dutch coastline and therefore it gives no reliable estimates.

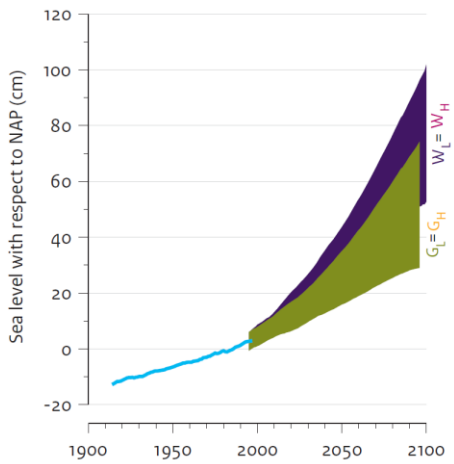


figure 57: Observed sea level at the Dutch North Sea coast and the projections in the KNMI'14 scenarios (KNMI, 2015).

Wind and Storm

In all scenarios, the human- induced changes in wind speed are small, they are within the natural variation range. Besides the wind speed also the wind direction is considerable. For the Netherlands, especially northerly winds are important because these causes the highest sea surges along the Dutch coast. For this variable, only the W_L and W_H scenario are elaborated, because they indicate the two different circulation patters and that will be essential in forecasting different scenarios. The scenarios indicate that the Northerly winds will not change much in future. In figure 58, for each wind direction the change in occurrence is shown for the W_L and W_H scenarios.

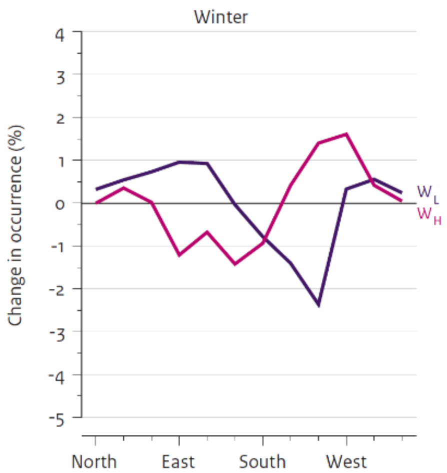


figure 58: Changes in wind direction at the Dutch coast in winter for the W_L and W_H scenarios for 2085 (KNMI, 2015).

Visibility, fog, hail and thunderstorms

The increased visibility and associated reduction in fog that is observed in the past is almost entirely due to the reduction in air pollution. The positive trend in visibility over the Netherlands will continue in the future, however it will continue at a lower rate. The changes are the same in all four scenarios, because the assumed future reductions in air pollution are the same. For 2050 the average number of hours of fog per year is estimated at 190. After 2050 a small further reduction is expected.

Hail and thunderstorms will become more heavy in the future. The biggest changes are seen in the WL and WH scenarios. There extreme hail occurs at least twice as often in 2050 compared to the reference period 1981-2010. These estimates are based on climate model calculations and the relationship between atmospheric water vapour and vertical velocity.

Clouds, solar radiation, evaporation and drought

In the GH and WH scenarios a small but significant decrease in cloudiness occurs in future summers. This is due to more easterly winds. Consequently, summertime solar radiation increases in these scenario's.

Calculations are made to approximate changes in potential evaporation under future climate conditions. It can be concluded that potential evaporation[4] increases linearly with solar radiation. In addition, the potential evaporation increases by about 2% per degree of temperature rise. However, actual evaporation changes may differ from these potential evaporation scenarios, because actual evaporation depends critically on soil water availability.

The trend of a small increase in drought is likely to continue in the future. The precipitation deficit during the growing season (from 1 April to 30 September) increase more strongly in the G_H and WH scenarios than in the GL and WL scenarios.

Overview

An overview of the four different scenarios and their characteristics is given in figure 59. figure 60 shows an overview of overall changes and scenario differences.

Variabele	Indicator	Climate 1981-2010	Scenario changes for the climate around 2050				Scenario changes for the climate around 2085				Natural variations averaged over 30 years
			G_L	G_H	W_L	W_H	G_L	G_H	W_L	W_H	
Global temperature rise:			+1 °C	+1 °C	+2 °C	+2 °C	+1.5 °C	+1.5 °C	+3.5 °C	+3.5 °C	
Change in air circulation pattern:			low value	high value	low value	high value	low value	high value	low value	high value	
Sea level at North Sea coast	absolute level	3 cm above NAP	+15 to +30 cm	+15 to +30 cm	+20 to +40 cm	+20 to +40 cm	+25 to +60 cm	+25 to +60 cm	+45 to +80 cm	+45 to +80 cm	±1.4 cm
	rate of change	2.0 mm/yr.	+1 to +5.5 mm/yr.	+1 to +5.5 mm/yr.	+3.5 to +7.5 mm/yr.	+3.5 to +7.5 mm/yr.	+1 to +7.5 mm/yr.	+1 to +7.5 mm/yr.	+4 to +10.5 mm/yr.	+4 to +10.5 mm/yr.	±1.4 mm/yr.
Temperature	mean	10.1 °C	+1.0 °C	+1.4 °C	+2.0 °C	+2.3 °C	+1.3 °C	+1.7 °C	+3.3 °C	+3.7 °C	±0.16 °C
Precipitation	mean amount	851 mm	+4 %	+2.5 %	+5.5 %	+5 %	+5 %	+5 %	+7 %	+7 %	±4.2 %
Solar radiation	solar radiation	354 kJ/cm²	+0.6 %	+1.6 %	-0.8 %	+1.2 %	-0.5 %	+1.1 %	-0.9 %	+1.4 %	±1.6 %

figure 59: Key figures of the KNMI'14 scenarios (KNMI, 2015)

[4] Potential evaporation refers to the amount of evaporation that would occur if sufficient water is available in the soil. (KNMI, 2014)

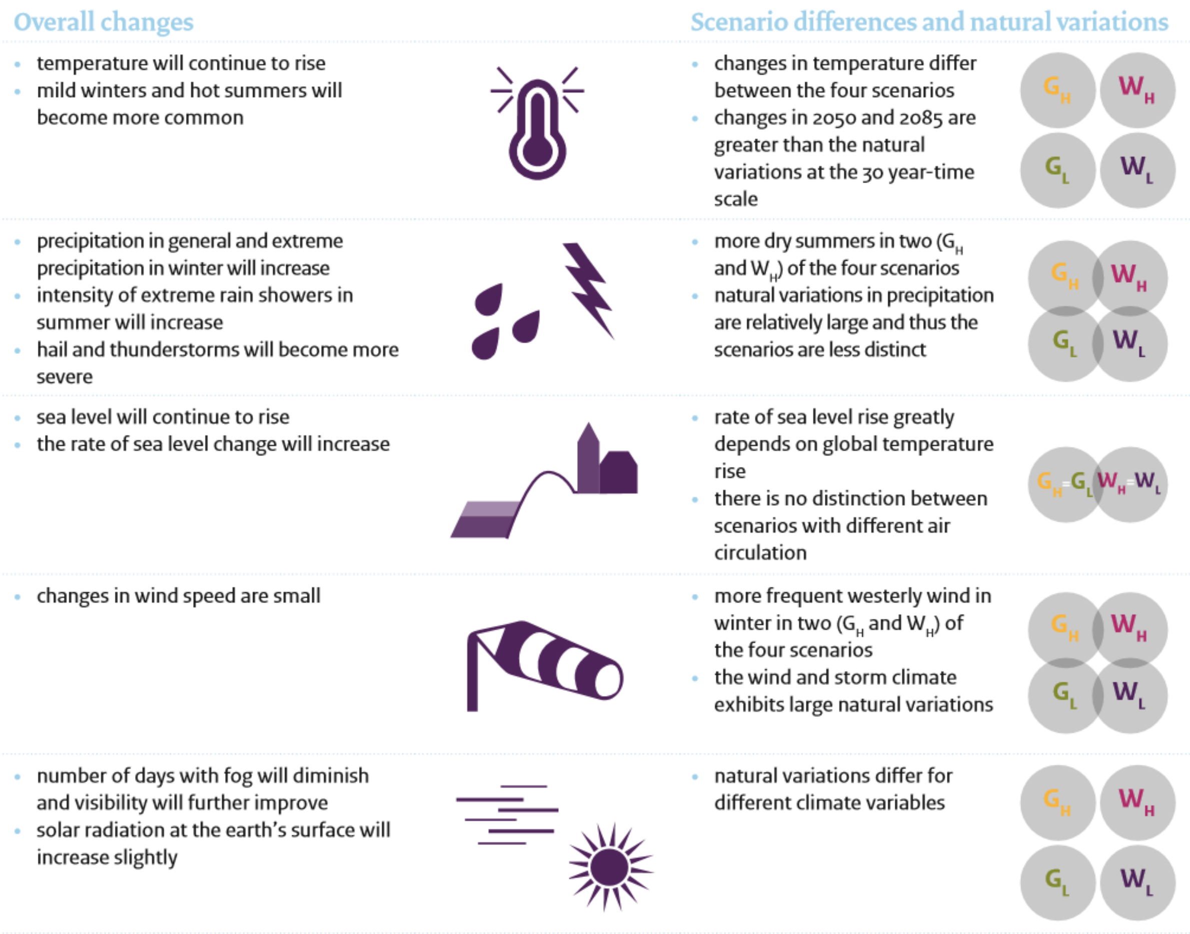


figure 60: Overview overall changes and scenario differences of KNMI'14 climate scenarios **(KNMI, 2015).**

Appendix IV

Economic scenarios

WLO scenarios

Appendix IV

Economic scenarios

WLO scenarios

WLO scenarios

The cooperation between the PBL (in dutch: Planbureau voor de Leefomgeving) and CPB (in dutch: Centraal Planbureau) has resulted into the study 'The Netherlands in 2030 – 2050: two reference scenarios – Foresight Welfare and Environment' (WLO) (translated from Dutch: 'Nederland in 2030 – 2050: twee referentiescenario's – Toekomstverkenning Welvaart en Leefomgeving') (CPB/PBL, 2015a). In this study demographic and economic trends are shown and developments in the environment have been analysed. The result of the study is launched in 2015, therefore we refer to this study as WLO 2015.

The WLO 2015 consist of one overarching cahier and six theme cahiers, namely: demography, macro economy, regional developments and urbanisation, climate and energy, mobility and agriculture. There are two reference scenarios developed: High and Low. Scenario High is combining a high economic growth of 2 percent per year with a relative strong population growth. In scenario Low there is a moderate economic growth of 1 percent per year and a limited demographic development. These reference scenarios are policy- neutral completed and therefore they give insight in future bottlenecks and opportunities. The two scenarios span a number of possible developments.

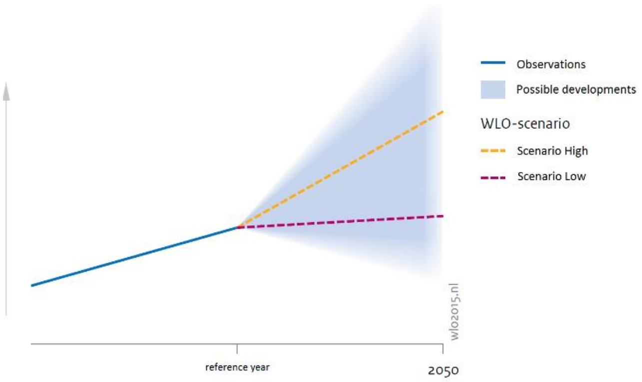


figure 61: Bandwidth in WLO scenarios (translated from: CPB/PBL, 2015a)

In the scenario High, there is a relative high international confidence with associated safety, trade, liberalization, competition and globalization. Therefore, international cooperation and relative fast technical development can take place which results into relative large economic growth. There will be climate agreements worldwide and therefore the temperature increase relative to 1990 will be limited to 2.5 to 3.0 degree Celsius.

In the scenario Low, there is less international confidence and therefore it is harder to make arrangement. liberalization, globalization and international trade go below, which results in less competition and innovation and therefore in a lower worldwide economic growth. There is little ambition for climate agreements and therefore the worldwide mean temperature increase relative to 1990 is 3.5 to 4.0 degree Celsius.

table 44 gives an overview of some basic assumptions of the two scenarios.

table 44: Basic assumptions of the WLO- scenarios High and Low (translated from: CPB/BPL, 2015a).

Uncertainty	Scenario High	Scenario Low
Demography	High migration Strong increase in life expectancy High fertility	Low migration Limited increase in life expectancy Low fertility
Economy	Strong grow world economy and international trade maintaining competitiveness Strong growth labour productivity More services	Limited world economy and international trade Maintaining competitiveness Moderate growth labour productivity Less services
Technology	Faster development	Slower development
Climate policy	Substantial	Limited
Energy prices	Low	High
Area	Continuing trend to concentration in the Randstad and some big cities	Weakening concentration trend
Consumer behaviour	No fundamental change in behaviour	No fundamental change in behaviour

Now the themes *Macro- economy, Mobility and Climate and Energy* will be discussed in more detail, because these subjects are important for this study and provides some necessary information.

Macro- economy

Economic growth and demographic growth are two important driving forces behind the development of the physical environment. Economic growth in terms of GDP can be split into the growth of labor productivity and the growth of employment. Technological development is the main cause of growing labor productivity. The grow of participation and grow of population determine together the amount of grow of employment.

Aspects such as technology, demography, financial markets and international trade are important for the economy of the Netherlands. Therefore, looking at these aspects individual and thereafter in relation to the Netherlands gives us a view of the development of the Dutch economy. For the complete description of these aspects a reference is made to the Cahier Macro- economy of the WLO (CPB/PBL, 2015b).

An important uncertainty is technology. How technology and thus the labor productivity will developed in the future is one of the biggest uncertainties. Therefore, each scenario takes one side of the possible future developments. In scenario High ICT contributes greatly and stimulates economic growth, while in scenario Low the ICT- sector is minimal and don't stimulate the economy anymore.

In scenario High, there is fast technologic growth and a growing population. Trust and cooperation leads to globalization and an increase in international trade. There is a stable financial system and this facilitates the economic development. Agreements are easy made and there is more optimism. The economic growth takes mainly place in the commercial services. In 2050 more than 85 percent of the population is working in the service sector, of which more than half of the population in the commercial services and one third of the population in government and health care sectors.

In scenario Low, there is a slow technical development and a shrinking population. This leads to a limited economic growth. There is lack in cooperation and trust, which leads to stagnation of international trade. The financial system is not sufficient to facilitate economic growth. However, in similarity with the high scenario also in this scenario almost 85 percent of the population will work in the service sector.

On basis of existing historic material, qualitative arguments and scientific literature the long term GDP- growth in scenario High is determined on 2 percent per year and in scenario Low 1 percent per year. These growth rates are consistent with other international studies done for the Netherlands. The development of GDP and other macro-economic key variables are shown in table 45.

table 45: Development of macro-economic key variables for scenario High and Low (translated from: CPB/PBL, 2015b).

	High			Low		
	2015-30	2030-50	2015-50	2015-30	2030-50	2015-50
Economic growth (GDP)	2,2%	2,0%	2,1%	1,2%	1,0%	1,1%
Employment	0,6%	0,2%	0,4%	0,1%	-0,2%	-0,1%
Labor productivity	1,6%	1,8%	1,7%	1,1%	1,2%	1,2%
Population	0,4%	0,3%	0,4%	0,1%	-0,2%	-0,1%
GDP per capita	1,8%	1,7%	1,7%	1,1%	1,2%	1,2%

In table 46 there are numbers shown for the economic variables GDP, labor productivity and Employment. These numbers are relative to the reference year 2013.

table 46: Development of GDP, labor productivity and employment in 2030 and 2050 for both scenarios (translated from: CPB/PBL, 2015b).

		Scenario High		Scenario Low	
	2013	2030	2050	2030	2050
	(niveaus)	(2013=100)			
GDP (in billion, market prices 2010)	644	140	205	120	145
Labor productivity		130	180	115	150
Employment (in million)	8,3	110	115	100	95

The levels in 2013 will be taken as reference value. Therewith we can calculate values for both scenarios in 2030 and 2050. These calculations are shown below.

Scenario high:

- 2030 $GPD = \frac{644}{100} * 140 = 901.6\ bln$
  $Employment = \frac{8.3}{100} * 110 = 9.13\ mln$

- 2050 $GPD = \frac{644}{100} * 205 = 1{,}320.2\ bln$
  $Employment = \frac{8.3}{100} * 115 = 9.55\ mln$

Scenario low:

- 2030 $GPD = \frac{644}{100} * 120 = 772.8\ bln$
  $Employment = \frac{8.3}{100} * 100 = 8.3\ mln$

- 2050 $GPD = \frac{644}{100} * 145 = 933.8\ bln$
  $Employment = \frac{8.3}{100} * 95 = 7.89\ mln$

An overview of these results is given in table 47.

table 47: Real numbers of the grow of GDP and Employment in 2030 and 2050 according to the WLO scenarios.

	Scenario High		**Scenario Low**	
year	**2030**	**2050**	**2030**	**2050**
GDP [in billion]	901.6	1,320.2	772.8	933.8
Employment [in million]	9.13	9.55	8.3	7.89

For this paragraph information is obtained from the cahier Mobility and general reference is made to CPB/PBL (2015c). The transport demand in the future is determined mainly by the population growth, macro- economic development and the distribution of the population and employment over the Netherlands. However, international developments relating to climate and energy or several uncertainties have also effect on the future developments of mobility. In addition, technical developments can change current transport modes and lead to a new mode of transport. Finally, the actual development depends also on the development of the existing network.

Mobility includes passenger transport and freight transport. In this study, we the focus is on freight transport. Transport of freight is done by different modes, namely by road, by rail, by inland shipping and by air transport. First the total transport of freight will be analysed briefly and after that the freight transport by shipping will be discussed more fully.

The annual growth of transport of freight over land is in both scenarios below the historic mean. It must be noted that the economic growth in both scenarios is also lower than the historic mean over the period 1970-2013. However, the economy and transport of freight is still growing, albeit at a lower rate than in the past. figure 62 shows the total transport of freight and how this is split into different types of transport, namely: inland transport, transport by sea, transport by land, transport by air and throughput. The grow of the total freight transport over land in the period 2011-2050 is in scenario High 52 percent and in scenario Low 14 percent. International and inland economic development are the most important driving forces behind this growth. In both scenarios, the international transport is growing faster than the inland transport.

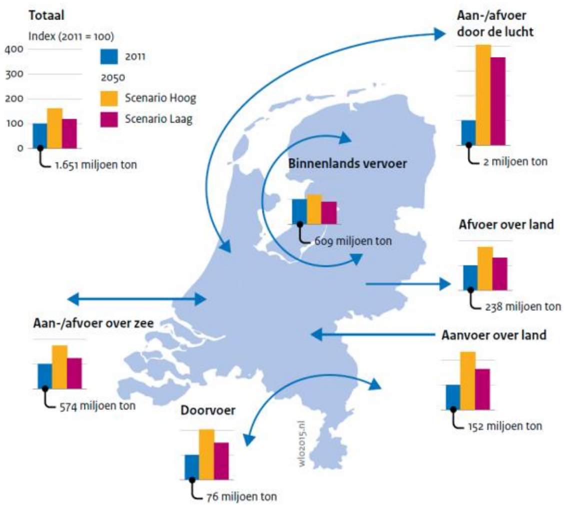


figure 62: Transport of freight according to the WLO scenarios (translated from: CPB/PBL, 2015c)

There are three modalities of transport over land, namely: transport by road, rail and inland shipping. In this study, the focus is on inland shipping. Inland shipping is still growing, but loses some market share. This is due to freight for which inland shipping has a big market share becomes less important. In addition, in the scenario High inland shipping will be taxed for CO_2 emission. The freight transport through the seaports is growing faster than the total inland transport of freight, namely 74 percent in scenario High and 24 percent in scenario Low. This is due to the strong growing international trade compared to, for example, inland trade. The development of the container throughput is going faster than the total throughput in the seaports, because more goods can be transported by container. However, the spread between the two scenarios is quite large. This means that there is a relative large uncertainty. In figure 64 and figure 63 the development of transport by inland shipping and the development of transport through the ports are shown. An overview of the total weight of transported goods and the distribution of this amount over the different transport modes is included in table 48.

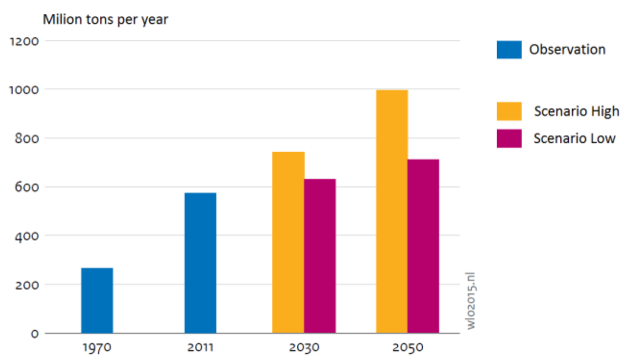


figure 64: Freight transport through the ports (translated from: CPB/PBL, 2015c)

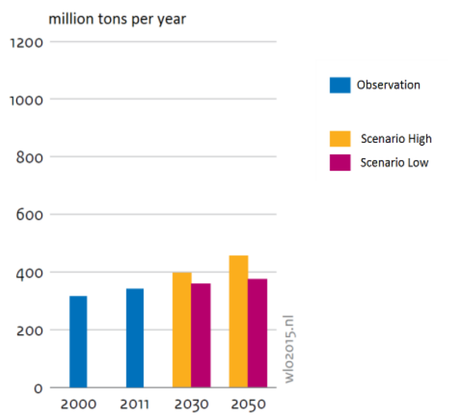


figure 63: Freight transport by inland shipping (translated from: CPB/PBL, 2015c)

	2011	Scenario High 2030	Scenario High 2050	Scenario Low 2030	Scenario Low 2050
	Mln ton	(2011=100)			
Weight transported goods	1075	121	152	105	114
by road	697	123	158	104	114
by rail	37	143	222	128	161
inland shipping	341	116	134	105	110
Road trips*	457	112	127	101	101

** in million number of trips*

table 48: Development of freight transport (translated from: CPB/PBL, 2015c)

In 2011 the weight of the transported goods by inland shipping is equal to 341 million tons. Taking this as reference value, we can calculate the weight of transported goods for both scenarios in 2030 and 2050. The calculations are shown below.

Scenario high:

- 2030 $\frac{341}{100} * 116 = 395.56\ mln\ tons$
- 2050 $\frac{341}{100} * 134 = 456.94\ mln\ tons$

Scenario low:

- 2030 $\frac{341}{100} * 105 = 358.05\ mln\ tons$
- 2050 $\frac{341}{100} * 110 = 375.10\ mln\ tons$

An overview of these results is given in table 49.

table 49: Weight of transported goods [in millions] by inland shipping

Year	Scenario High	Scenario Low
2030	395.56	358.05
2050	456.94	375.10

Climate and Energy

The WLO scenarios include the most important uncertainties in the field of climate and energy. These uncertainties are the climate policy, air policy, the size of the supply of fossil fuels, the technological developments, political tensions, acceptation of new technology by the society and the economic growth. The most dominant uncertainty is the climate policy. For the Netherlands, the international climate policy is given for a great extend until 2030. The starting point for the two scenarios are the pledges of the United Nations climate agreement (UNEP 2013) for 2020. These pledges are part conditional and therefore they have a bandwidth. Thereafter the two scenarios go different ways and diverge further from each other.

The WLO scenarios are consistent with the global climate scenarios that lead to a global mean temperature increase of 2.5 – 3 degrees in WLO scenario High and 3.5 – 4 degrees in WLO scenario Low. In figure 65 the different possibilities of global warming and both WLO scenarios are shown. More about these global temperature changes and their effects can be found in the fifth assessment of the Intergovernmental Panel on Climate Change (IPCC 2015).

In the highest scenario, there is relative a lot of international cooperation and the international climate policy will be a fact. Due to the higher economic growth, the society is willing to strengthen the climate policy further. This reduces the emission of greenhouse gasses by 65 percent in 2050 relative to 1990 and maximizes the global mean temperature rise to 2.5 to 3 degrees after de 21st century. The relative strong technical development reduces the costs of sustainable energy. Also, the political tensions are limited and therefore the fuel prices are low.

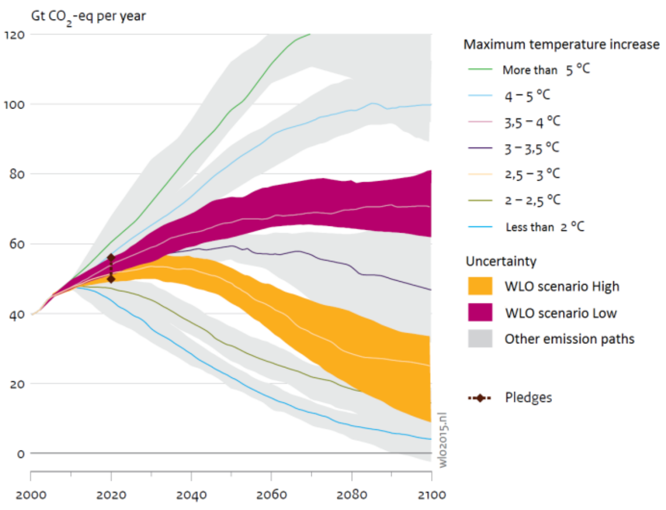


figure 65: Global warming related to emission of greenhouse gasses (translated from: CPB/PBL, 2015d)

Scenario Low will be characterized by low economic growth and a limited international cooperation, whereby countries are less willing to strengthen the climate policy. There is almost no progress and this leads to a global mean temperature increase of 3.5 to 4 degrees after de 21st century. In this scenario, geopolitical tensions lead to relative high fossil fuel prices. (CPB/PBL, 2015d)

A short overview of the climate policy for each scenario is given in table 50.

table 50: Climate policy in WLO scenarios High and Low

	Scenario High	**Scenario Low**
Temperature increase	2.5 – 3 °C	3.5 – 4 °C
Datum global climate agreement	± 2025	± 2030
Emission reduction NL in 2030	40%	30%
Emission reduction NL in 2030	65%	45%
Climate policy	- Global emission trade system after 2030 for all sectors - Additional climate policy is being phased out after 2030 and replaced by global research and development (R&D) policy	- In 2025 the EU is adjusting the 2030- goal from -40% to -30% - The Europe emission trade system will not be extended - Additional climate policy continues

Appendix V

<u>WLC costs</u>

Construction costs – Index number method

Construction costs – Formula method

Effect of head on construction costs

Construction costs – Index number method

In this stadium of the research project there is no (pre)design for the specific weir- and lock- complexes. Therefore, a rough estimate for the WLCs will be made. Based on the cost estimation for a canalized River Rhine (Waal) by Ad van der Toorn (2010) a first cost overview for the canalization of the River Waal is made. Van der Toorn has used several reference projects in order to determine a so-called index number. The index number for the weir is based on the fact that the cost of a weir is strongly related with the width, the retaining height and the head over the weir. For the lock a kind similar relation is valid; the index number depends on the length, width and head of the lock.

From his analysis, he came to an index number for a weir complex of *30.000 €/m³* and for a navigation lock-complex of *5.000 €/m³*.

The derivation of index numbers for dike raising is more problematic, because such ‘projects' are rather special and unique. Based on data of Eigenraam, the following index numbers for different dikes are estimated:

- Road dikes with one-sided buildings – *18 million €/km*m*
- Road dikes with buildings at both sides – *36 million €/km*m*
- Grass- dike – *6 million €/km*m*
- Firm road dike or another reinforcement on top – *12 million €/km*m*

For the maintenance costs an assumption is made of 1% of the total investing costs (Molenaar et al., 2011). So, this results in:

$$C_{maintain} = 1\% \; x \; C_{constr.}$$

$$C_{constr.} = n * (C_{lock} + C_{weir} + C_{dikes})$$

Where:
$n = amount\ of\ weir - and\ lock - complexes$
$C_{lock} = construction\ costs\ of\ lock$
$C_{weir} = construction\ costs\ of\ weir$
$C_{dikes} = costs\ of\ mitigating\ measures$

The operational costs are based on the report of Deltares (2008) *"Verkenning kosteneffectiviteit van grootschalige maatregelen tegen droogteschade als gevolg van de G+ en W+ klimaatscenario's"*. An assumption of 10 employees per WLC and some extra exploitation costs results in 1 million Euro per year.

Taking over the assumptions of Van der Toorn, the first cost estimates are as follows.

Lock – 5.000 €/m³

Dimensions: (LxWxH) = 280 x 40 x 5

Construction costs of lock: $C_{lock} = 280$ Million Euro

Weir – 30.000 €/m³

Dimensions: (WxdxH) = 300 x 10 x 5

Construction costs of weir: $C_{weir} = 450$ Million Euro
Dikes – 6 Million €/km grass dike

Because there are various discharges during the year in the River Rhine and River Waal there occur also extreme high discharges. Therefore, the dikes along the river are designed for such extreme discharges and water levels in the river. This means that in times of low discharges there is some reserve in dike height. So, it sounds likely that measures such as dike rising and reinforcement are not required in that large extend as might be expected. Therefore, it is estimated that 10% of the dike length should be raised by 1 meter. For the different stretches, this results are included in table 51.

Section	L [km]	C_{dike} [€]
Rotterdam - Duisburg	220	€ 132,000,000
Rotterdam - Germany	140	€ 84,000,000
Woudrichem - Duisburg	171	€ 102,600,000
Woudrichem - Germany	92	€ 55,200,000

table 51: Costs of dike raising for different stretches

The total costs depend on the number of WLCs. For the different stretches, much or less WLCs are needed, depending of the total head. An average head of 5 meters leads to the number of WLCs and costs that is shown in table 52. The construction costs ($C_{construction}$) are the summation of the costs for the WLCs (=C_{weir} + C_{locks}) and the costs for mitigating measures (= C_{dikes}). However, these are not all costs that determine the total WLC costs. The maintenance costs and operational costs must also be added to the construction costs to obtain the total costs for the exploitation of the WLCs. In this calculation, the price level of 2010 is taken. This means that the maintenance costs, which are determined in 2008, have to be corrected for inflation and are equal to 1,03 Million Euro price level 2010. All costs are included in table 52 and table 53 and finally the total WLC costs are shown in table 54.

Section	L [km]	H_{tot} [m]	N	C_{weirs}	C_{locks}	C_{dikes}	$C_{construction}$ [€]
Rotterdam - Duisburg	220	26,4	5	€ 1,400,000,000	€ 2,250,000,000	€ 132,000,000	€ 3,782,000,000
Rotterdam - Germany	140	16,8	3	€ 840,000,000	€ 1,350,000,000	€ 84,000,000	€ 2,274,000,000
Woudrichem - Duisburg	171	20,52	4	€ 1,120,000,000	€ 1,800,000,000	€ 102,600,000	€ 3,022,600,000
Woudrichem - Germany	92	11,04	2	€ 560,000,000	€ 900,000,000	€ 55,200,000	€ 1,515,200,000

table 52: Construction costs for different stretches

Section	Maintenance costs [€]	Operational costs [€]
Rotterdam - Duisburg	€ 840,444,444	€ 114,444,444
Rotterdam - Germany	€ 505,333,333	€ 68,666,667
Woudrichem - Duisburg	€ 671,688,889	€ 91,555,556
Woudrichem - Germany	€ 336,711,111	€ 45,777,778

table 53: Total maintenance and operational costs for different stretches

Section	Total WLC costs [€]	WLC costs per year [€]
Rotterdam - Duisburg	€ 4,736,888,889	€ 215,805,042
Rotterdam - Germany	€ 2,848,000,000	€ 129,750,301
Woudrichem - Duisburg	€ 3,785,844,444	€ 172,476,986
Woudrichem - Germany	€ 1,897,688,889	€ 86,455,655

table 54: Total WLC costs and annual WLC costs per year for different stretches

Construction costs – Formula method

The method that will be used in this chapter in order to make an estimate of the construction costs is based on the relation between the head over the structure and the construction costs. A general reference is made to Molenaar et al. (2011) who has described this relation. Below, the different relations are discussed.

Relation Variable costs – Head

The construction costs of n weirs for the full length of the river amounts to (Molenaar et al., 2011):

$$C_{constr,n} = n * c_{weir} = nC_1 + nC_2\left(H^2d + \frac{1}{3}H^3 + Hd^2\right)$$

Where:

$C_1 = fixed\ costs$ [Euro]
$C_2 = constant\ [Euro/m^2]$
$\mathrm{H} = water\ head\ (average\ in\ time)$
$d = downstream\ water\ depth\ relative\ to\ the\ foundation$

A first estimate of the parameters C1 and C2 is made, the values are respectively 100,000,000 and 100,000.

In figure 66, the relation between the variable costs and the head (the difference in water level on both sides of the structure). It can be observed this graph is not linear but goes to an exponential relation. This means that by increasing head the costs will increase much more. According to this relationship the head over the structure has to be limited.

However, it seems that the number of weirs have been more decisive for the total construction costs than the head. Only for very large retaining heads this parameter becomes more important.

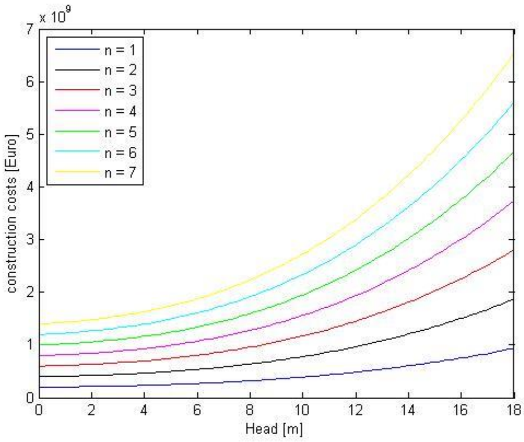


figure 66: Relation between construction costs and head

Relation Mitigation costs – number of weirs

The mitigating costs are costs required for dike raising, dike enforcement and bed protection. The mitigating costs amounts to (Molenaar et al., 2011):

$$C_{mit,n} = C_4 * \frac{H_{tot}^2}{n^2} + C_5 * \frac{H_{tot}}{n} \qquad [Euro * m/km]$$

Where:

$C_4 = [\mathrm{Euro/m/km}]$
$C_5 = [\mathrm{Euro/m^2/km}]$
$\mathrm{H_{tot}} = Total\ water\ head$
$n = number\ of\ weirs$

A first estimate of the parameters C4 and C5 is made, the values are respectively 50,000 and 500.000.

The relation between the costs for mitigating measures and the number of weirs is shown in figure 67.

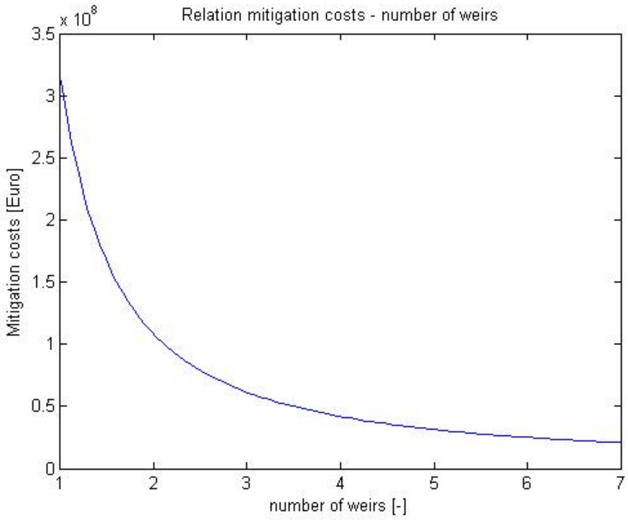


figure 67: Relation between mitigating costs and number of weirs

However, the question arises whether this approach is quite reliable. The relation shown above is clear and logic but it will not be said that it is valid for each case. Looking at the River Waal there are a lot of dikes and structures protecting the environment against flooding. The requirements set on these flood protections are quite high and this means that there is a certain over height of the dikes along the River Waal. In addition, the weirs will be constructed for the situation where the discharge and water level is quite small. In that case the remaining dike 'over' height is even higher and this can be used by applying weirs in the River Waal. Therefore, the construction and/or reinforcement of the dikes is not so large as expected by the relation shown above. According to van der Toorn it is assumed that 10% of the total dike length should be heightened by 1 meter.

Total construction costs per number of weirs/locks

Using the information from above the first calculation can be made. It is assumed that the total head is 16.8 meter and the locations of the weirs/locks are determined by equal space between the WLCs. The results are shown in the table below. From figure 68and figure 69 it can be observed that the lowest costs for a total head of 16.8 will be obtained by 2 WLCs.

H [m]	4.2	5.6	8.4	16.8	
n	4	3	2	1	
Cmit [mln]	2.98	4.37	7.73	22.51	Paramters:
Cmit,tot [mln]	**41.75**	61.15	108.19	315.17	C1 = 100 Mln
Cvar[mln]	**17.8**	29.7	65.6	310.5	C2 = 100,000
Ccon [mln]	942.6	778.2	**662.5**	821.0	C4 = 50,000
Ctot [mln]	984.3	839.3	**770.7**	1136.1	C5 = 500,000
Cmaintain [mln]	196.9	167.9	**154.1**	227.2	
Coperational [mln]	80.0	60.0	40.0	**20.0**	
Total Costs[mln]	1261.2	1067.2	**964.9**	1383.4	

table 55: Overview of WLC costs for various number of WLCs

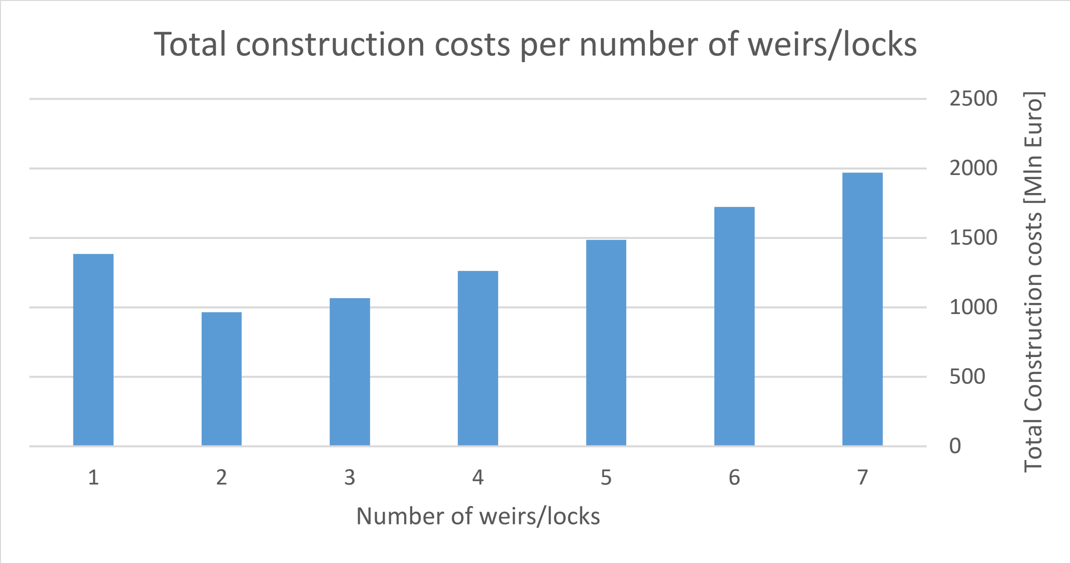


figure 68: WLC costs for various number of WLCs

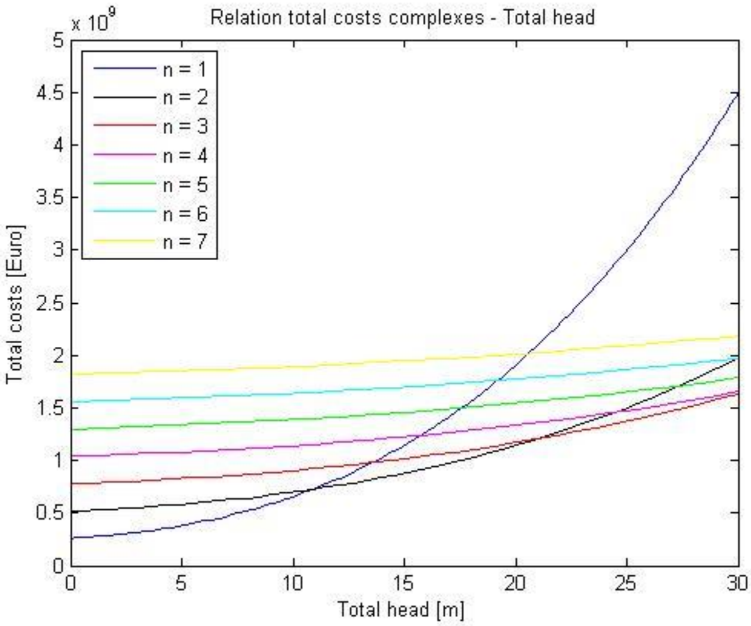


figure 69: Relation between total WLC costs and total head

Conclusion

It can be concluded that the parameters C1 and C2 are important for the choice between the number of WLCs that is most favourable with regards to the total costs of the WLCs. The parameters C4 and C5 do contribute on the total costs, but this is only relevant at the level of costs.

From the figures shown in this appendix, it can be observed that the minimum WLC costs will be obtained in case of one, two or three WLCs depending on the total head. Only in case of relative very high variable costs this amount can be increase to four WLCs when the total head is about 20 meters. A total head of 20 meters is quite large and will not be relevant because as has been said earlier, the stretch between Rotterdam and Germany will have a maximum height difference of 17 meters. Therefore, it can be concluded that the area of interest, relating the number of WLCs, is from one to three WLCs. Further research will focus on these amounts and more detailed information about the inland shipping costs will be obtained for these three situations. If this further research shows that the option for four WLCs might still relevant, then this variant will be still included.

Effect of head on construction costs

Relative high fixed construction costs

In the tables and figures below the fixed construction costs are increased to 200 million Euro and 300 million Euro respectively. It can be observed that in case of relative higher fixed costs compared to the variable construction costs a fewer number of complexed becomes cheaper. This was expected beforehand, because the fixed costs will be multiplied by the number of WLCs, so twice more WLCs mean twice as high construction costs.

H [m]	4.2	5.6	8.4	16.8
n	4	3	2	1
Cmit [mln]	2.98	4.37	7.73	22.51
Cmit,tot [mln]	**41.75**	61.15	108.19	315.17
Cvar[mln]	17.8	29.7	65.6	310.5
Ccon [mln]	1742.6	1378.2	**1062.5**	1021.0
Ctot [mln]	1784.3	1439.3	1170.7	1336.1
Cmaintain [mln]	356.9	287.9	**234.1**	267.2
Coperational [mln]	80.0	60.0	**40.0**	20.0
Total Costs[mln]	2221.2	1787.2	**1444.9**	1623.4

Paramters:
C1 = 200 Mln
C2 = 100,000
C4 = 50,000
C5 = 500,000

table 56: Overview of costs for relative high fixed construction costs

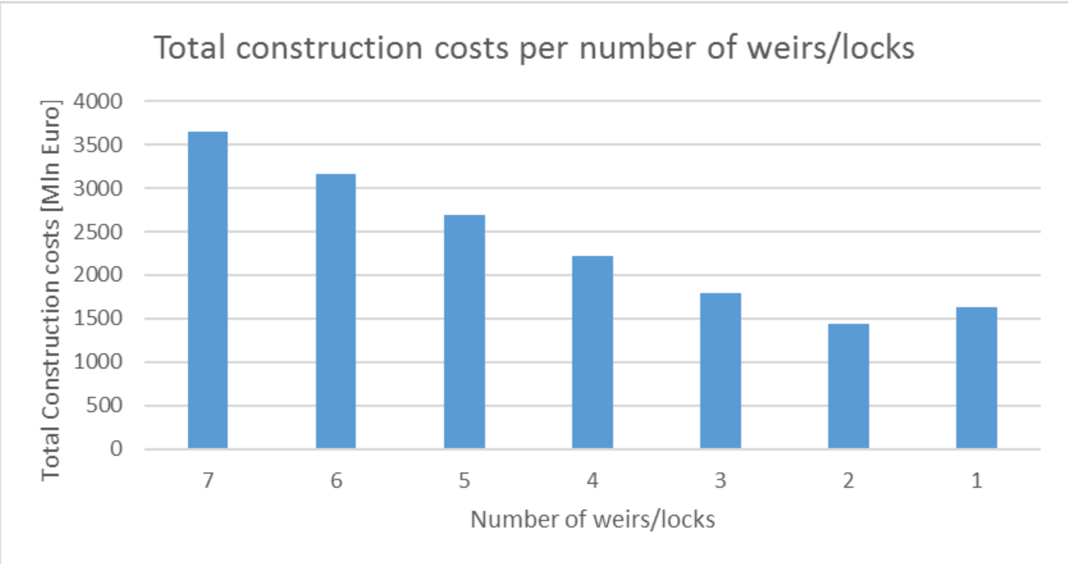


figure 70: Graph of total costs for relative high fixed construction costs

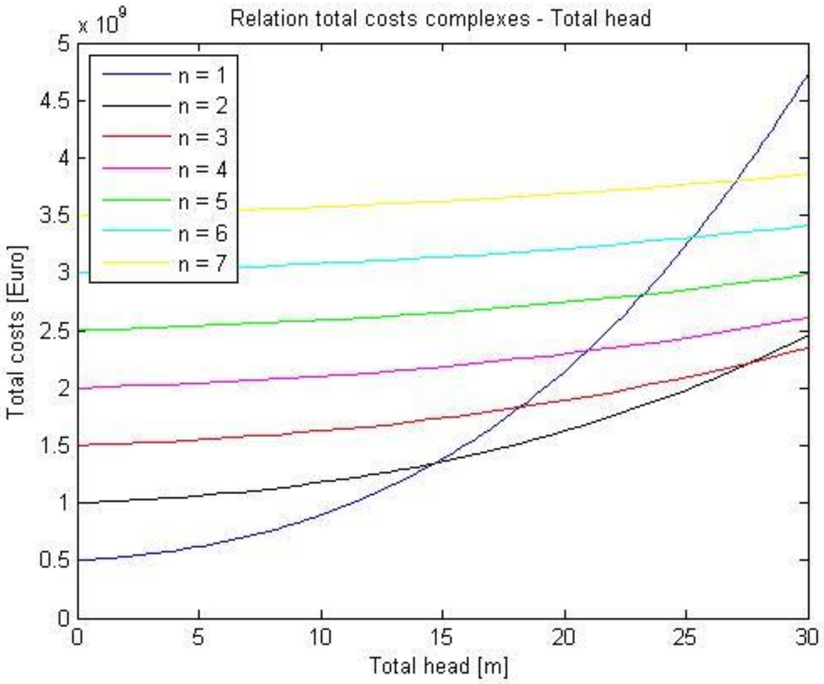


figure 71: Relation between total costs and total head for relative high fixed construction costs

H [m]	4.2	5.6	8.4	16.8	
n	4	3	2	1	
Cmit [mln]	2.98	4.37	7.73	22.51	<u>Paramters:</u>
Cmit,tot [mln]	**41.75**	61.15	108.19	315.17	C1 = 300 Mln
Cvar[mln]	17.8	29.7	65.6	310.5	C2 = 100,000
Ccon [mln]	2542.6	1978.2	**1462.5**	1221.0	C4 = 50,000 C5 = 500,000
Ctot [mln]	2584.3	2039.3	1570.7	1536.1	
Cmaintain [mln]	516.9	407.9	**314.1**	307.2	
Coperational [mln]	80.0	60.0	**40.0**	20.0	
Total Costs[mln]	3181.2	2507.2	**1924.9**	1863.4	

table 57: Overview of total costs for C1=300 mln and C2=100,000

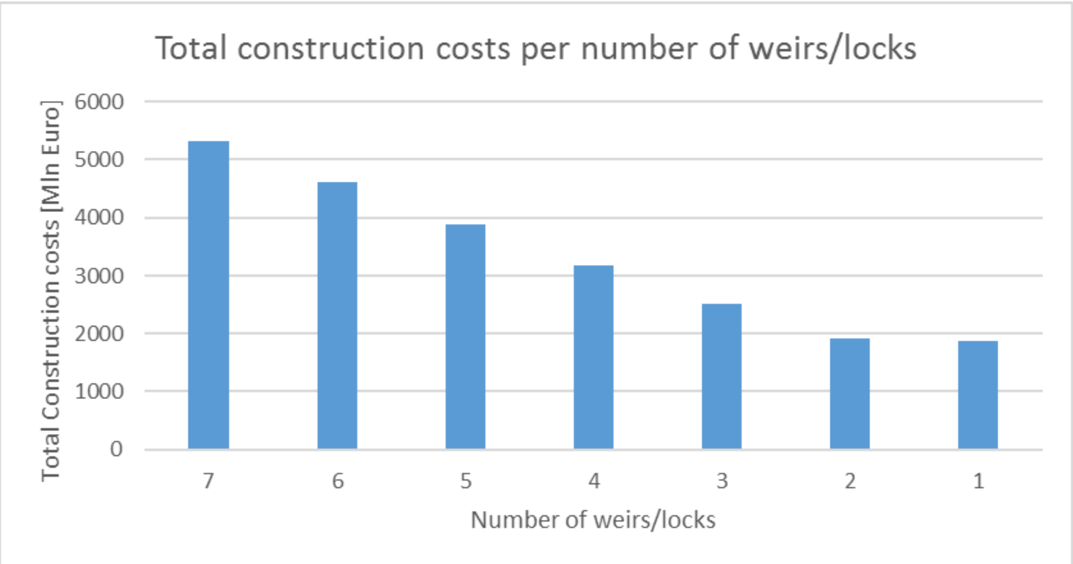


figure 72: Graph of total costs for C1=300 mln and C2=100,000

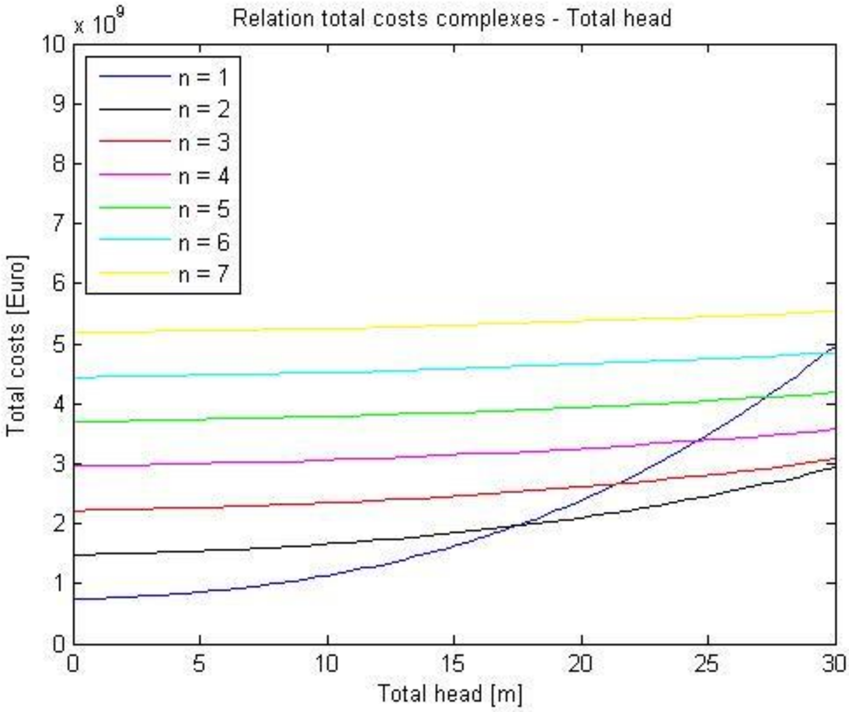


figure 73: Relation between total costs and total head for C1=300 mln and C2=100,000

Relative high variable construction costs

From the tables and figures below it can be observed that in case of high variable costs the number of WLCs will increase to obtain the lowest construction costs. A reduced head will have a greater effect in a situation with relative low fixed costs compared to a case with relative high fixed costs.

H [m]	4.2	5.6	8.4	16.8	
n	4	3	2	1	
Cmit [mln]	2.98	4.37	7.73	22.51	Paramters: C1 = 50 Mln C2 = 100,000 C4 = 50,000 C5 = 500,000
Cmit,tot [mln]	**41.75**	61.15	108.19	315.17	
Cvar[mln]	17.8	29.7	65.6	310.5	
Ccon [mln]	542.6	478.2	**462.5**	721.0	
Ctot [mln]	584.3	539.3	570.7	1036.1	
Cmaintain [mln]	116.9	107.9	**114.1**	207.2	
Coperational [mln]	80.0	60.0	**40.0**	20.0	
Total Costs[mln]	781.2	707.2	**724.9**	1263.4	

table 58: Overview of total costs for C1=50 mln and C2=100,000

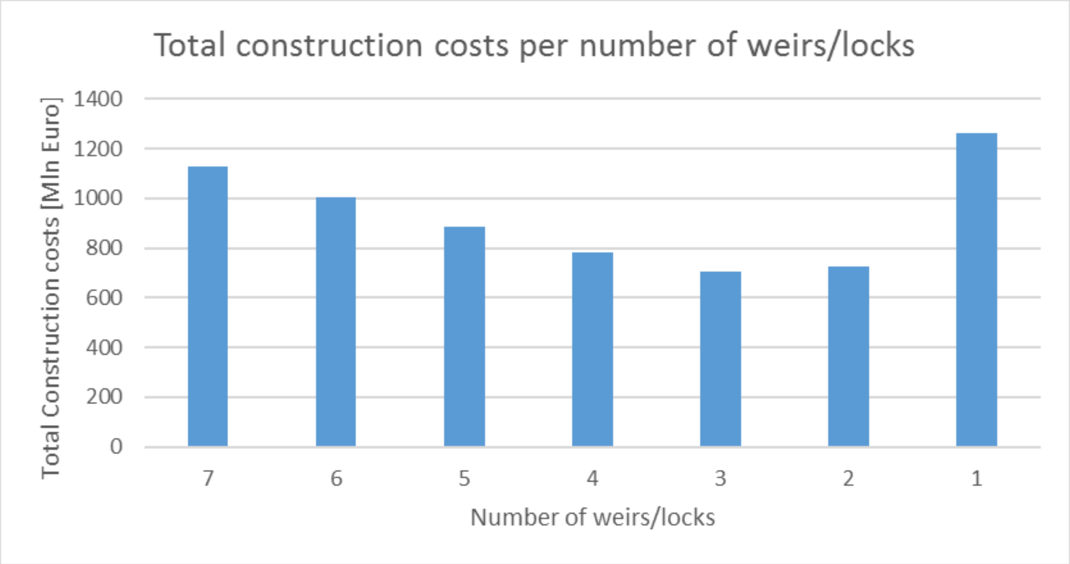


figure 74: Graph of total costs for C1=300 mln and C2=100,000

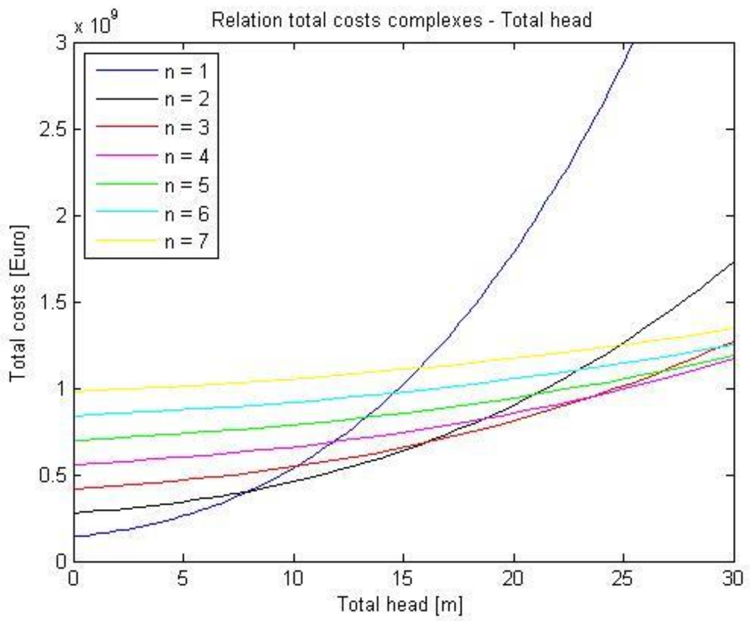


figure 75: Relation between total costs and total head for C1=50 mln and C2=100,000

H [m]	4.2	5.6	8.4	16.8	
n	4	3	2	1	
Cmit [mln]	2.98	4.37	7.73	22.51	Paramters: C1 = 50 Mln C2 = 250,000 C4 = 50,000 C5 = 500,000
Cmit,tot [mln]	**41.75**	61.15	108.19	315.17	
Cvar[mln]	44.6	74.2	164.1	776.2	
Ccon [mln]	756.4	**745.4**	856.3	1652.4	
Ctot [mln]	798.2	806.5	964.5	1967.6	
Cmaintain [mln]	**159.6**	161.3	192.9	393.5	
Coperational [mln]	80.0	60.0	40.0	**20.0**	
Total Costs[mln]	1037.8	**1027.9**	1197.4	2381.1	

table 59: Overview of total costs for C1=50 mln and C2=250,000

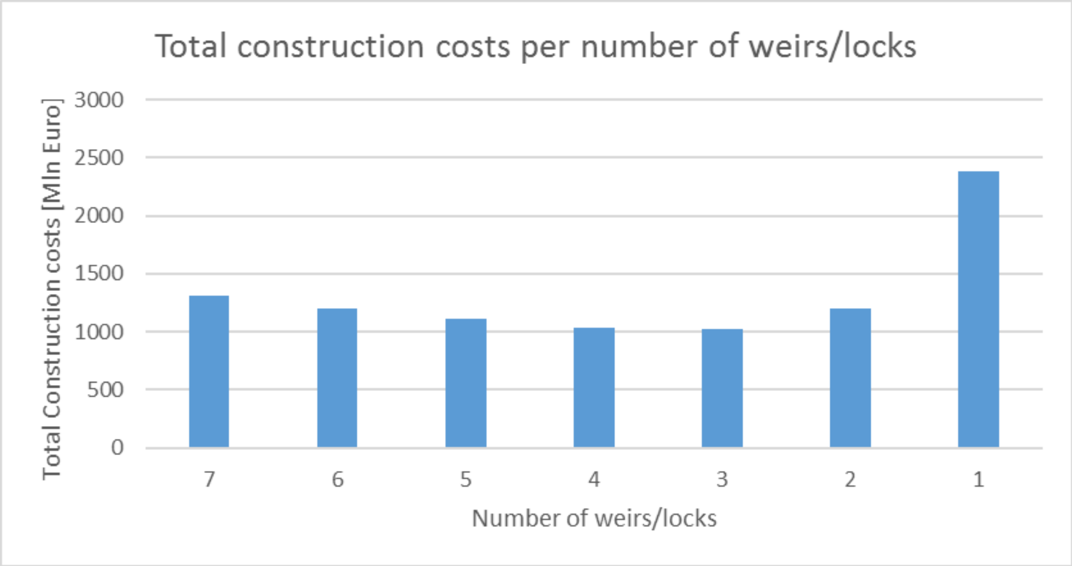


figure 76: Graph of total costs for C1=50 mln and C2=250,000

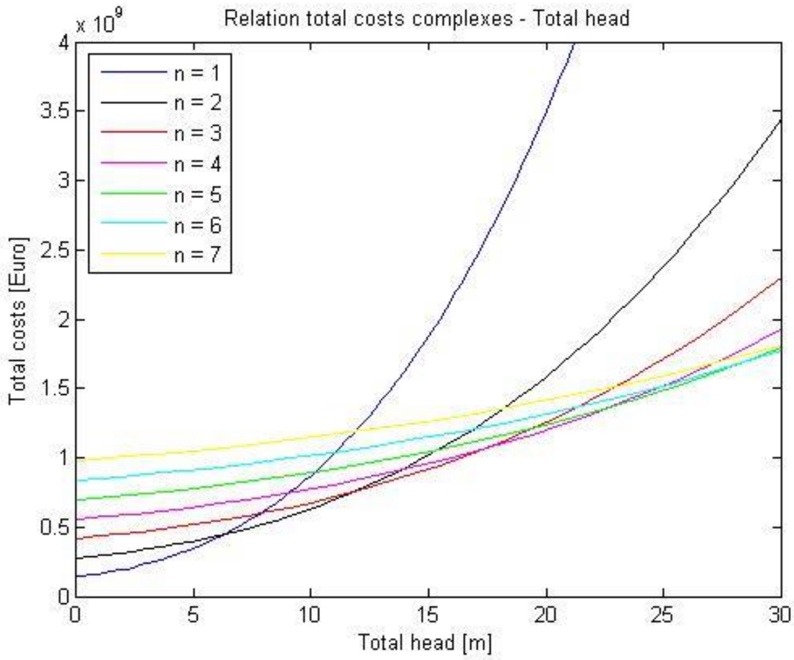


figure 77: Relation between total costs and total head for C1=50 mln and C2=250,000

More or less mitigation cost

In table 60 and table 61 the results are shown of a smaller and larger value of the parameter C4 respectively. table 62 and table 63 shows respectively the results of a smaller and larger value of parameter C5. It can be concluded that these parameters do not affect a lot the number of WLCs that leads the minimum costs, because the distribution of the costs over the different numbers of WLCs remains more or less the same. Of course, in case of a larger value for the parameters C4 and C5 the total costs will increase and a smaller value leads to less total costs, but this is self- evident.

H [m]	4.2	5.6	8.4	16.8	
n	4	3	2	1	
Cmit [mln]	2.19	2.96	4.55	9.81	Paramters: C1 = 100 Mln C2 = 100,000 C4 = 5,000 C5 = 500,000
Cmit,tot [mln]	**30.63**	41.40	63.74	137.36	
Cvar[mln]	17.8	29.7	65.6	310.5	
Ccon [mln]	942.6	778.2	**662.5**	821.0	
Ctot [mln]	973.2	819.6	726.3	958.3	
Cmaintain [mln]	194.6	163.9	**145.3**	191.7	
Coperational [mln]	80.0	60.0	**40.0**	20.0	
Total Costs[mln]	1247.8	1043.5	**911.5**	1170.0	

table 60: Overview of total costs for C4=5,000 and C5=500,000

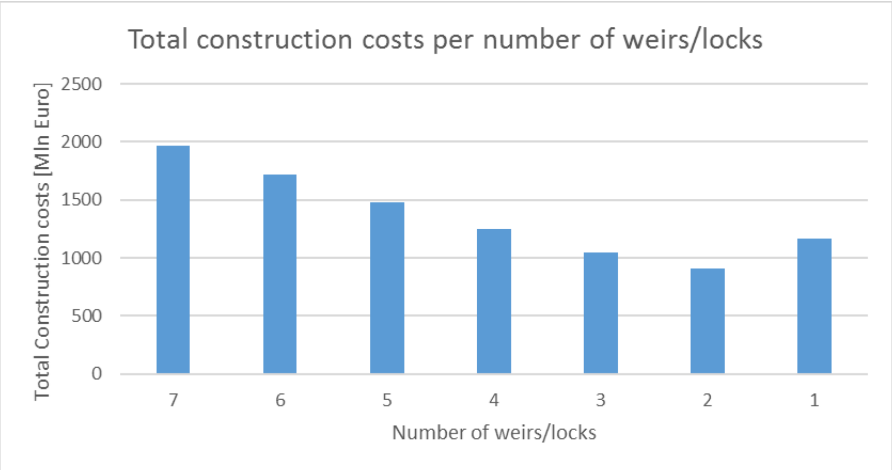


figure 78: Graph of total costs for C4=5,000 and C5=500,000

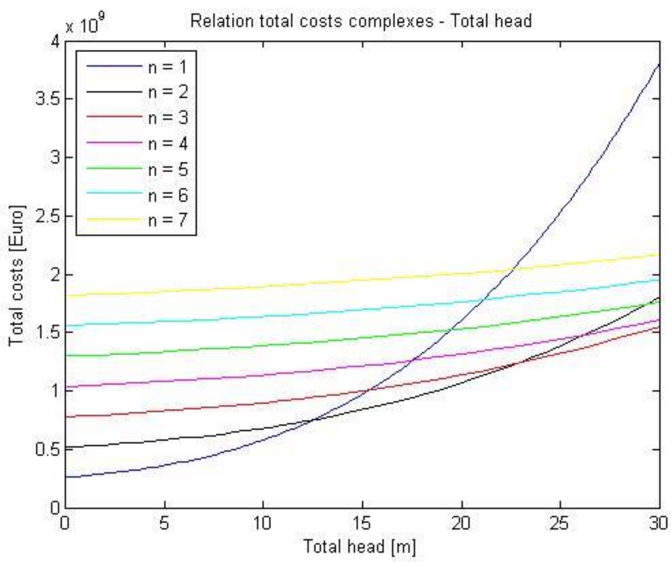


figure 79: Relation between total costs and total head for C4=5,000 and C5=500,000

H [m]	4.2	5.6	8.4	16.8
n	4	3	2	1
Cmit [mln]	3.86	5.94	11.26	36.62
Cmit,tot [mln]	**54.10**	83.10	157.58	512.74
Cvar[mln]	17.8	29.7	65.6	310.5
Ccon [mln]	942.6	778.2	**662.5**	821.0
Ctot [mln]	996.7	861.3	820.1	1333.7
Cmaintain [mln]	199.3	172.3	**164.0**	266.7
Coperational [mln]	80.0	60.0	**40.0**	20.0
Total Costs[mln]	1276.0	1093.5	**1024.1**	1620.4

Paramters:
C1 = 100 Mln
C2 = 100,000
C4 = 100,000
C5 = 500,000

table 61: Overview of total costs for C4=100,000 and C5=500,000

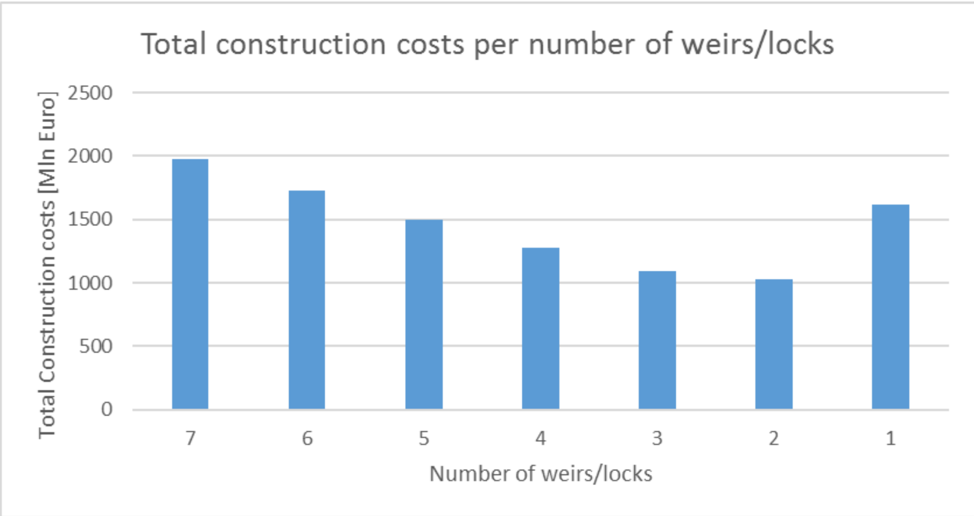


figure 80: Graph of total costs for C4=100,000 and C5=500,000

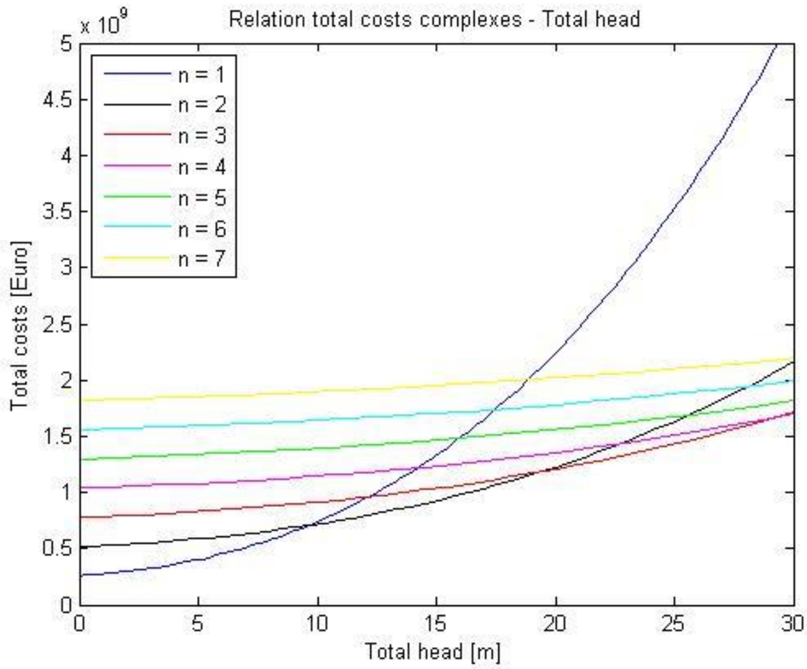


figure 81: Relation between total costs and total head for C4=100,000 and C5=500,000

H [m]	4.2	5.6	8.4	16.8	
n	4	3	2	1	
Cmit [mln]	1.30	2.13	4.37	15.79	Paramters:
Cmit,tot [mln]	**18.23**	29.79	61.15	221.09	C1 = 100 Mln
Cvar[mln]	17.8	29.7	65.6	310.5	C2 = 100,000
Ccon [mln]	942.6	778.2	**662.5**	821.0	C4 = 50,000 C5 = 100,000
Ctot [mln]	960.8	808.0	723.7	1042.0	
Cmaintain [mln]	192.2	161.6	**144.7**	208.4	
Coperational [mln]	80.0	60.0	**40.0**	20.0	
Total Costs[mln]	1233.0	1029.5	**908.4**	1270.5	

table 62: Overview of total costs for C4=50,000 and C5=100,000

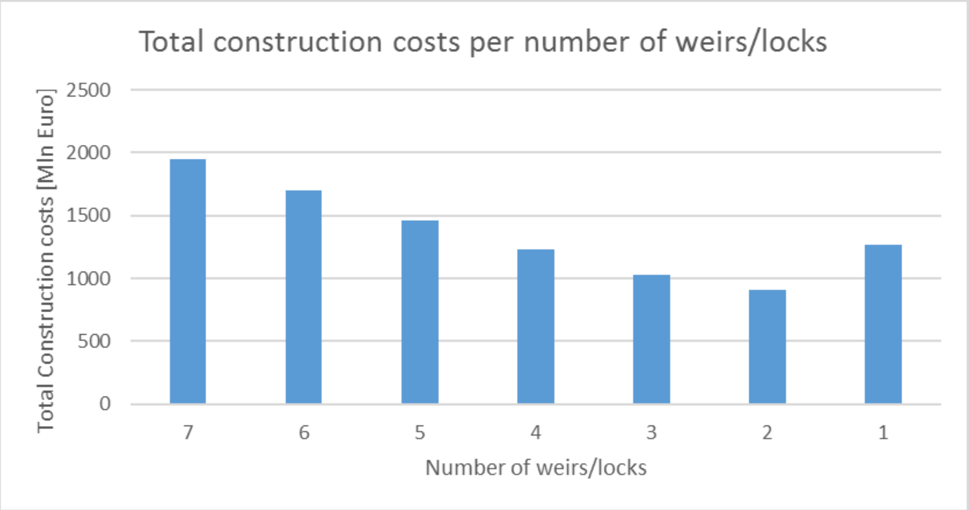


figure 82: Graph of total costs for C4=50,000 and C5=100,000

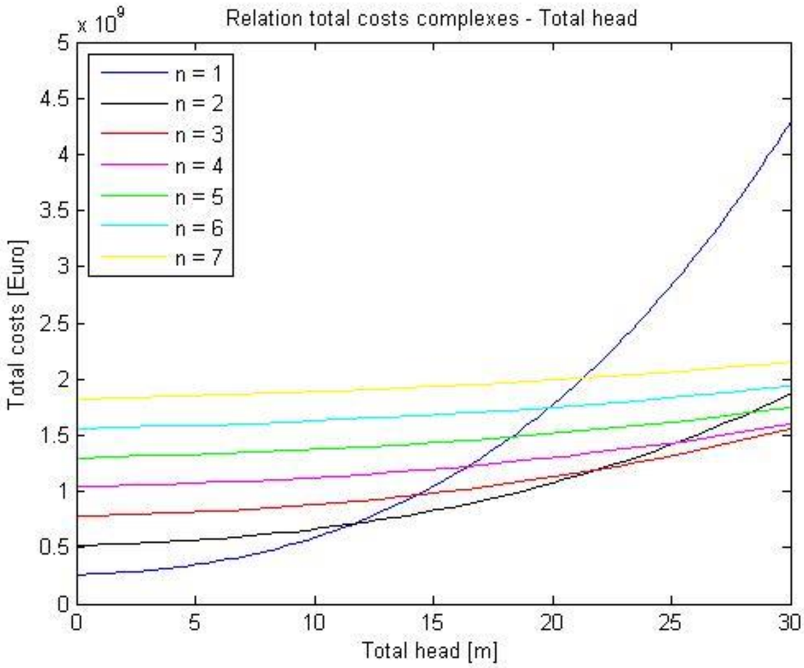


figure 83: Relation between total costs and total head for C4=50,000 and C5=100,000

H [m]	4.2	5.6	8.4	16.8	
n	4	3	2	1	
Cmit [mln]	5.08	7.17	11.93	30.91	Paramters:
Cmit,tot [mln]	**71.15**	100.35	166.99	432.77	C1 = 100 Mln
Cvar[mln]	17.8	29.7	65.6	310.5	C2 = 100,000
Ccon [mln]	942.6	778.2	**662.5**	821.0	C4 = 50,000
Ctot [mln]	1013.7	878.5	829.5	1253.7	C5 = 1 Mln
Cmaintain [mln]	202.7	175.7	**165.9**	250.7	
Coperational [mln]	80.0	60.0	**40.0**	20.0	
Total Costs[mln]	1296.5	1114.2	**1035.4**	1524.5	

table 63: Overview of total costs for C4=50,000 and C5=1Mln

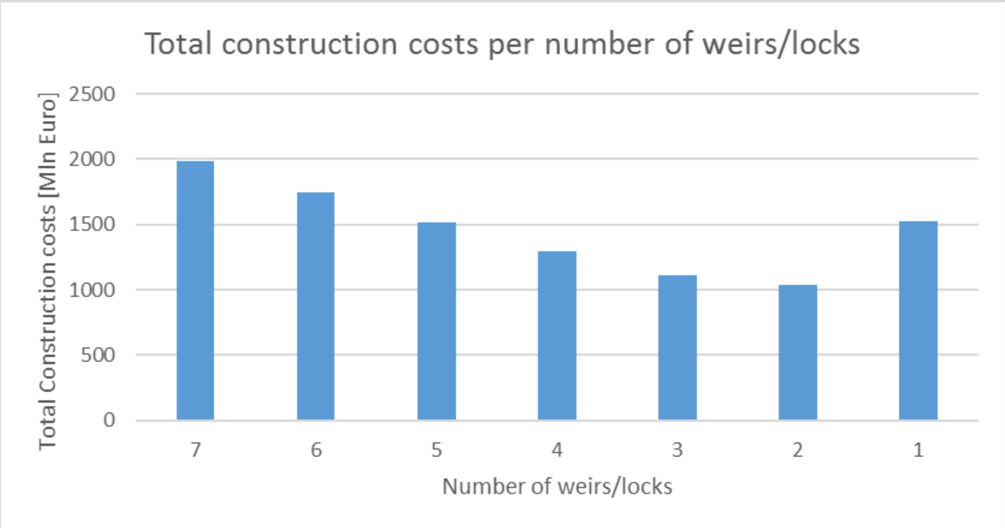


figure 84: Graph of total costs for C4=50,000 and C5=1Mln

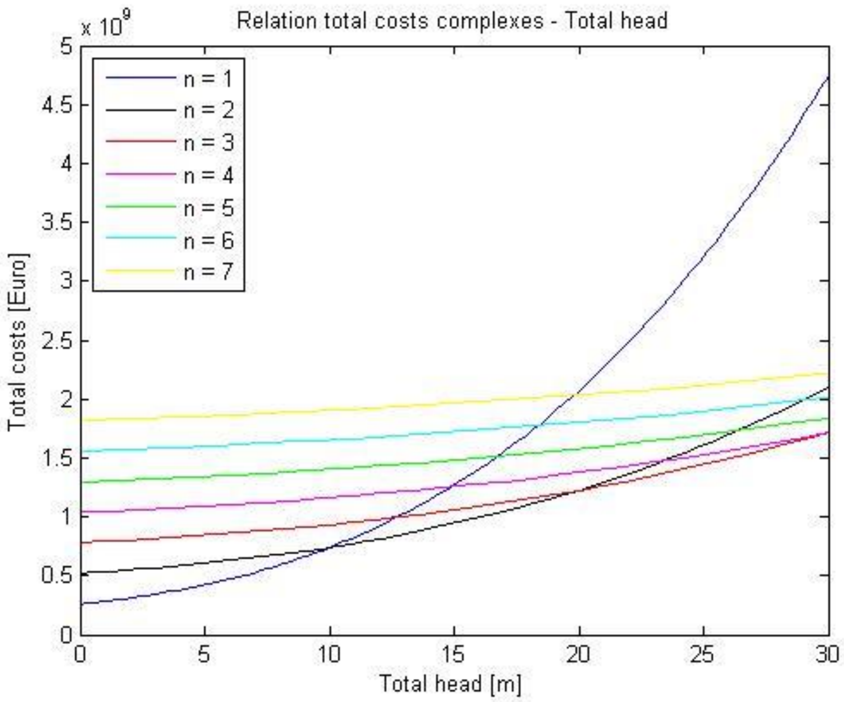


figure 85: Relation between total costs and total head for C4=50,000 and C5=1 Mln

Appendix VI

model set up

Cost figures 2008

Discounted costs

Equivalent annual costs

Cargo type distribution

Normative vessel

QH- relation at Nijmegen

Reference situation

Cost figures 2008

	Dry bulk			Liquid bulk coated			Container		
RWS- class	loaded costs/hr	unloaded costs/hr	Waiting costs/hr	loaded costs/hr	unloaded costs/hr	Waiting costs/hr	loaded costs/hr	unloaded costs/hr	Waiting costs/hr
BI	€ 207.33	€ 159.69	€ 116.69	€ 157.21	€ 109.58	€ 71.17	€ 219.44	€ 171.80	€ 133.39
BII-1	€ 265.82	€ 185.54	€ 136.29	€ 201.03	€ 120.75	€ 75.70	€ 282.01	€ 201.74	€ 156.68
BII-2b	€ 403.80	€ 303.51	€ 203.67	€ 347.89	€ 247.00	€ 157.28	€ 435.07	€ 334.78	€ 244.46
BII-2I	€ 374.92	€ 264.40	€ 203.67	€ 319.02	€ 208.49	€ 157.28	€ 406.20	€ 295.67	€ 244.46
BII-4	€ 527.03	€ 421.39	€ 307.50	€ 486.83	€ 381.19	€ 280.71	€ 595.19	€ 489.56	€ 389.07
BII-6b	€ 572.96	€ 522.18	€ 374.19	€ 566.45	€ 515.66	€ 383.38	€ 679.62	€ 628.83	€ 496.55
BII-6I	€ 592.02	€ 484.57	€ 374.19	€ 585.50	€ 478.05	€ 383.38	€ 698.67	€ 591.22	€ 496.55
BIIL-1	€ 309.04	€ 221.49	€ 166.32	€ 249.66	€ 162.11	€ 112.94	€ 329.95	€ 242.40	€ 193.23
BO1	€ 104.49	€ 89.54	€ 71.75	€ 42.41	€ 27.45	€ 12.57	€ 103.26	€ 88.30	€ 73.42
BO2	€ 120.94	€ 98.51	€ 73.28	€ 60.47	€ 38.04	€ 15.72	€ 121.17	€ 98.74	€ 76.41
BO3	€ 126.80	€ 101.88	€ 74.17	€ 66.59	€ 41.67	€ 16.86	€ 127.66	€ 102.73	€ 77.92
BO4	€ 129.15	€ 104.23	€ 76.52	€ 71.01	€ 46.09	€ 21.28	€ 131.88	€ 106.96	€ 82.15
C1b	€ 104.96	€ 159.69	€ 59.25	€ 96.62	€ 85.87	€ 50.14	€ 115.97	€ 105.22	€ 72.64
C1I	€ 89.70	€ 185.54	€ 59.25	€ 81.33	€ 74.17	€ 50.14	€ 320.56	€ 93.64	€ 72.64
C2b	€ 268.31	€ 192.59	€ 106.74	€ 275.69	€ 199.97	€ 115.33	€ 333.97	€ 258.25	€ 176.01
C2I	€ 254.90	€ 185.98	€ 106.74	€ 260.33	€ 191.41	€ 115.33	€ 320.56	€ 251.22	€ 176.01
C3b	€ 389.44	€ 254.21	€ 145.74	€ 393.81	€ 258.58	€ 158.82	€ 515.47	€ 380.24	€ 277.94
C3I	€ 362.39	€ 245.91	€ 145.74	€ 364.67	€ 248.19	€ 158.85	€ 488.43	€ 371.95	€ 277.94
C4	€ 469.42	€ 318.24	€ 185.53	€ 512.34	€ 361.16	€ 236.50	€ 636.90	€ 485.72	€ 358.51
M0	€ 58.46	€ 54.46	€ 34.78	€ 69.74	€ 65.31	€ 45.84	€ 59.03	€ 54.60	€ 36.22
M1	€ 75.50	€ 64.70	€ 39.75	€ 101.06	€ 90.26	€ 64.93	€ 81.06	€ 70.26	€ 46.44
M2	€ 96.54	€ 81.00	€ 44.37	€ 129.74	€ 114.19	€ 76.99	€ 107.73	€ 92.19	€ 56.90
M3	€ 106.59	€ 95.47	€ 50.40	€ 146.46	€ 135.33	€ 89.99	€ 125.37	€ 114.24	€ 70.91
M4	€ 140.88	€ 109.54	€ 56.26	€ 186.11	€ 154.77	€ 101.44	€ 167.54	€ 136.20	€ 85.00
M5	€ 171.69	€ 133.48	€ 73.24	€ 225.61	€ 187.39	€ 127.54	€ 211.42	€ 173.21	€ 115.52
M6	€ 205.11	€ 155.32	€ 80.47	€ 265.19	€ 215.39	€ 141.65	€ 254.74	€ 204.95	€ 133.03
M7	€ 236.75	€ 186.90	€ 106.65	€ 305.84	€ 255.98	€ 178.43	€ 313.81	€ 263.95	€ 187.53
M8	€ 298.03	€ 237.08	€ 126.73	€ 657.54	€ 296.59	€ 194.94	€ 403.68	€ 342.72	€ 238.54
M9	€ 387.07	€ 294.61	€ 164.69	€ 470.71	€ 378.25	€ 262.34	€ 538.33	€ 445.86	€ 324.87
M10	€ 464.75	€ 354.05	€ 189.14	€ 589.74	€ 479.04	€ 331.87	€ 636.37	€ 525.67	€ 372.02

table 64: Cost key figures for loaded-, unloaded- and waiting costs per hour, from NEA (2008)

RWS-class class	Dry bulk				Liquid bulk				Container sea port		Container inland port	
	Loading	Loading incl. waiting	Unloading	Unloading incl. waiting	Loading	Loading incl. waiting	Unloading	Unloading incl. waiting	Loading incl. waiting	Unloading incl. waiting	Loading incl. waiting	Unloading incl. waiting
BI	€ 692	€ 2,780	€ 1,086	€ 3,282	€ 272	€ 1,320	€ 409	€ 1,378	€ 876	€ 876	€ 770	€ 770
BII-1	€ 888	€ 3,201	€ 1,411	€ 3,800	€ 326	€ 1,344	€ 491	€ 1,361	€ 1,901	€ 1,901	€ 1,174	€ 1,174
BII-2l	€ 2,583	€ 6,249	€ 3,676	€ 7,596	€ 1,536	€ 4,249	€ 1,688	€ 4,866	€ 6,746	€ 6,746	€ 3,893	€ 3,893
BII-2b	€ 2,583	€ 6,249	€ 3,676	€ 7,596	€ 1,536	€ 4,559	€ 1,998	€ 5,952	€ 7,117	€ 7,117	€ 3,893	€ 3,893
BII-4	€ 6,623	€ 15,233	€ 8,460	€ 17,839	€ 4,380	€ 14,634	€ 5,475	€ 18,253	€ 22,655	€ 22,655	€ 11,820	€ 11,820
BII-6I	€ 12,310	€ 34,013	€ 14,753	€ 37,859	€ 13,068	€ 42,817	€ 14,854	€ 51,744	€ 43,369	€ 43,369	€ 22,262	€ 22,262
BII-6b	€ 12,310	€ 34,013	€ 14,753	€ 37,859	€ 13,068	€ 42,817	€ 14,854	€ 51,744	€ 43,369	€ 43,369	€ 22,262	€ 22,262
BIIL-1	€ 1,202	€ 3,462	€ 1,933	€ 4,303	€ 552	€ 2,074	€ 831	€ 2,458	€ 2,813	€ 2,813	€ 2,044	€ 2,044
B01	€ 220	€ 1,094	€ 298	€ 1,365	€ 20	€ 180	€ 31	€ 215	€ 313	€ 313	€ 168	€ 168
B02	€ 289	€ 1,206	€ 420	€ 1,525	€ 33	€ 212	€ 50	€ 252	€ 349	€ 349	€ 216	€ 216
B03	€ 305	€ 1,238	€ 447	€ 1,568	€ 36	€ 222	€ 55	€ 262	€ 367	€ 367	€ 232	€ 232
B04	€ 314	€ 1,277	€ 461	€ 1,617	€ 44	€ 267	€ 66	€ 316	€ 437	€ 437	€ 244	€ 244
C1l	€ 268	€ 728	€ 401	€ 946	€ 94	€ 353	€ 141	€ 422	€ 331	€ 331	€ 245	€ 245
C1b	€ 268	€ 728	€ 401	€ 946	€ 94	€ 353	€ 141	€ 422	€ 331	€ 331	€ 245	€ 245
C2l	€ 757	€ 2,297	€ 1,216	€ 3,179	€ 457	€ 1,567	€ 688	€ 1,975	€ 2,282	€ 2,282	€ 1,748	€ 1,748
C2b	€ 757	€ 2,297	€ 1,216	€ 3,179	€ 457	€ 1,567	€ 688	€ 1,975	€ 2,282	€ 2,282	€ 1,748	€ 1,748
C3l	€ 1,471	€ 3,803	€ 2,175	€ 5,272	€ 1,567	€ 4,359	€ 1,869	€ 5,021	€ 7,755	€ 7,755	€ 3,876	€ 3,876
C3b	€ 1,471	€ 3,803	€ 2,175	€ 5,272	€ 1,567	€ 4,359	€ 1,869	€ 5,021	€ 7,755	€ 7,755	€ 3,876	€ 3,876
C4	€ 2,503	€ 5,935	€ 3,635	€ 8,319	€ 3,112	€ 8,278	€ 4,102	€ 10,272	€ 18,701	€ 18,701	€ 10,608	€ 10,608
M0	€ 65	€ 305	€ 80	€ 380	€ 36	€ 442	€ 55	€ 490	€ 132	€ 132	€ 69	€ 69
M1	€ 132	€ 422	€ 184	€ 539	€ 114	€ 625	€ 172	€ 692	€ 187	€ 187	€ 113	€ 113
M2	€ 182	€ 519	€ 267	€ 672	€ 170	€ 721	€ 256	€ 783	€ 251	€ 251	€ 169	€ 169
M3	€ 234	€ 627	€ 352	€ 817	€ 234	€ 852	€ 353	€ 901	€ 323	€ 323	€ 247	€ 247
M4	€ 284	€ 731	€ 433	€ 955	€ 293	€ 953	€ 442	€ 977	€ 452	€ 452	€ 341	€ 341
M5	€ 393	€ 981	€ 607	€ 1,282	€ 406	€ 1,199	€ 612	€ 1,185	€ 641	€ 641	€ 526	€ 526
M6	€ 473	€ 1,111	€ 741	€ 1,456	€ 509	€ 1,283	€ 767	€ 1,161	€ 919	€ 919	€ 749	€ 749
M7	€ 669	€ 1,469	€ 1,057	€ 1,935	€ 788	€ 1,728	€ 1,187	€ 1,390	€ 1,820	€ 1,820	€ 1,257	€ 1,257
M8	€ 849	€ 1,659	€ 1,353	€ 2,216	€ 1,014	€ 1,854	€ 1,526	€ 1,673	€ 3,762	€ 3,762	€ 1,950	€ 1,950
M9	€ 1,224	€ 2,072	€ 1,976	€ 2,940	€ 1,621	€ 2,522	€ 2,462	€ 2,582	€ 6,306	€ 6,306	€ 3,314	€ 3,314
M10	€ 1,545	€ 2,301	€ 2,516	€ 3,423	€ 2,468	€ 3,277	€ 3,641	€ 3,682	€ 11,226	€ 11,226	€ 4,531	€ 4,531

table 65: Cost key figures for Loading- and unloading costs from NEA (2008)

Discounted costs

The calculation of the total WLC costs is expressed at the price level of 2010.

The operational costs are determined in 2008 and therefore these costs have to be corrected for inflation in order to obtain the costs expressed in the price level of 2010.

The historic inflation of 2008 and 2009 are 1.94% and 1.11% respectively. This results in an average inflation of 1.52%. Using this information, the operational costs at price level 2010 can be calculated.

$$Annual\ aintenance\ Costs\ (2010) = \frac{Maintenance\ costs\ 2008}{(1+i)^t} = \frac{€1Mln}{(1+1.52)^2} = €1.03\ Mln$$

So, the annual maintenance costs are 1.03 Million Euro price level 2010.

In the same way, the costs are discounted to the price level of the shipping costs (2008 and 2016)

Equivalent annual costs

Equivalent annual cost is the annual rental payment sufficient to cover the present value of all the costs of owning and operating it. It is a way of converting a present value to an annual cost (Brealey, Richard A).

The equivalent annual costs are determined as follows:

$$Equivalent\ annual\ costs = \frac{Present\ value}{annuity\ factor}$$

$$Annuity\ factor\ = \frac{1}{r} - \frac{1}{r * (1+r)^t}$$

Where *r* is the annual interest rate and *t* is the number of years.

Cargo type distribution

In figure 86 the cargo distribution of the throughput in 2016 of the Port of Rotterdam is shown.

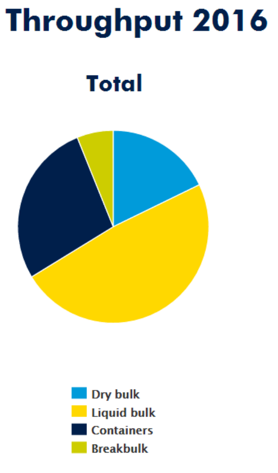


figure 86: Cargo throughput distribution (in gross weight) of the port in Rotterdam in 2016 (Port of Rotterdam, n.d.[a])

Normative vessel

Year 2003

According to Centraal Bureau voor de Statistiek (CBS, December 2009) data with respect to freight transport by inland shipping for the year 2003 is shown in the table below.

Total freight transport [ton]	136,621,000
Total number of trips [-]	181738
Average total loading capacity [ton]	371,392,000
Number of loaded trips [-]	113988
Average total loading capacity [ton]	216,166,000

table 66: Data of inland shipping transport

Using these data, the average loading capacity can be determined. By dividing the average loading capacity by the total number of trips, an average loading capacity of about 2050 ton will be obtained. This average loading capacity is used as loading capacity for the normative vessel. Looking at the different vessel types according to the CEMT and/or RWS Classes (see Appendix I: CEMT class characteristics) the ships with quite similar loading capacities are used for determining the normative vessel. These similar vessels are included in table 67.

RWS Class	Type	Loading capacity [ton]	Length [m]	Width [m]	Depth [m]
M8	Big Rhine ship	≥2050	95 - 110	11.4	3.5
BII-1	Europa II Push barge	1801 - 2450	95 - 110	11.4	3.5
C2b/I	Class IV + Europa I	901 - 3350	85 – 105/ 170 – 185	19 / 9.5	3.0
Normative vessel		2050	95	9.5	3.3

table 67: characteristics of equivalent vessels for 2003

In the tables below the corresponding cost prices are shown.

	Loaded shipping costs per hour			
RWS- Class	Dry bulk	Liquid Bulk	Container	Average*
M8	€ 298.03	€ 657.54	€ 403.68	€ 504.20
BII-1	€ 265.82	€ 201.03	€ 282.01	€ 237.47
C2b	€ 268.31	€ 275.69	€ 333.97	€ 288.42
Normative vessel	*€ 272.92*	*€ 372.97*	*€ 335.42*	***€ 338.57***

*The distribution is ¼ dry bulk, ½ liquid bulk and ¼ container transport.

	Unloaded shipping costs per hour			
RWS- Class	Dry bulk	Liquid Bulk	Container	Average*
M8	€ 237.08	€ 296.59	€ 342.72	€ 293.25
BII-1	€ 185.54	€ 120.75	€ 201.74	€ 157.20
C2b	€ 192.59	€ 199.97	€ 258.25	€ 212.70
Normative vessel	*€ 205.07*	*€ 205.77*	*€ 267.57*	***€ 221.05***

*The distribution is ¼ dry bulk, ½ liquid bulk and ¼ container transport.

	Loading costs incl. waiting costs				
RWS- Class	Dry bulk	Liquid Bulk	Container sea port	Container inland port	Average*
M8	€ 1,659	€ 1,854	€ 3,762	€ 1,950	€ 2,055.82
BII-1	€ 3,201	€ 1,344	€ 1,901	€ 1,174	€ 1,856.55
C2b	€ 2,297	€ 1,567	€ 2,282	€ 1,748	€ 1,861.20
***Normative* vessel**	*€ 2,385.86*	*€ 1,588.09*	*€ 2,648.09*	*€ 1,624.04*	***€ 1,924.52***

*The distribution is ¼ dry bulk, ½ liquid bulk and 1/8 container sea port and 1/8 container inland port.

	Unloading costs incl. waiting costs				
RWS- Class	Dry bulk	Liquid Bulk	Container sea port	Container inland port	Average*
M8	€ 2,216	€ 1,854	€ 3,762	€ 1,950	€ 2,195.08
BII-1	€ 3,800	€ 1,361	€ 1,901	€ 1,174	€ 2,015.19
C2b	€ 2,297	€ 3,179	€ 2,282	€ 1,748	€ 2,667.48
***Normative* vessel**	*€ 2,771.19*	*€ 2,131.54*	*€ 2,648.09*	*€ 1,624.04*	***€ 2,292.58***

*The distribution is ¼ dry bulk, ½ liquid bulk and 1/8 container sea port and 1/8 container inland port.

Year 2050

The average load capacity that passes the border at Lobith in the year 2030 is expected to be 3000 tons (Rijkswaterstaat, 2007). According to Dienst Verkeer en Scheepvaart of Rijkswaterstaat an average growth of 59 tons/year for fairway class VI from 2021 to 2040 is expected. After 2040 the growth in loading capacity is expected to be 0. Using these data for 2050, the average loading capacity for vessels on the River Waal will be 3590 ton. However, a study of 2013 to berths of an overnight port at Lobith (Rijkswaterstaat, 2013) shows that the average loading capacity was already 2900 ton in 2012. Therefore, the earlier prognosis is a bit adjusted to these new data. The expected average loading capacity for the year 2040 is equal to 3200 tons. Until the year 2050 it is assumed that the upscaling will continue and combining both studies results in an expectation of the average loading capacity of 3500 ton

Looking at the different vessel types according to the CEMT and/or RWS Classes (see Appendix I: CEMT class characteristics) the ships with quite similar loading capacity will be used for determining the normative vessel. These equivalent ships with their characteristics are listed in table 68. The characteristics for the normative vessel can be determined by taking the average of the vessels included in the table. In the lower row the normative vessel with their characteristics is shown.

RWS class	*Average loading capacity [ton]*	*Length [m]*	*Width [m]*	*Draught [m]*
BIIL-1	3201 - 3950	95 - 110	11.4	4
C2b	901 – 3350	85 – 110	19.0	3
C2I	901 – 3350	170 – 190	9.5	3
C3b	3351 - 7250	85 – 105	22.8	4
C3I	3351 - 7250	170 – 190	11.4	4
M8	2410	95 – 110	11,4	3.5
M9	3900	135	11,4	3.5
Normative vessel	**3500**	**110**	**11,4**	**3.7**

table 68: characteristics of equivalent vessels for 2050

Cost price

The shipping costs that corresponds to this normative vessel will be calculated by taking the average of the shipping costs for the three equivalent ships, one of each type (Motor vessel, push bar, push convoy). However, not for each type is one equivalent vessel, in that case the average of the most equivalent vessels are taken. This analysis is shown in table 69 and the results are included in the lowest row.

Characteristics			*Costs*				
RWS Class	Average loading capacity [ton]	Draught [m]	Average waiting costs/hr	Average loaded costs/hr	Average unloaded costs/hr	Average costs for loading + waiting time	Average costs for unloading + waiting time
BIIL-1	3550	4	€ 146.36	€ 284.58	€ 197.03	€ 2,509.66	€ 2,912
C2b	2900	3	€ 128.35	€ 288.42	€ 212.70	€ 1,861.20	€ 2,286
C2I	2900	3	€ 128.35	€ 274.03	€ 205.01	€ 1,861.20	€ 2,286
C3b	4500	4	€ 185.33	€ 423.13	€ 287.90	€ 4,584.08	€ 5,282
C3I	4500	4	€ 185.35	€ 395.04	€ 278.56	€ 4,584.08	€ 5,282
M8	2410	3.5	€ 188.79	€ 504.20	€ 293.25	€ 2,055.82	€ 2,105
M9	3900	3.5	€ 253.56	€ 466.71	€ 374.24	€ 2,981	€ 3,228
Normative vessel	**3500**	**3.7**	**€ 174.79**	**€ 371.73**	**€ 258.94**	**€ 2,750**	**€ 3,121**

table 69: Cost prices corresponding to the equivalent vessels and to the normative vessel

QH- relation at Nijmegen

The water depth at Nijmegen is assumed normative for the entire route between Duisburg and Rotterdam. Therefore, a relation between the discharge and water depth at this location will be used for determining the water depth corresponding to a certain discharge. However, hysteresis in river discharge takes place during unsteady flow. This unsteady flow occurs when the water surface slope changes due to either rapidly rising or falling water levels. Hysteresis is a phenomenon whereby the response to an external force not only depends on the magnitude, but also on the history of the system (Encyclopedia of Snow, Ice and Glaciers, 2014). In figure 88 this phenomenon with its different characteristics is shown. Looking at the measured data from 2003, which is shown in figure 87, also a hysteresis can be observed.

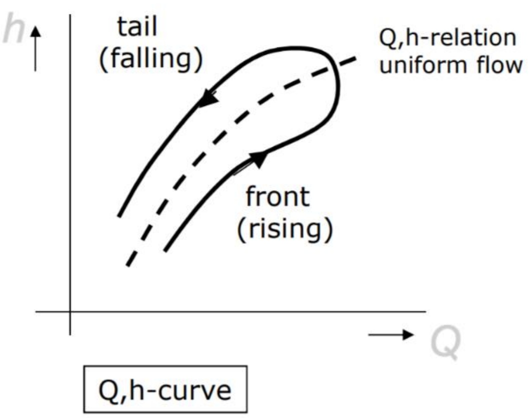


figure 88: Discharge hysteresis (Blom, 2016b)

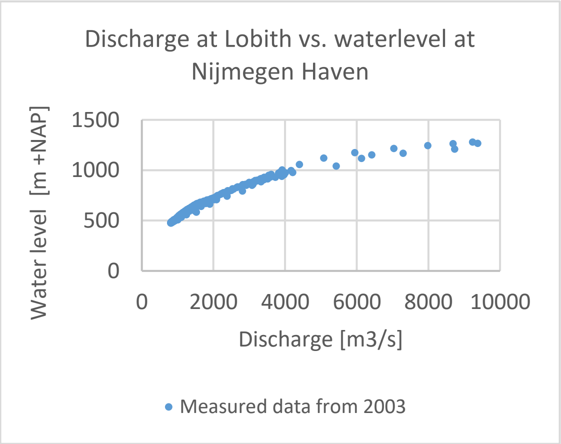


figure 87: Relation between Rhine discharge and water level at Nijmegen from 2003

When compiling a Q/H-relation it is assumed that there is steady flow. So, adding a trendline results in the steady state relationship between the Discharge and water level.

Data of 5 years, from 2001 to 2005, is used to compute the relation between the discharge at Lobith and the water level at Nijmegen Haven. The graph in figure 89 shows these measured data and Q/H relation.

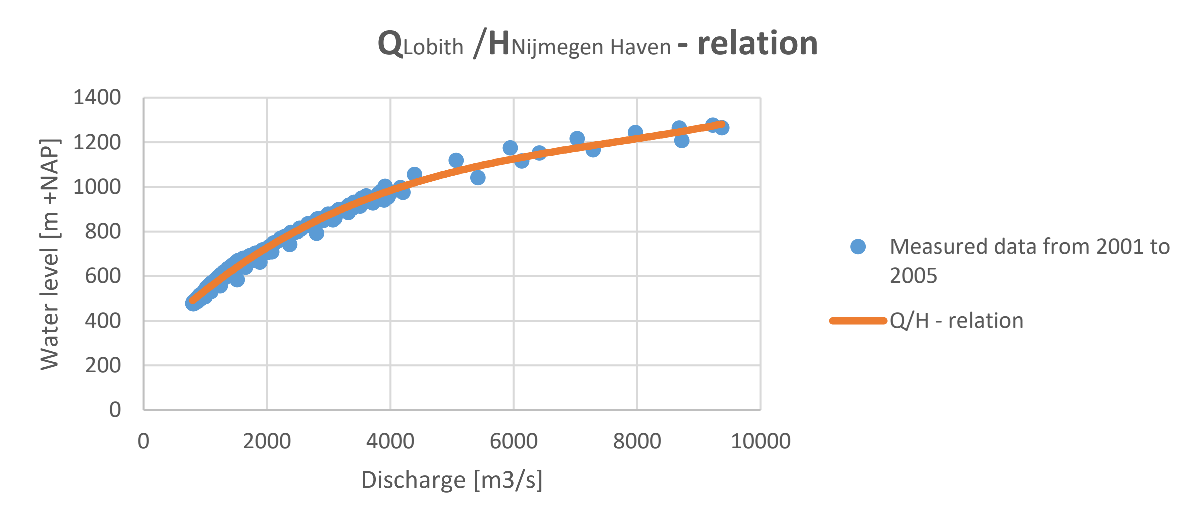


figure 89: Q/H relation at Nijmegen

There are several options for the type of trendline. With the third power polynomial and the normal log the measured data is best simulated. With a control check the deviation of the simulated data relative to the measured data is investigated. A third option for the trendline is added by taking the average of the two trendline types. The average deviation for these three options is included in table 70.

Trendline type	**Polynomial**	**Log normal**	**Average trend**
Average deviation [m]	0.25	0.17	0.17

table 70: Deviation for three trendline options

As can be observed from the table above, the log normal and the average trend simulate the results most accurately. However, it is most important that water levels corresponding to a relative low discharge will be simulated most accurate, because these water levels have influence on the navigability of the river. Therefore, a check with respect to the number of days that a certain water level occur gives more insight in the performance of the different types. For the period 2001 to 2005 the data is analysed and the number of days that certain water depths occur is investigated and included in table 71. This water depth is obtained by subtracting the bottom level from the water level. As can be observed, the normal log relation gives quite few days with a low average depth. This is not observed in the measured data and therefore the average trend gives the most accurate simulated data.

Average depth [m]	*Number of days*			
	Measured data	***Polynomial***	***Normal log***	***Average trend***
<2.2	0	0	14	1
2.3	8	0	11	11
2.5	14	5	28	12
2.7	29	13	33	29
2.9	39	35	42	44
3.1	46	56	47	47
3.3	54	65	54	66
3.5	58	67	36	46
3.7	56	70	70	66
≥3.8	1522	1515	1491	1504
Total	**1826**	**1826**	**1826**	**1826**

table 71: Occurrence of water depths for four trendline options

Climate model validation

Date	Discharge [m³/s] (measured data)	Waterlevel +m NAP (measured data)	Water level +m NAP (QH- relation)	Waterlevel +m NAP (SOBEK)
1-1-2003	5416	10.42	11.26	6.87
2-1-2003	6127	11.17	11.81	10.93
3-1-2003	6412	11.52	12.03	11.48
4-1-2003	7284	11.67	12.64	11.85
5-1-2003	8722	12.08	13.61	12.25
6-1-2003	9372	12.66	14.06	12.48
7-1-2003	9224	12.78	13.96	12.50
8-1-2003	8681	12.64	13.59	12.39
9-1-2003	7971	12.45	13.11	12.22
10-1-2003	7027	12.17	12.46	11.98
11-1-2003	5941	11.75	11.67	11.61
12-1-2003	5066	11.2	10.96	11.11
13-1-2003	4388	10.57	10.35	10.49
14-1-2003	3910	10.03	9.87	9.85
15-1-2003	3607	9.6	9.54	9.39
16-1-2003	3411	9.31	9.32	9.09
17-1-2003	3304	9.13	9.19	8.92
18-1-2003	3221	9	9.09	8.80
19-1-2003	3180	8.91	9.04	8.73
20-1-2003	3102	8.85	8.95	8.65
21-1-2003	2995	8.74	8.81	8.53
22-1-2003	2893	8.6	8.68	8.41
23-1-2003	2910	8.5	8.70	8.37
24-1-2003	3098	8.6	8.94	8.50
25-1-2003	3315	8.86	9.20	8.74
26-1-2003	3391	9.06	9.29	8.90
27-1-2003	3409	9.12	9.31	8.95
28-1-2003	3409	9.13	9.31	8.97
29-1-2003	3416	9.12	9.32	8.97
30-1-2003	3507	9.15	9.43	9.04
31-1-2003	3718	9.29	9.66	9.22
1-2-2003	3959	9.54	9.92	9.46
2-2-2003	3999	9.75	9.96	9.59
3-2-2003	3808	9.71	9.76	9.49
4-2-2003	3600	9.48	9.53	9.29
5-2-2003	3586	9.33	9.52	9.19
6-2-2003	3895	9.41	9.85	9.38
7-2-2003	4204	9.76	10.17	9.69
8-2-2003	4162	9.98	10.12	9.79
9-2-2003	3854	9.82	9.81	9.60
10-2-2003	3534	9.5	9.46	9.27
11-2-2003	3327	9.18	9.22	8.99
12-2-2003	3161	8.98	9.02	8.77
13-2-2003	2991	8.79	8.81	8.57
14-2-2003	2812	8.57	8.57	8.35
15-2-2003	2664	8.36	8.37	8.14
16-2-2003	2526	8.16	8.18	7.96
17-2-2003	2388	7.97	7.98	7.78
18-2-2003	2275	7.77	7.80	7.63
19-2-2003	2196	7.61	7.68	7.51
20-2-2003	2118	7.48	7.56	7.41
21-2-2003	2064	7.36	7.47	7.33
22-2-2003	2025	7.26	7.40	7.28
23-2-2003	1974	7.2	7.32	7.22
24-2-2003	1928	7.11	7.24	7.18
25-2-2003	1894	7.09	7.18	7.14
26-2-2003	1857	7.03	7.12	7.10
27-2-2003	1818	6.97	7.05	7.06
28-2-2003	1802	6.94	7.02	7.04
1-3-2003	1809	6.93	7.03	7.03
2-3-2003	1814	6.93	7.04	7.04
3-3-2003	1885	6.92	7.17	7.09
4-3-2003	2077	7.09	7.49	7.24
5-3-2003	2368	7.42	7.95	7.52
6-3-2003	2800	7.93	8.56	7.98
7-3-2003	3069	8.52	8.90	8.40
8-3-2003	3094	8.74	8.94	8.56
9-3-2003	3026	8.72	8.85	8.54
10-3-2003	2951	8.63	8.76	8.46
11-3-2003	2860	8.57	8.64	8.36
12-3-2003	2778	8.43	8.53	8.25
13-3-2003	2729	8.35	8.46	8.17
14-3-2003	2643	8.27	8.34	8.07
15-3-2003	2552	8.13	8.21	7.96
16-3-2003	2489	8	8.12	7.87

17-3-2003	2426	7.93	8.03	7.79
18-3-2003	2326	7.82	7.88	7.68
19-3-2003	2215	7.69	7.71	7.55
20-3-2003	2106	7.49	7.54	7.41
21-3-2003	2041	7.33	7.43	7.31
22-3-2003	1979	7.22	7.33	7.24
23-3-2003	1906	7.12	7.20	7.16
24-3-2003	1856	7.04	7.11	7.11
25-3-2003	1807	6.98	7.03	7.05
26-3-2003	1772	6.94	6.96	7.01
27-3-2003	1714	6.87	6.86	6.96
28-3-2003	1691	6.83	6.81	6.93
29-3-2003	1686	6.8	6.81	6.92
30-3-2003	1646	6.8	6.73	6.90
31-3-2003	1617	6.73	6.67	6.87
1-4-2003	1604	6.72	6.65	6.81
2-4-2003	1643	6.73	6.72	6.82
3-4-2003	1673	6.78	6.78	6.87
4-4-2003	1705	6.8	6.84	6.93
5-4-2003	1801	6.85	7.02	7.00
6-4-2003	1837	6.96	7.08	7.05
7-4-2003	1838	6.95	7.08	7.06
8-4-2003	1788	6.97	6.99	7.03
9-4-2003	1727	6.9	6.88	6.98
10-4-2003	1649	6.81	6.74	6.91
11-4-2003	1612	6.77	6.66	6.87
12-4-2003	1572	6.72	6.59	6.77
13-4-2003	1533	6.7	6.51	6.69
14-4-2003	1515	6.62	6.47	6.63
15-4-2003	1528	6.61	6.50	6.62
16-4-2003	1510	6.6	6.46	6.61
17-4-2003	1486	6.58	6.41	6.58
18-4-2003	1449	6.52	6.34	6.52
19-4-2003	1418	6.44	6.27	6.46
20-4-2003	1388	6.34	6.21	6.40
21-4-2003	1368	6.29	6.17	6.35
22-4-2003	1359	6.25	6.15	6.31
23-4-2003	1363	6.23	6.16	6.31
24-4-2003	1364	6.25	6.16	6.31
25-4-2003	1374	6.23	6.18	6.32
26-4-2003	1394	6.26	6.22	6.34
27-4-2003	1439	6.32	6.32	6.41
28-4-2003	1435	6.45	6.31	6.44
29-4-2003	1418	6.41	6.27	6.43
30-4-2003	1407	6.36	6.25	6.41
1-5-2003	1483	6.33	6.41	6.47
2-5-2003	1533	6.45	6.51	6.57
3-5-2003	1552	6.48	6.55	6.64
4-5-2003	1572	6.52	6.59	6.69
5-5-2003	1601	6.56	6.64	6.73
6-5-2003	1639	6.61	6.72	6.80
7-5-2003	1653	6.68	6.74	6.84
8-5-2003	1660	6.7	6.76	6.87
9-5-2003	1630	6.72	6.70	6.85
10-5-2003	1617	6.64	6.67	6.82
11-5-2003	1628	6.6	6.70	6.81
12-5-2003	1681	6.65	6.80	6.87
13-5-2003	1737	6.75	6.90	6.95
14-5-2003	1751	6.82	6.93	6.97
15-5-2003	1736	6.83	6.90	6.97
16-5-2003	1763	6.8	6.95	6.98
17-5-2003	1777	6.87	6.97	7.00
18-5-2003	1783	6.87	6.98	7.01
19-5-2003	1808	6.86	7.03	7.03
20-5-2003	1823	6.92	7.06	7.04
21-5-2003	1897	6.95	7.19	7.10
22-5-2003	2003	7.06	7.37	7.19
23-5-2003	1997	7.17	7.36	7.23
24-5-2003	1993	7.16	7.35	7.23
25-5-2003	2025	7.16	7.40	7.25
26-5-2003	2022	7.18	7.40	7.25
27-5-2003	2008	7.19	7.38	7.24
28-5-2003	1928	7.18	7.24	7.19
29-5-2003	1837	7.03	7.08	7.10
30-5-2003	1778	6.93	6.98	7.03
31-5-2003	1775	6.85	6.97	7.00
1-6-2003	1786	6.84	6.99	7.01
2-6-2003	1788	6.85	6.99	7.01
3-6-2003	1823	6.87	7.06	7.04
4-6-2003	1815	6.93	7.04	7.04

5-6-2003	1754	6.88	6.93	7.00
6-6-2003	1702	6.81	6.84	6.95
7-6-2003	1697	6.73	6.83	6.93
8-6-2003	1709	6.73	6.85	6.94
9-6-2003	1789	6.75	7.00	6.99
10-6-2003	1789	6.86	7.00	7.01
11-6-2003	1792	6.86	7.00	7.02
12-6-2003	1794	6.88	7.00	7.02
13-6-2003	1781	6.86	6.98	7.01
14-6-2003	1722	6.83	6.87	6.97
15-6-2003	1688	6.78	6.81	6.93
16-6-2003	1675	6.69	6.78	6.92
17-6-2003	1728	6.73	6.88	6.94
18-6-2003	1740	6.8	6.91	6.96
19-6-2003	1697	6.79	6.83	6.94
20-6-2003	1665	6.72	6.77	6.91
21-6-2003	1681	6.68	6.80	6.91
22-6-2003	1649	6.7	6.74	6.90
23-6-2003	1624	6.64	6.69	6.87
24-6-2003	1590	6.62	6.62	6.80
25-6-2003	1495	6.55	6.43	6.67
26-6-2003	1413	6.38	6.26	6.51
27-6-2003	1373	6.25	6.18	6.39
28-6-2003	1355	6.19	6.14	6.32
29-6-2003	1327	6.14	6.08	6.27
30-6-2003	1310	6.06	6.04	6.22
1-7-2003	1334	6.07	6.09	6.23
2-7-2003	1348	6.12	6.12	6.26
3-7-2003	1342	6.13	6.11	6.27
4-7-2003	1366	6.13	6.16	6.29
5-7-2003	1417	6.2	6.27	6.36
6-7-2003	1448	6.27	6.34	6.43
7-7-2003	1451	6.31	6.34	6.47
8-7-2003	1454	6.32	6.35	6.48
9-7-2003	1447	6.36	6.33	6.48
10-7-2003	1387	6.32	6.21	6.42
11-7-2003	1319	6.21	6.06	6.30
12-7-2003	1267	6.08	5.94	6.18
13-7-2003	1232	5.95	5.86	6.09
14-7-2003	1201	5.86	5.79	6.02
15-7-2003	1160	5.78	5.69	5.94
16-7-2003	1128	5.7	5.62	5.86
17-7-2003	1141	5.63	5.65	5.84
18-7-2003	1154	5.68	5.68	5.85
19-7-2003	1104	5.65	5.56	5.82
20-7-2003	1088	5.52	5.52	5.76
21-7-2003	1076	5.48	5.49	5.72
22-7-2003	1108	5.48	5.57	5.74
23-7-2003	1159	5.59	5.69	5.82
24-7-2003	1181	5.69	5.74	5.89
25-7-2003	1173	5.72	5.72	5.91
26-7-2003	1171	5.72	5.72	5.91
27-7-2003	1160	5.68	5.69	5.90
28-7-2003	1209	5.67	5.81	5.94
29-7-2003	1240	5.81	5.88	6.01
30-7-2003	1257	5.86	5.92	6.06
31-7-2003	1268	5.92	5.95	6.09
1-8-2003	1266	5.93	5.94	6.11
2-8-2003	1260	5.93	5.93	6.10
3-8-2003	1227	5.91	5.85	6.06
4-8-2003	1195	5.83	5.78	6.00
5-8-2003	1179	5.77	5.74	5.95
6-8-2003	1146	5.72	5.66	5.90
7-8-2003	1109	5.65	5.57	5.82
8-8-2003	1082	5.53	5.50	5.75
9-8-2003	1054	5.49	5.43	5.69
10-8-2003	1021	5.41	5.34	5.62
11-8-2003	994	5.32	5.27	5.56
12-8-2003	974	5.24	5.22	5.50
13-8-2003	970	5.23	5.21	5.47
14-8-2003	954	5.19	5.16	5.45
15-8-2003	939	5.16	5.12	5.41
16-8-2003	914	5.11	5.05	5.37
17-8-2003	893	5.02	4.99	5.31
18-8-2003	896	4.97	5.00	5.29
19-8-2003	945	5.03	5.14	5.34
20-8-2003	1000	5.15	5.29	5.45
21-8-2003	998	5.25	5.28	5.51
22-8-2003	992	5.26	5.27	5.51
23-8-2003	976	5.25	5.22	5.49

24-8-2003	950	5.2	5.15	5.45
25-8-2003	926	5.13	5.09	5.40
26-8-2003	918	5.11	5.06	5.36
27-8-2003	905	5.06	5.03	5.33
28-8-2003	905	5.05	5.03	5.31
29-8-2003	913	5.04	5.05	5.32
30-8-2003	954	5.11	5.16	5.37
31-8-2003	952	5.15	5.16	5.41
1-9-2003	960	5.14	5.18	5.42
2-9-2003	987	5.21	5.25	5.46
3-9-2003	990	5.24	5.26	5.49
4-9-2003	992	5.25	5.27	5.50
5-9-2003	1008	5.27	5.31	5.53
6-9-2003	1014	5.29	5.33	5.55
7-9-2003	994	5.32	5.27	5.53
8-9-2003	966	5.21	5.20	5.49
9-9-2003	1009	5.2	5.31	5.51
10-9-2003	1069	5.33	5.47	5.60
11-9-2003	1115	5.5	5.58	5.71
12-9-2003	1077	5.6	5.49	5.73
13-9-2003	1018	5.48	5.34	5.64
14-9-2003	974	5.32	5.22	5.54
15-9-2003	951	5.21	5.16	5.46
16-9-2003	951	5.19	5.16	5.43
17-9-2003	958	5.19	5.18	5.43
18-9-2003	949	5.18	5.15	5.42
19-9-2003	911	5.15	5.04	5.37
20-9-2003	880	5.06	4.96	5.30
21-9-2003	859	4.95	4.89	5.23
22-9-2003	852	4.87	4.87	5.20
23-9-2003	853	4.93	4.88	5.18
24-9-2003	859	4.92	4.89	5.19
25-9-2003	846	4.94	4.86	5.18
26-9-2003	826	4.9	4.80	5.14
27-9-2003	805	4.86	4.73	5.10
28-9-2003	795	4.78	4.70	5.06
29-9-2003	801	4.77	4.72	5.05
30-9-2003	808	4.77	4.74	5.06
1-10-2003	800	4.8	4.72	5.06
2-10-2003	823	4.8	4.79	5.07
3-10-2003	873	4.87	4.94	5.15
4-10-2003	913	4.97	5.05	5.26
5-10-2003	995	5.08	5.28	5.40
6-10-2003	981	5.25	5.24	5.47
7-10-2003	991	5.25	5.26	5.49
8-10-2003	1090	5.32	5.52	5.61
9-10-2003	1240	5.57	5.88	5.86
10-10-2003	1472	5.97	6.39	6.24
11-10-2003	1648	6.41	6.73	6.63
12-10-2003	1776	6.7	6.97	6.92
13-10-2003	1814	6.85	7.04	7.02
14-10-2003	1815	6.9	7.04	7.04
15-10-2003	1733	6.92	6.89	6.99
16-10-2003	1637	6.8	6.71	6.91
17-10-2003	1544	6.65	6.53	6.78
18-10-2003	1448	6.48	6.34	6.60
19-10-2003	1367	6.34	6.16	6.42
20-10-2003	1296	6.19	6.01	6.27
21-10-2003	1250	6.08	5.90	6.15
22-10-2003	1223	5.96	5.84	6.06
23-10-2003	1191	5.88	5.77	6.00
24-10-2003	1202	5.81	5.79	5.97
25-10-2003	1206	5.85	5.80	5.98
26-10-2003	1190	5.82	5.76	5.96
27-10-2003	1174	5.79	5.73	5.93
28-10-2003	1162	5.77	5.70	5.91
29-10-2003	1142	5.76	5.65	5.87
30-10-2003	1127	5.66	5.61	5.83
31-10-2003	1117	5.64	5.59	5.81
1-11-2003	1123	5.64	5.60	5.80
2-11-2003	1159	5.64	5.69	5.84
3-11-2003	1222	5.7	5.84	5.94
4-11-2003	1266	5.92	5.94	6.04
5-11-2003	1289	6	5.99	6.12
6-11-2003	1311	6.04	6.04	6.17
7-11-2003	1313	6.11	6.05	6.20
8-11-2003	1280	6.09	5.97	6.17
9-11-2003	1242	6	5.89	6.11
10-11-2003	1195	5.91	5.78	6.02
11-11-2003	1158	5.83	5.69	5.93

12-11-2003	1111	5.72	5.57	5.84
13-11-2003	1082	5.65	5.50	5.76
14-11-2003	1052	5.54	5.42	5.69
15-11-2003	1033	5.46	5.38	5.63
16-11-2003	1020	5.42	5.34	5.60
17-11-2003	1053	5.38	5.43	5.61
18-11-2003	1127	5.52	5.61	5.72
19-11-2003	1200	5.68	5.79	5.87
20-11-2003	1229	5.85	5.86	5.98
21-11-2003	1244	5.91	5.89	6.03
22-11-2003	1233	5.94	5.87	6.04
23-11-2003	1191	5.89	5.77	6.00
24-11-2003	1145	5.8	5.66	5.91
25-11-2003	1125	5.72	5.61	5.84
26-11-2003	1103	5.68	5.55	5.79
27-11-2003	1072	5.62	5.48	5.73
28-11-2003	1051	5.52	5.42	5.68
29-11-2003	1068	5.5	5.47	5.67
30-11-2003	1093	5.49	5.53	5.70
1-12-2003	1133	5.56	5.63	5.77
2-12-2003	1229	5.69	5.86	5.91
3-12-2003	1319	5.94	6.06	6.10
4-12-2003	1318	6.14	6.06	6.19
5-12-2003	1255	6.08	5.92	6.15
6-12-2003	1204	5.96	5.80	6.05
7-12-2003	1182	5.85	5.75	5.97
8-12-2003	1155	5.78	5.68	5.91
9-12-2003	1140	5.79	5.64	5.87
10-12-2003	1108	5.72	5.57	5.81
11-12-2003	1087	5.65	5.51	5.76
12-12-2003	1066	5.6	5.46	5.71
13-12-2003	1072	5.53	5.48	5.69
14-12-2003	1167	5.59	5.71	5.79
15-12-2003	1515	5.84	6.47	6.23
16-12-2003	1886	6.63	7.17	6.87
17-12-2003	1885	7.06	7.17	7.09
18-12-2003	1811	7.03	7.03	7.06
19-12-2003	1720	6.92	6.87	6.98
20-12-2003	1616	6.81	6.67	6.89
21-12-2003	1500	6.64	6.44	6.72
22-12-2003	1430	6.45	6.30	6.54
23-12-2003	1443	6.38	6.33	6.47
24-12-2003	1518	6.41	6.48	6.54
25-12-2003	1612	6.53	6.66	6.68
26-12-2003	1696	6.7	6.82	6.84
27-12-2003	1679	6.79	6.79	6.91
28-12-2003	1652	6.75	6.74	6.89
29-12-2003	1607	6.72	6.65	6.83
30-12-2003	1592	6.66	6.63	6.78
31-12-2003	1573	6.63	6.59	6.74

table 72: Values of the water level at Nijmegen according to three different methods

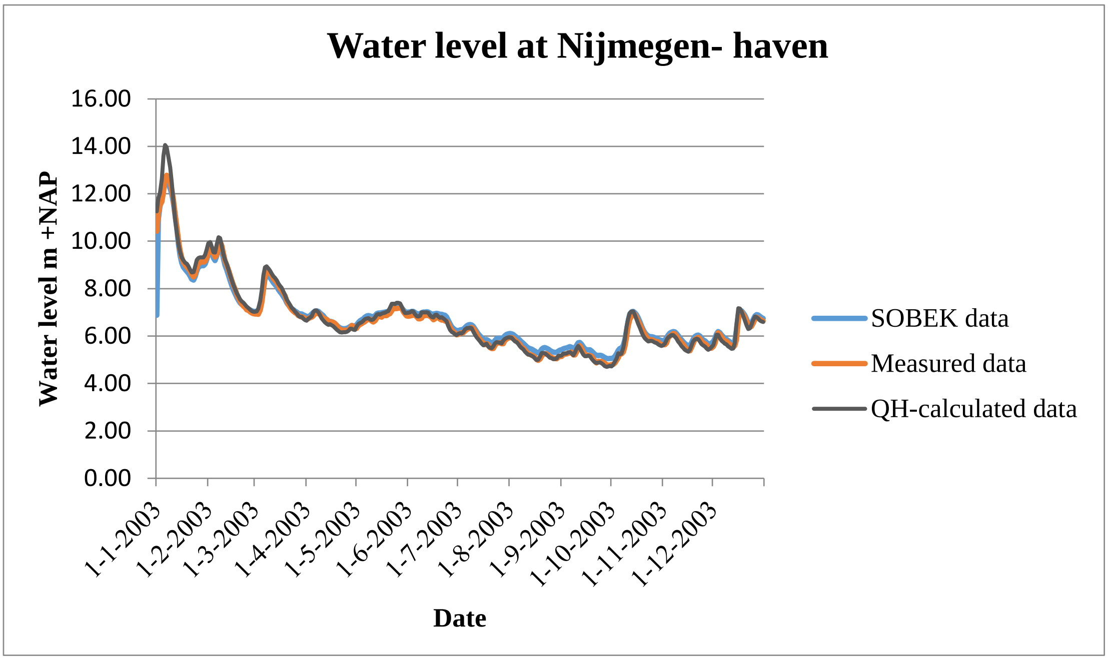


figure 90: Water level at Nijmegen according to measured data from 2003, SOBEK data and climate model data

Reference situation

The characteristics of the normative vessel are determined by the fleet model and the results are included in table 73. The shipping costs that correspond to this normative vessel are included in table 74. An overview of these calculations is included in Appendix VI: Normative vessel.

table 73: Characteristics of normative vessel from 2003

Type	Loading capacity [ton]	Length [m]	Width [m]	Depth [m]
Normative vessel	2050	95	9.5	3.3

table 74: Cost prices corresponding to the normative vessel of 2003

Type of costs	Cost price
Loaded shipping costs per hour	***€ 338.57***
Unloaded shipping costs per hour	***€ 221.05***
Loading costs inclusive waiting costs*	***€ 1,924.52***
Unloading costs inclusive waiting costs*	***€ 2,292.58***

*The cargo distribution is ¼ dry bulk, ½ liquid bulk and 1/8 container sea port and 1/8 container inland port.

Freight transport

According to Centraal Bureau voor de Statistiek (…) the data with respect to freight transport by inland shipping for the year 2003 is shown in the table below.

Total freight transport [ton]	136,621,000
Total number of trips [-]	181738
Average total loading capacity [ton]	371,392,000
Number of loaded trips [-]	113988
Average total loading capacity [ton]	216,166,000

table 75: Data of inland shipping transport

Navigation depth

Using the water levels at Nijmegen Haven from 2003 (Waterbase, 2017), the water depth and the number of days with a certain depth can be determined. An overview of these results is given in table 76.

Average depth [m]	*Number of days*
< 2.2	0
2.3	8
2.5	14
2.7	29
2.9	14
3.1	31
3.3	29
3.5	22
3.7	18
≥ 3.8	200
Total	**365**

table 76: Occurrence of water depth in 2003

Results

For each water depth, the loading factor and therefore the shipping costs per tonne for the normative vessel can be calculated. The results of these calculations are shown in table 77.

Water depth [m]	≤ 2.2	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	≥ 3.8
navigation depth [m]	≤ 1.8	2	2.2	2.4	2.6	2.8	3	3.2	3.4	≥ 3.5
Costs/ton [€]	**€ 10.14**	**€ 8.45**	**€ 7.28**	**€ 6.42**	**€ 5.76**	**€ 4.99**	**€ 4.99**	**€ 4.99**	**€ 4.99**	**€ 4.99**
Extra costs/ton [€]	**€ 5.15**	**€ 3.46**	**€ 2.29**	**€ 1.43**	**€ 0.77**	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00

table 77: Shipping costs per ton according to the navigation depth

Using the data from table 76, the required number of loaded trips can be calculated with the corresponding average load capacity. Subsequently, the total number of 'required' trips can be determined by the assumption that 70% of the sailing vessels are loaded. Using the information of total freight transport by inland shipping, the costs per tonne, the number of days corresponding to a certain water depth and the characteristics of the normative vessel, the shipping costs for the year 2003 can be determined using the effect model. The results are summarized in table 78.

Total freight transport [ton]	136,621,000
Number of required loaded trips [-]	85602
Average loading capacity [ton]	1900
Total number of 'required' trips	135879
Average loading capacity [ton]	2050

table 78: Data of 2003 about inland shipping transport across the German border

Now, the number of required trips, the costs per tonne, the number of days corresponding to a certain water depth and the characteristics of the normative vessel are known and the shipping costs for the year 2003 can be determined using the effect model. The results are summarized in table 79.

Total shipping costs	**€ 891,148,348**
Shipping costs without restriction	**€ 939,499,310**
Extra shipping costs	**€ 48,350,962**

table 79: Shipping costs for transport across the German border in 2003 obtained with the effect model

Based on literature research it was found that 90% of the vessels that passes the Rhine at Lobith will pass the River Waal. Using this data, the calculation for inland shipping transport costs on the route over the Waal can be made. The tables below show the information for this situation.

Total freight transport [ton]	122958900
Number of required loaded trips [-]	77042
Average loading capacity [ton]	1900
Total number of 'required' trips	122289
Average loading capacity [ton]	2050

table 80: Calculated data for the River Waal in the reference situation

Total shipping costs	**€ 845,549,379**
Shipping costs without restriction	**€ 802,033,514**
Extra shipping costs	**€ 43,515,865**

table 81: Shipping costs for the River Waal in 2003 obtained with the effect model

It must be noted that this calculation does not take into account all aspects and therefore it has some limitations. The following important aspects are relevant for the outcome and interpretation of the calculation:

- It is assumed that all trips have the route Rotterdam – Duisburg, so other routes are not considered;
- Alternative shipping routes to avoid loading limitations are not considered;
- Waiting time to increase the loading capacity are not take into account (so, waiting on periods with higher water levels)

Appendix VII

Improvements for previous assumptions

Comparing index number method and formula method

Cost figures 2014 for inland shipping

Bottom slope

Dike height

Comparing index number method and formula method

Two methods to estimate the construction costs of the weir- and lock- complexes have been discussed. The first method that is used in this report are index numbers. These index numbers are based on reference projects of weirs/ barriers and locks in the Netherlands. The second method used in this research are formulas that are based on the relation between the variable construction costs and the head over the structure. These formula uses 2 coefficients, one for fixed costs and one for the variable costs.

Both methods are based on different assumptions. The index number of a weir has the dimension of Width x Height x head, while the coefficient of variable costs has the dimension of downstream water depth x $Head^2$. Both are expressed in €/m^3, but have different meanings.

The index numbers have the following values:

C_{weir} = 30,000 €/m^3

C_{lock} = 5,000 €/m^3

The coefficients used in the formula, are:

Fixed costs – C1= €100 million

Variable costs – C2 = 100,000 €/m^3

The least measured water depth in 2002 were 2.3 meter at Nijmegen, therefore this value will be used for the minimum water depth downstream of the structure. With the assumption of 1 WLC and a head of 7.1 meter, width of 300 meter and height of 10 meter (2.3 + 7.1 + some extra), the calculation for the construction costs with both methods can be done.

Index method: $C_{weir} = 30{,}000 * 7.1 * 300 * 10 = € \ 639$ Million Euro

Variable costs method: $C_{complex} = € \ 310{,}4 \ \ Million$

It must be noted that the method of variable costs resulted in the total WLC costs, this means that the costs for the lock and mitigating measures are included. In the Method of index numbers, it is unclear of the mitigating measures are included.

To calculate the costs of the lock using the index method, the following dimensions of the lock are assumed:

LxWxH = 280 x 40 x 5

This results in the following costs of the lock:

$\mathrm{C_{lock}} = 5{,}000 * 280 * 40 * 7.1 = € \ 397{,}6$ Million

The total WLC costs based on the index number method are €1,034 Million.

All values are given at price level of 2010. Therefore, they can be compared directly to each other.

After all, it can be concluded that both methods are quite rough and therefore the outcomes are not very accurate or reliable. Because the formula method is based on the squared relation between the head and variable construction costs, this method describes the relation more realistic and therefore this method will be used for the next steps in this study. However, it is expected that the WLC costs obtained in the first analysis are somewhat low, the coefficients will be adapted to obtain some larger values for the WLC costs. Therefore, a value of €200 million for C1 and €750,000 €/m^3 for C2 will be used in the next calculations.

In addition, in the foregoing calculations when using the formula of Molenaar, the assumption is made that the costs for the whole WLC, so the lock and weir together, are equal to twice the costs of the weir(s). However, the formula is intended for calculating the costs of a weir and therefore the assumption of the lock costs that is based on the index number method will be used. The costs of a lock are equal to €5000*280*40*H.

However, it must be checked whether one WLC is still most optimal when applying these changed parameters. An overview of this analysis is shown in table 82.

C1=200 mln, C2=750,000					
# WLCs	*H [m]*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
1	7.2	€ 8,618,570	€ 8,931,819	€ 50,696,308	€ 68,246,697
	7.5		€ 3,676,168	€ 52,991,794	€ 65,286,532
	7.8		€ 608,972	€ 55,364,882	€ 64,592,424
	8.1		€ 0	€ 57,817,948	€ 66,436,518
2	4.5	€ 17,237,141	€ 9,988,552	€ 65,606,378	€ 92,832,071
	4.8		€ 3,213,218	€ 69,008,636	€ 89,458,995
	5.1		€ 151,899	€ 72,528,196	€ 89,917,236
	5.4		€ 0	€ 76,169,808	€ 93,406,949
3	3.3	€ 25,855,711	€ 11,430,412	€ 79,020,887	€ 116,307,010
	3.6		€ 5,912,558	€ 83,423,333	€ 115,191,602
	3.9		€ 608,972	€ 87,970,795	€ 114,435,478
	4.2		€ 0	€ 92,670,401	€ 118,526,112

table 82: Costs due to canalization after improving the WLC costs

It can be concluded that one WLC is still most optimal in order to canalize the River Waal. As mentioned earlier, the accuracy of the WLC costs is doubtful, but this does not have to be a problem as situations are compared. Therefore, these results can be used to determine the most optimal number of WLCs to canalize the River Waal.

Cost figures 2014 for inland shipping

A new cost tool for inland shipping of Rijkswaterstaat (2014) gives more realistic values for the cost indication. However, these values are somewhat smaller than the cost figures from 2008 and therefore the calculations done before do not result in realistic costs for inland shipping. These costs are estimated too large and this can have consequences for the conclusions drawn and the choices made. Therefore, it will be checked whether the results will change a lot. First, a comparison can be made between the used costs figures of 2008 and the 'new' costs figures from 2014 obtained with the inland shipping cost tool. The cost figures for the normative vessel in 2050 are used. The results of several costs and the rate between the two different cost figures are shown in table 83

Type of shipping costs	**2050 - Tool cost key figures**	**2050 - NEA cost key figures**	**Rate: NEA / Tool**
Loaded [€/hr]	€ 219.09	€ 371.73	1.7
Unloaded [€/hr]	€ 182.03	€ 258.94	1.42
Waiting [€/hr]	€ 113.67	€ 174.79	1.54
		Average	1.55

table 83: Comparing Tool cost key figures (2014) and NEA cost key figures (2008)

For the calculation of the shipping costs, the costs for loading and unloading inclusive waiting time cannot be obtained by using the cost tool of 2014. Therefore, the key figures of 2008 are adapted due to dividing the values by the rate for waiting costs (see table 83 for the value of this rate). The values that will be used are for loaded, unloaded, loading incl. waiting time and unloading incl. waiting time are respectively €219.09 per hour, €182.03 per hour, €1,786 and €2,027.

Because the load factor is linear related to the shipping costs, it is expected that it is accurate enough to divide the shipping costs by the NEA/Tool rate in order to obtain the more realistic values resulted from the Tool cost key figures. It will be not exactly the same as in case of doing the entire calculation with the 'new' cost key figures, because the number of days with a certain restriction are not taken into account yet and it is foreseen that this will lead to a small difference between this first estimate and the calculation. The results of this first estimate are shown in table 84. It can be observed that one WLC is still most optimal, but the head over the structure is lowered to 7.5 m regarding the lowest total costs.

C1=200 mln, C2=750,000					
# WLCs	*H [m]*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
1	7.2	€ 5,596,474	€ 5,762,464	€ 56,994,743	€ 68,353,681
	7.5		€ 2,371,721	€ 59,575,732	€ 67,543,927
	7.8		€ 392,885	€ 62,243,975	€ 68,233,334
	8.1		€ 0	€ 65,002,145	€ 70,598,619
2	4.5	€ 11,192,949	€ 6,444,227	€ 73,137,950	€ 90,775,126
	4.8		€ 2,073,044	€ 76,878,724	€ 90,144,717
	5.1		€ 97,999	€ 80,745,929	€ 92,036,877
	5.4		€ 0	€ 84,744,906	€ 95,937,855
3	3.3	€ 16,789,423	€ 7,374,459	€ 88,497,893	€ 112,661,775
	3.6		€ 3,814,554	€ 93,385,097	€ 113,989,074
	3.9		€ 392,885	€ 98,429,894	€ 115,612,202
	4.2		€ 0	€ 103,640,298	€ 120,429,721

table 84: Costs due to canalization calculated by the NEA/Tool rate

The magnitude of 'error' between the results of this first estimate and the entire calculation is unknown. Therefore, only for the situation of one WLC the shipping costs will be calculated in order to check whether this rough estimate was accurate enough. The results of this calculation are shown in table 85.

C1=200 mln, C2=750,000					
# WLCs	*H [m]*	*Delay costs*	*Shipping costs*	*WLC costs*	*Total*
1	7.2	€ 5,604,687	€ 5,626,650	€ 56,994,743	€ 68,226,080
	7.5		€ 2,312,804	€ 59,575,732	€ 67,493,223
	7.8		€ 381,752	€ 62,243,975	€ 68,230,414
	8.1		€ 0	€ 65,002,145	€ 70,606,832

table 85: Costs due to canalization using cost key figures from 2014

For this calculation, the same situation is most optimal. It can be concluded that the new cost figures lead to about 1.5 times smaller shipping costs than the cost key figures from 2008. For all number of WLCs a lower head leads to smaller costs due to canalization. Therefore, the effect of these smaller shipping costs is that a lower head becomes more attractive. From now on, the cost figures from 2014 will be used, because these give more reliable results for the shipping costs.

Bottom slope

The river bottom of the Waal contains shoals and drops and therefore the longitudinal bottom slope is irregular. In order to improve the results of the first analysis a linear assumption is not acceptable anymore. Therefore, the real bottom, with its irregular form, has to be taken into account. According to Blom (n.d.) the bottom level from Gorinchem to Lobith is computed. At the locations where the real bottom differs much from the linear bottom a shoal or drop is assumed. These irregularities are included in the schematization of the river bottom. Between these irregularities, the longitudinal bottom slope is assumed to be linear. The result of this bottom level schematization is shown in figure 91.

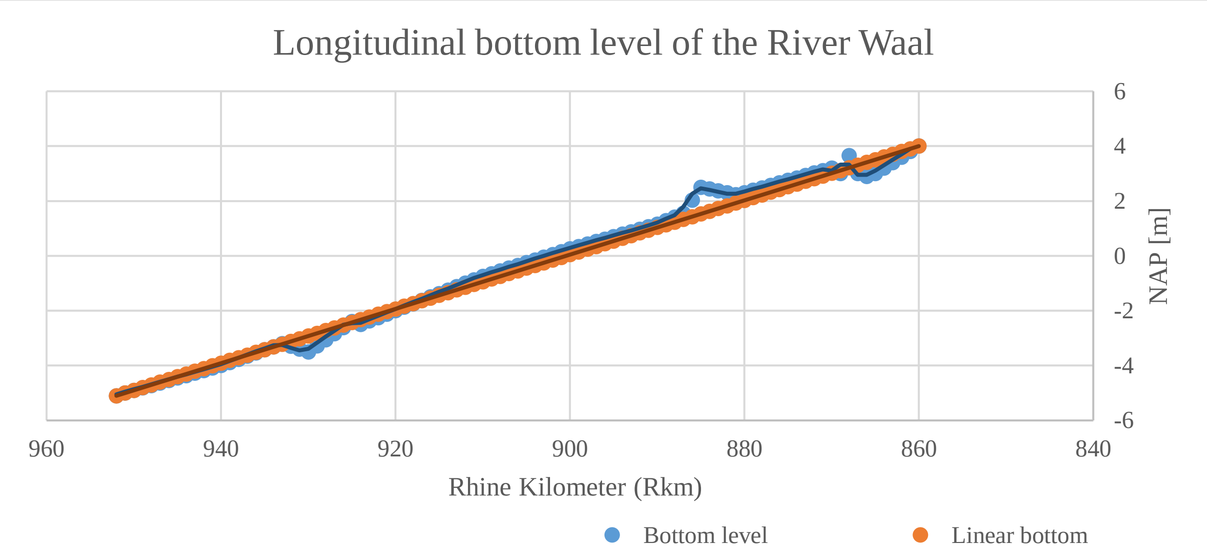


figure 91: Longitudinal bottom level based on two assumptions

Now, the bed level is known and therefore the water depth can be computed. The water depth is calculated by using the backwater curve theory. The water level relative to NAP could be determined by adding the water depth at the bottom level +m NAP. However, the water surface will be not continuous now, because it is equal to the abrupt peaks and drops of the bottom. This is not very realistic and therefore the water depth has to be corrected for the irregular bottom slope. The water depth is corrected by the differences between the real bottom level and a linear bottom level. The result is shown in figure 92. All data for each location is included in table 86. By adding the corrected water depth by the real bottom level a smooth water surface in longitudinal direction of the river is obtained and the water level relative to NAP is known. This result is shown in figure 93.

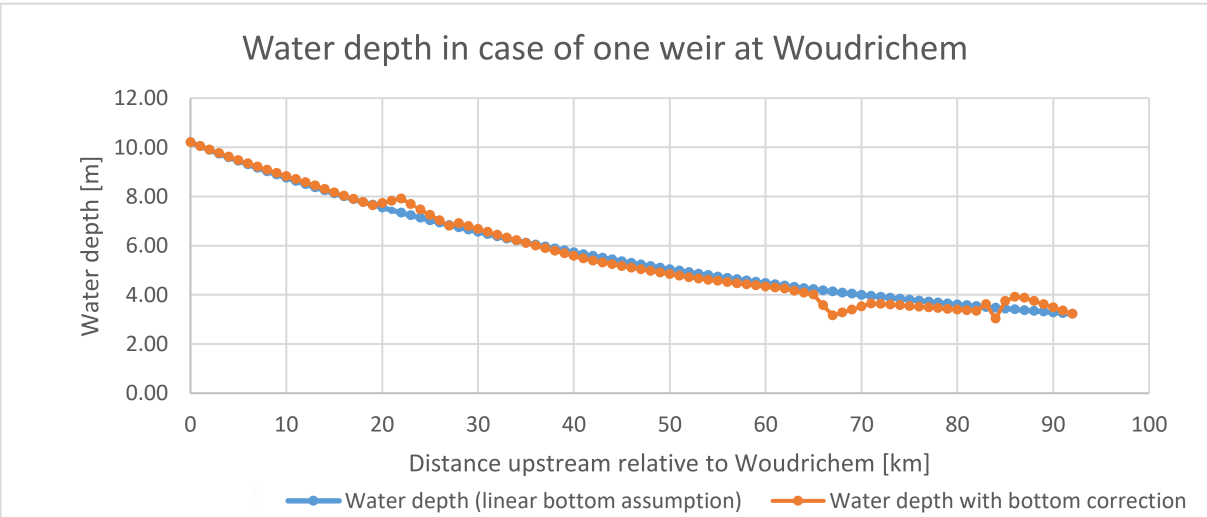


figure 92: Water depth in case of one weir at Woudrichem based on two assumptions

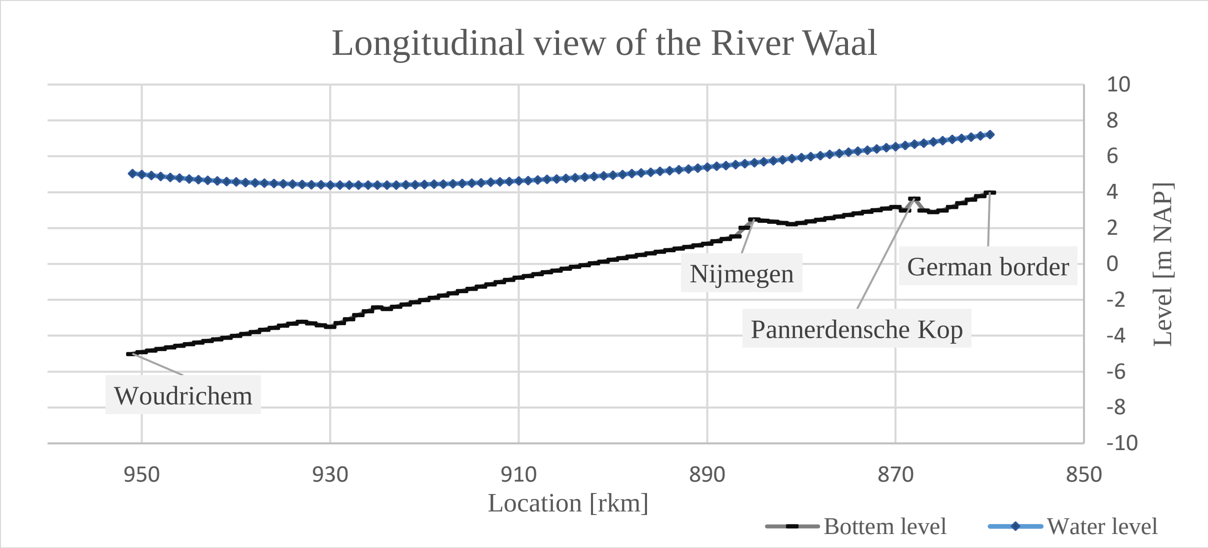


figure 93: 'Real' longitudinal bottom slope and water level of the River Waal

From now on, the real bottom slope is considered and therefore the corrected water depth. So, in the second analysis the shoals as can be observed in figure 93 will lead to smaller navigation depths and higher shipping costs. The optimal way of canalization will be determined based on the assumption of the water depth with bottom correction.

Dike height

Due to the construction of a weir, the water level is increasing upstream of the weir. The dike level must be sufficient for the water level caused by the canalization of the river. This water level depends on the head over the weir and the normal water depth. The dike test level is determined for a certain norm frequency. If the dike height meet the requirements already, then it can be assumed that it is not necessary to take extra measurements like dike raising or dike reinforcement. First, the normative situation will be described. Thereafter, the test level of dikes will be discussed.

The situation of 1 weir is normative as regards the water level, because the head, and therefore the water depth at the weir must be larger than in case of more complexes to improve the navigability upstream of the weir. This situation is used to check whether the dike level is sufficient. In addition, the maximum head for the most optimal solution that is determined in the first analysis is taken, but according to the cost figures of 2014. This lead to a retaining height of 2.3 + 7.5 = 9.8 m.

Now, only the test level of dikes along the river Waal have to be known. The test level is equal to the water level that corresponds to the norm frequency. This information is obtained from Hydraulische Randvoorwaarden Primaire Waterkeringen (Ministerie van Verkeer en Waterstaat, 2007) and is shown in figure 94.

In table 86, data for the situation of an equilibrium depth of 2.3 meter is shown. By increasing the discharge and thus equilibrium depth, the water level over the entire river will increase, except at the location of the weir, because the head over the wear will decrease by increasing discharge and thus the total water height at the weir will remain the same. Therefore, it does not matter which situation is taken in order to check whether the dike is sufficient. In figure 95, the dike test level, the water level and the schematization of the bottom is shown. It can be observed that the water level does not exceed the dike test level and therefor it can be concluded that the dike height is sufficient for this normative situation. This means that the cost for mitigating measures such as dike raising or dike reinforcement do not have to be taken into account in the second analysis. However, when the option with the lowest cost corresponds to a higher maximum head, it has to be checked whether the dike height is still sufficient.

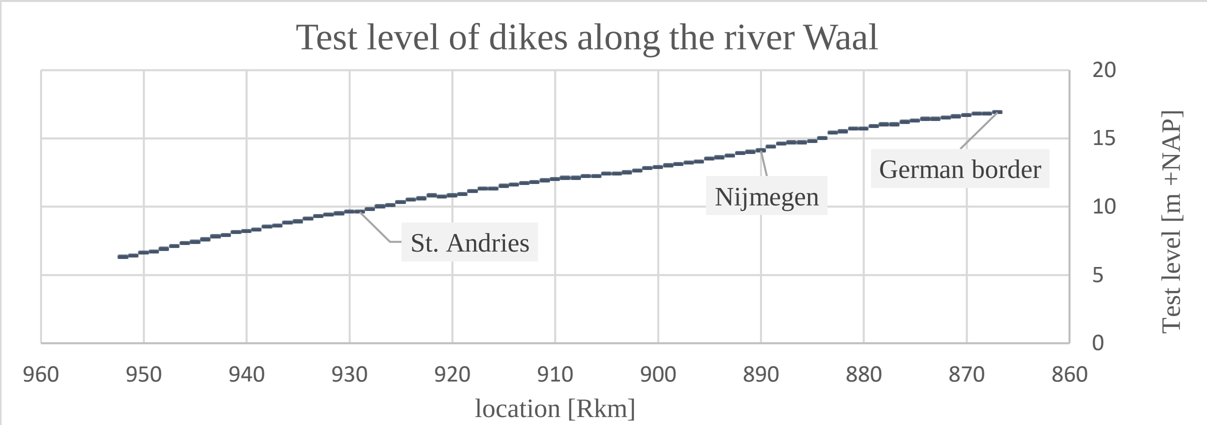


figure 94: Test level of dikes along the River Waal from Woudrichem to the German border

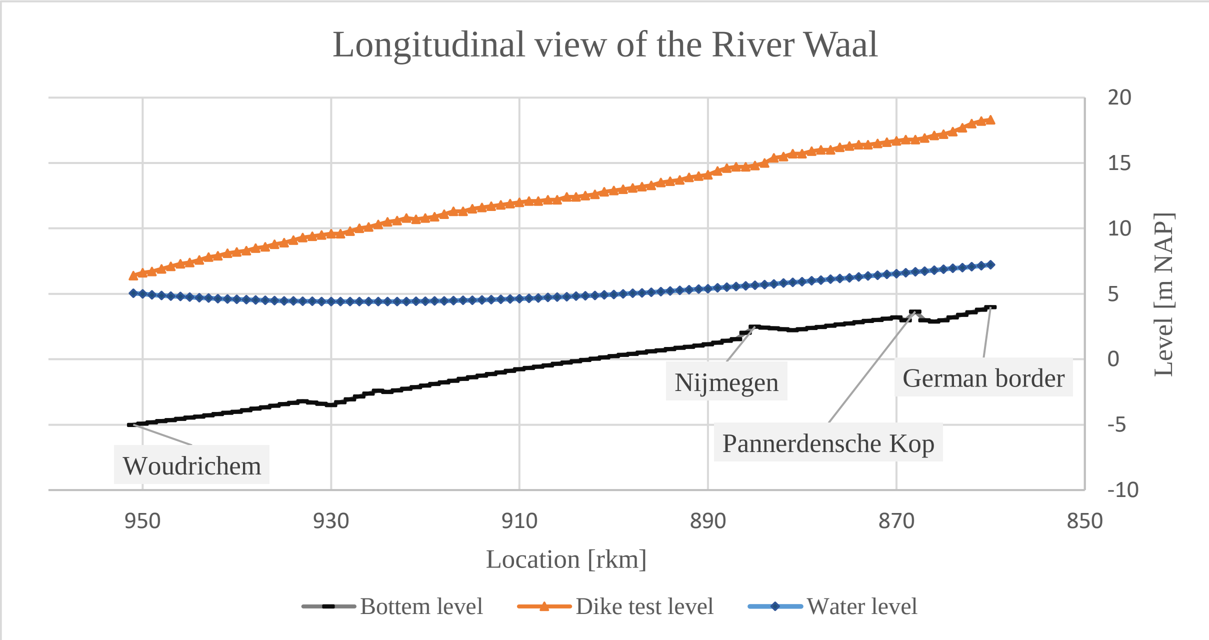


figure 95: Situation shown for 1 weir with a head of 7.5 meter and an equilibrium depth of 2.3 meter

Location [Rkm]	*Upstream distance relative to Woudrichem*	*Description*	*Bottom level relative to NAP [m]*	*linear bottom level relative to NAP*	*Difference in bottom level [m]*	*Water depth [m]*	*Water level relative to NAP [m]*	*Water level relative to NAP with bottom correction [m]*	*Dike test level [m NAP]*	*Water depth with bottom correction [m]*
860	92	Border	4	4	0.00	3.43	7.43	7.43	18.3	3.43
861	91		3.8	3.90	0.10	3.46	7.26	7.36	18.2	3.56
862	90	Lobith	3.6	3.80	0.20	3.48	7.08	7.29	18	3.69
863	89		3.4	3.70	0.30	3.51	6.91	7.21	17.7	3.81
864	88		3.2	3.60	0.40	3.53	6.73	7.14	17.4	3.94
865	87		3	3.51	0.51	3.56	6.56	7.07	17.2	4.07
866	86		2.9	3.41	0.51	3.59	6.49	6.99	17.1	4.09
867	85	Millingen	3	3.31	0.31	3.61	6.61	6.92	16.9	3.92
868	84		3.7	3.21	-0.49	3.64	7.29	6.85	16.8	3.20
869	83		3	3.11	0.11	3.67	6.67	6.78	16.8	3.78
870	82		3.2	3.01	-0.19	3.70	6.90	6.71	16.7	3.51
871	81	Kerkerdom	3.11	2.91	-0.20	3.73	6.84	6.64	16.6	3.53
872	80		3.02	2.81	-0.21	3.76	6.78	6.57	16.5	3.55
873	79		2.93	2.71	-0.22	3.79	6.72	6.50	16.4	3.57
874	78		2.84	2.62	-0.22	3.82	6.66	6.44	16.4	3.60
875	77	Erlecom	2.75	2.52	-0.23	3.85	6.60	6.37	16.3	3.62
876	76	Ooij	2.66	2.42	-0.24	3.89	6.55	6.30	16.2	3.64
877	75		2.57	2.32	-0.25	3.92	6.49	6.24	16	3.67
878	74		2.48	2.22	-0.26	3.95	6.43	6.17	16	3.69
879	73		2.39	2.12	-0.27	3.99	6.38	6.11	15.9	3.72
880	72		2.3	2.02	-0.28	4.03	6.33	6.05	15.7	3.75
881	71		2.23	1.92	-0.31	4.06	6.30	5.98	15.7	3.75
882	70		2.30	1.82	-0.48	4.10	6.40	5.92	15.5	3.62
883	69		2.37	1.73	-0.64	4.14	6.50	5.86	15.4	3.50
884	68	Brug Nijmegen	2.43	1.63	-0.81	4.18	6.61	5.80	15	3.37
885	67	Nijmegen	2.5	1.53	-0.97	4.22	6.72	5.74	14.8	3.24
886	66		2.03	1.43	-0.60	4.26	6.28	5.68	14.7	3.66
887	65	Weurt	1.55	1.33	-0.22	4.30	5.85	5.63	14.7	4.08
888	64		1.42	1.23	-0.19	4.34	5.76	5.57	14.6	4.15
889	63		1.28	1.13	-0.15	4.38	5.67	5.51	14.4	4.23
890	62	Beuningen	1.15	1.03	-0.12	4.43	5.58	5.46	14.1	4.31
891	61		1.06	0.93	-0.13	4.47	5.53	5.41	14	4.35
892	60		0.97	0.83	-0.14	4.52	5.49	5.35	13.9	4.38
893	59	Ewijk	0.88	0.74	-0.14	4.57	5.45	5.30	13.7	4.42
894	58		0.79	0.64	-0.15	4.61	5.40	5.25	13.6	4.46
895	57	Winsen	0.70	0.54	-0.16	4.66	5.36	5.20	13.5	4.50
896	56		0.61	0.44	-0.17	4.71	5.32	5.15	13.3	4.54
897	55		0.52	0.34	-0.18	4.76	5.28	5.10	13.2	4.58
898	54		0.43	0.24	-0.19	4.82	5.25	5.06	13.1	4.63
899	53	Deest	0.34	0.14	-0.20	4.87	5.21	5.01	13	4.67
900	52		0.25	0.04	-0.21	4.92	5.17	4.97	12.9	4.72
901	51		0.15	-0.06	-0.21	4.98	5.13	4.92	12.8	4.77
902	50		0.05	-0.15	-0.20	5.04	5.09	4.88	12.6	4.83
903	49	Druten	-0.05	-0.25	-0.20	5.09	5.04	4.84	12.5	4.89
904	48		-0.15	-0.35	-0.20	5.15	5.00	4.80	12.4	4.95
905	47		-0.25	-0.45	-0.20	5.21	4.96	4.76	12.4	5.01
906	46	Ochten	-0.35	-0.55	-0.20	5.27	4.92	4.72	12.2	5.07
907	45		-0.45	-0.65	-0.20	5.34	4.89	4.69	12.2	5.14
908	44	Boven- Leeuwen	-0.55	-0.75	-0.20	5.40	4.85	4.65	12.1	5.20
909	43		-0.65	-0.85	-0.20	5.47	4.82	4.62	12.1	5.27
910	42	Beneden-Leeuwen	-0.75	-0.95	-0.20	5.54	4.79	4.59	12	5.34
911	41		-0.88	-1.04	-0.17	5.60	4.73	4.56	11.9	5.43
912	40		-1.00	-1.14	-0.14	5.67	4.67	4.53	11.8	5.53
913	39		-1.13	-1.24	-0.12	5.74	4.62	4.50	11.7	5.63
914	38	Wamel	-1.25	-1.34	-0.09	5.82	4.57	4.48	11.6	5.73
915	37		-1.38	-1.44	-0.07	5.89	4.52	4.45	11.5	5.83
916	36		-1.50	-1.54	-0.04	5.97	4.47	4.43	11.3	5.93
917	35		-1.63	-1.64	-0.01	6.05	4.42	4.41	11.3	6.03
918	34		-1.75	-1.74	0.01	6.13	4.38	4.39	11.1	6.14
919	33	Dreumel	-1.88	-1.84	0.04	6.21	4.33	4.37	10.9	6.25

920	32		-2	-1.93	0.07	6.29	4.29	4.35	10.8	6.35
921	31		-2.13	-2.03	0.09	6.37	4.25	4.34	10.7	6.46
922	30		-2.25	-2.13	0.12	6.46	4.21	4.33	10.8	6.58
923	29	Heerewaarden	-2.38	-2.23	0.14	6.55	4.17	4.32	10.6	6.69
924	28		-2.5	-2.33	0.17	6.64	4.14	4.31	10.5	6.81
925	27		-2.4	-2.43	-0.03	6.73	4.33	4.30	10.3	6.70
926	26		-2.62	-2.53	0.09	6.82	4.20	4.30	10.1	6.92
927	25	Rossum	-2.84	-2.63	0.21	6.92	4.08	4.29	10	7.13
928	24		-3.06	-2.73	0.33	7.02	3.96	4.29	9.8	7.35
929	23	Hurwenen	-3.28	-2.83	0.45	7.12	3.84	4.29	9.6	7.57
930	22		-3.5	-2.92	0.58	7.22	3.72	4.30	9.6	7.80
931	21	Opijnen	-3.40	-3.02	0.38	7.32	3.92	4.30	9.5	7.70
932	20		-3.30	-3.12	0.18	7.43	4.13	4.31	9.4	7.61
933	19		-3.2	-3.22	-0.02	7.54	4.34	4.32	9.3	7.52
934	18		-3.31	-3.32	-0.01	7.65	4.33	4.33	9.1	7.64
935	17	Zaltbommel	-3.43	-3.42	0.01	7.76	4.33	4.34	8.9	7.77
936	16		-3.54	-3.52	0.03	7.88	4.34	4.36	8.8	7.90
937	15	Haaften	-3.66	-3.62	0.04	8.00	4.34	4.38	8.6	8.04
938	14		-3.77	-3.72	0.06	8.12	4.35	4.40	8.5	8.17
939	13		-3.89	-3.81	0.07	8.24	4.35	4.43	8.3	8.31
940	12	Nieuwaal	-4	-3.91	0.09	8.37	4.37	4.45	8.2	8.45
941	11		-4.09	-4.01	0.08	8.49	4.40	4.48	8.1	8.57
942	10		-4.18	-4.11	0.07	8.63	4.44	4.51	7.9	8.70
943	9	Zuilichem	-4.27	-4.21	0.06	8.76	4.49	4.55	7.8	8.82
944	8		-4.36	-4.31	0.05	8.90	4.53	4.59	7.6	8.95
945	7		-4.45	-4.41	0.05	9.04	4.58	4.63	7.4	9.08
946	6	Brakel	-4.55	-4.51	0.04	9.18	4.63	4.67	7.3	9.22
947	5		-4.64	-4.61	0.03	9.32	4.69	4.72	7.1	9.36
948	4		-4.73	-4.70	0.02	9.47	4.75	4.77	6.9	9.50
949	3		-4.82	-4.80	0.01	9.62	4.81	4.82	6.7	9.64
950	2		-4.91	-4.90	0.01	9.78	4.87	4.88	6.6	9.79
951	1	Slot Loevestein	-5	-5.00	0.00	9.94	4.94	4.94	6.4	9.94
952	0	Woudrichem	-5.1	-5.1	0.00	10.10	5.00	5.00	6.3	10.10

table 86: Bottom corrections and Dike test levels for several locations along the River Waal

Appendix VIII

Effects of climate change on river navigability

Occurrence of discharge ranges at Lobith

Occurrence of discharge ranges for the River Waal

Occurrence of water depths at Nijmegen

Q/H- relation of the River Waal at Vuren

Occurrence of discharge ranges at Lobith

Climate scnearios		2003	2050GH	2050GL	2050WH	2050Whdry	2050WL	2085GH	2085GL	2085WH	2085Whdry	2085WL
Discharge at Lobith		*Number of days*										
>=	<											
0	437	0	0	0	0	0	0	0	0	0	0	0
437	479	0	0	0	0	0	0	0	0	0	0	0
479	523	0	0	0	0	0	0	0	0	0	0	0
523	567	0	0	0	0	0	0	0	0	0	1	0
567	612	0	0	0	0	1	0	0	0	0	3	0
612	657	0	0	0	0	2	0	0	0	0	4	0
657	705	0	0	0	1	3	0	0	0	1	6	0
705	755	0	0	0	1	5	0	1	0	3	8	1
755	804	3	1	0	3	5	1	2	0	3	8	2
804	855	7	2	1	4	7	2	3	2	4	8	3
855	907	8	3	2	4	6	4	4	2	5	8	4
907	959	16	4	2	5	7	3	5	3	6	9	4
959	964	1	0	0	0	1	0	0	0	1	1	1
964	1019	20	5	4	6	8	5	5	4	7	9	5
1019	1073	12	5	4	6	9	6	6	4	6	10	6
1073	1180	40	13	10	14	18	12	14	11	14	17	12
1180	1237	20	8	6	9	11	7	8	7	8	9	8
1237	1296	14	8	7	8	11	9	9	7	9	10	7
1296	1355	11	10	8	9	11	9	9	8	9	11	8
1355	1476	14	20	20	20	22	19	21	18	18	21	17
1476	1539	14	10	10	11	12	9	11	9	9	9	8
1539	1601	11	11	10	11	11	11	10	10	9	9	9
1601	1665	8	11	10	11	10	11	12	9	11	9	10
1665		166	254	269	242	204	256	245	271	239	197	258
Sum < 1665		199	111	96	123	161	109	120	94	126	168	107
Number of days per year		*365*	*365*	*365*	*365*	*365*	*365*	*365*	*365*	*365*	*365*	*365*

table 87: Occurrence of discharge ranges at Lobith for several climate scenarios

Occurrence of discharge ranges for the River Waal

Climate scnearios		2003	2050GH	2050GL	2050WH	2050Whdry	2050WL	2085GH	2085GL	2085WH	2085Whdry	2085WL
Discharge Waal		*Number of days*										
>=	<											
0	437	0	0	0	0	0	0	0	0	0	2	0
437	479	0	0	0	0	2	0	0	0	0	3	0
479	523	0	0	0	0	4	0	0	0	1	7	0
523	567	1	0	0	1	6	0	1	0	3	9	0
567	612	2	2	1	4	7	2	2	1	4	10	0
612	657	4	3	2	4	9	4	4	2	5	9	0
657	705	5	4	3	6	8	5	5	3	7	10	0
705	755	6	5	5	7	10	6	6	5	9	10	1
755	804	7	6	5	7	11	7	7	5	8	11	2
804	855	9	8	6	9	11	7	9	7	10	10	3
855	907	9	9	7	10	12	9	9	7	9	11	4
907	959	12	9	9	10	14	9	11	8	11	12	4
959	964	1	1	1	1	1	1	1	1	1	1	1
964	1019	12	12	10	11	14	11	11	10	11	14	5
1019	1073	13	12	11	11	13	11	12	10	11	12	6
1073	1180	25	23	23	25	26	22	24	21	21	22	12
1180	1237	13	13	12	13	11	13	13	11	13	11	8
1237	1296	16	14	14	14	12	14	14	13	11	11	7
1296	1355	15	14	13	11	12	13	13	13	10	10	8
1355	1476	31	26	28	23	22	25	24	28	21	19	17
1476	1539	14	13	13	12	10	11	12	12	10	9	8
1539	1601	12	12	13	11	10	12	13	12	9	8	9
1601	1665	12	12	12	10	10	12	11	12	9	8	10
1665		146	167	180	164	130	171	161	183	170	133	258
Sum < 1665		219	219	198	185	201	235	194	204	182	195	232
Number of days per year		365	365	365	365	365	365	365	365	365	365	365

table 88: Occurrence of discharge ranges for the River Waal for several climate scenarios

Occurrence of water depths at Nijmegen

		Climate scenarios									
Average depth	**2003**	**2050WHdry**	**2050GH**	**2050WL**	**2050GL**	**2050WH**	**2085WHdry**	**2085GH**	**2085WL**	**2085GL**	**2085WH**
		#days	#days	#days	#days	#days	#days	#days	#days	#days	
>4.0	180	226	278	279	282	266	217	269	278	293	261
<1.6	0	1	0	0	0	0	5	0	0	0	0
	180	**227**	**278**	**279**	**282**	**266**	**222**	**269**	**278**	**293**	**261**
1.7	0	3	0	0	0	0	5	0	0	0	0
1.9	0	5	0	0	1	1	8	0	1	0	2
2.1	0	7	1	1	2	3	10	2	2	0	4
2.3	8	9	3	3	3	5	10	4	4	2	6
2.5	14	8	4	5	4	6	10	5	5	3	6
2.7	29	11	6	6	6	8	12	7	7	5	10
2.9	14	13	7	8	6	9	14	9	9	7	9
3.1	31	13	10	9	8	10	13	11	9	8	11
3.3	29	16	11	11	10	13	14	12	12	9	13
3.5	22	17	13	14	11	13	16	13	12	11	14
3.7	18	18	16	14	15	14	16	16	13	13	14
3.9	20	18	16	15	17	17	15	17	13	14	15
Sum	**185**	**138**	**87**	**86**	**83**	**99**	**143**	**96**	**87**	**72**	**104**
Total	365	*365*	*365*	*365*	*365*	*365*	*365*	*365*	*365*	*365*	*365*

table 89: Occurrence of water depths at Nijmegen for several climate scenarios

Q/H- relation of the River Waal at Vuren

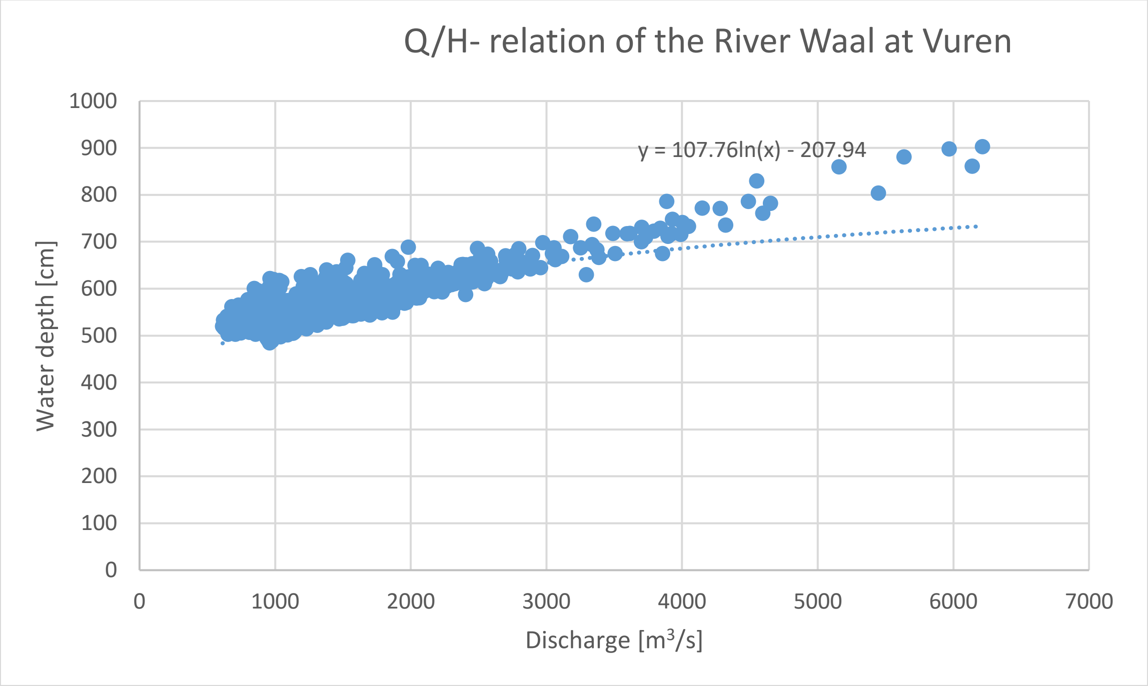


figure 96: Q/H- relation of the River Waal at Vuren

Appendix IX

Sensitivity Analysis

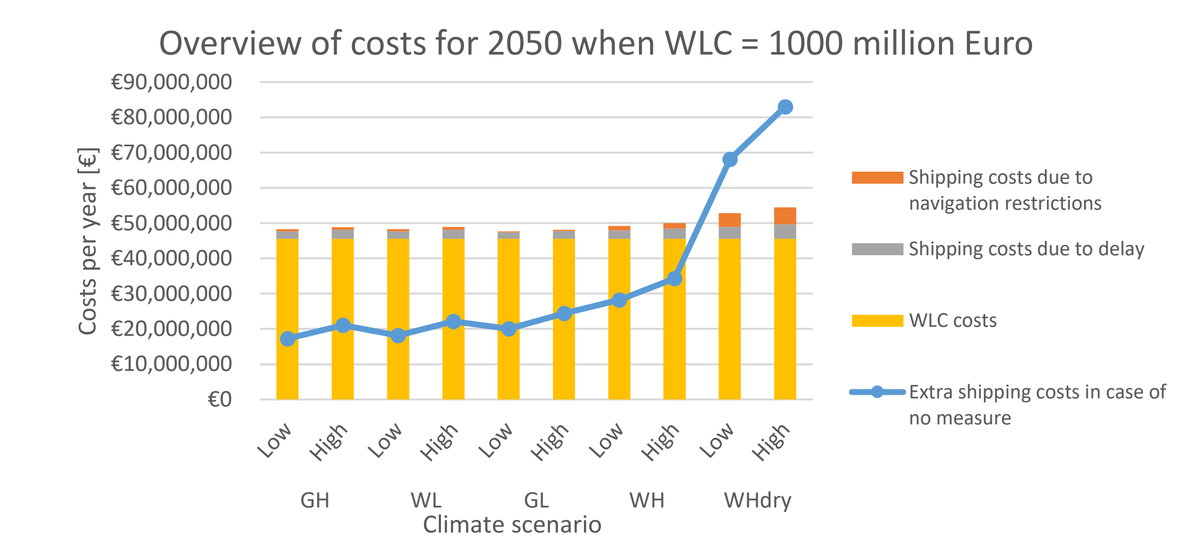


figure 97: Costs for 2050 in case of WLC = 1000 million Euro

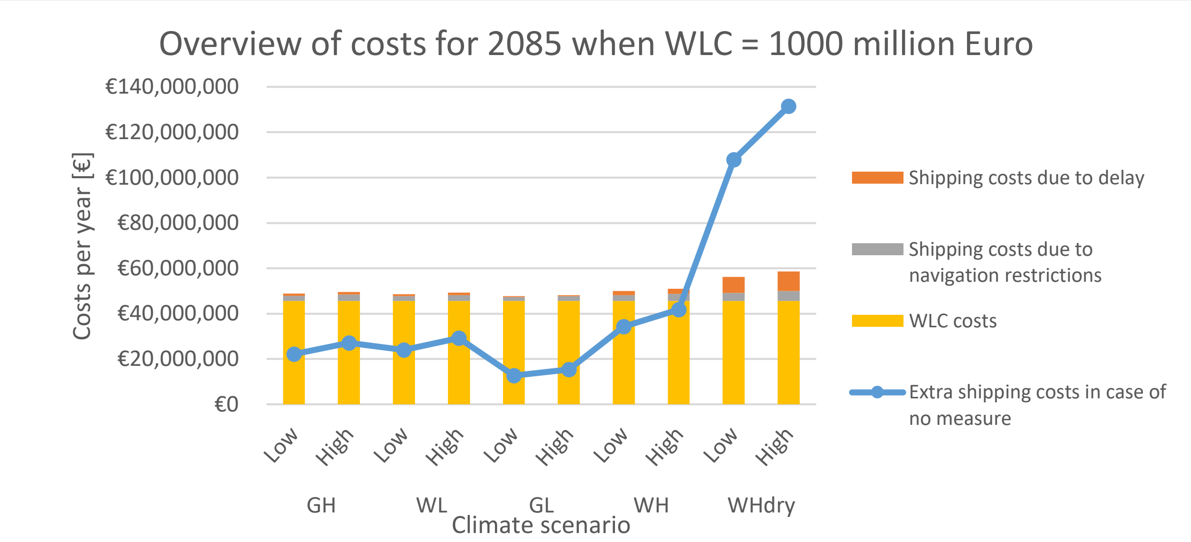


figure 98: Costs for 2085 in case of WLC = 1000 million Euro

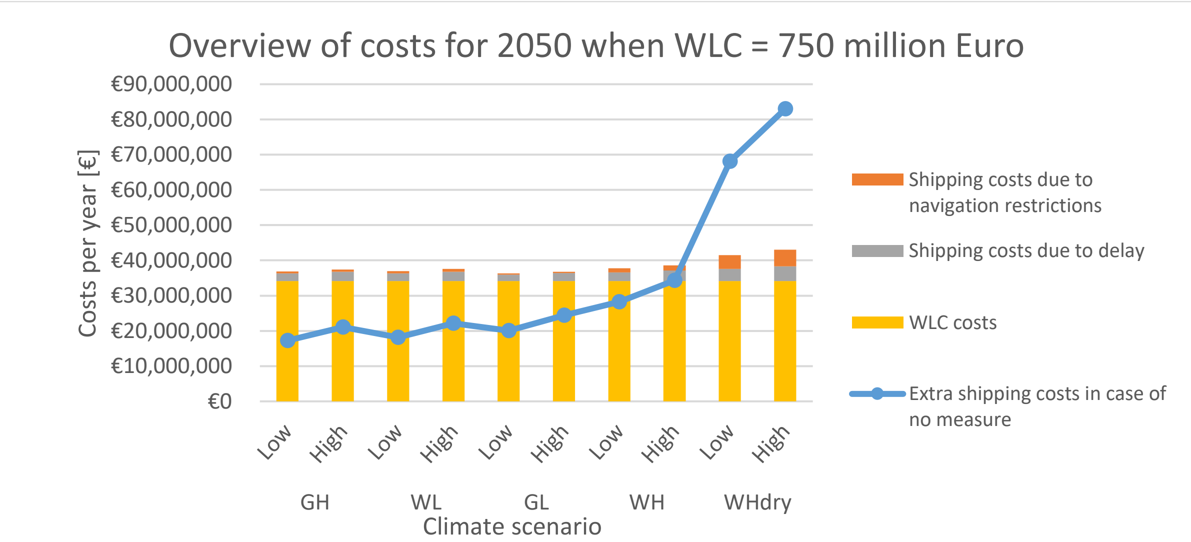


figure 99: Costs for 2050 in case of WLC = 750 million Euro

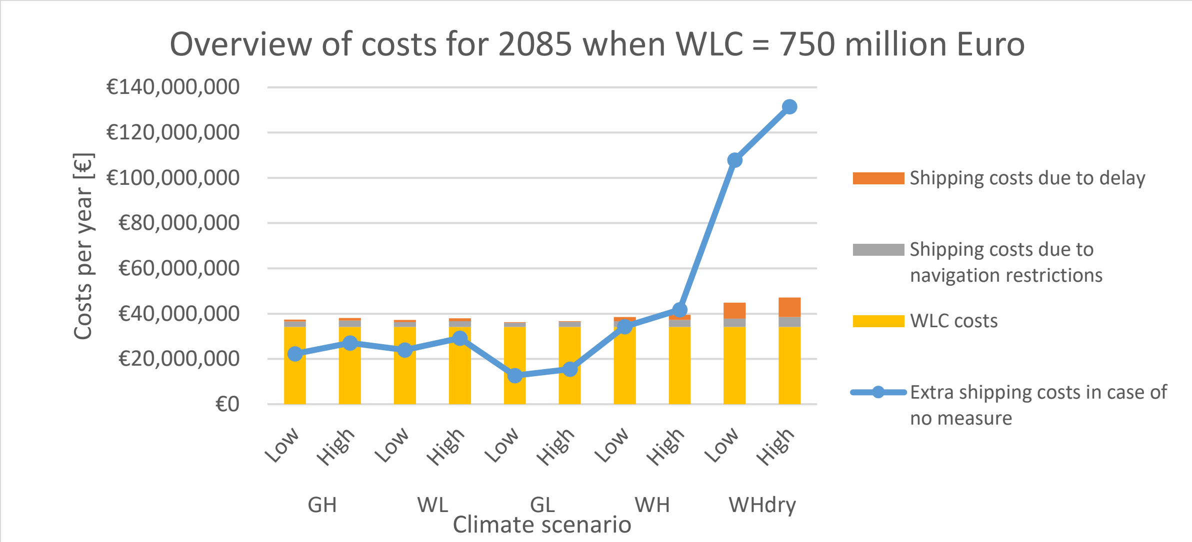


figure 100: Costs for 2085 in case of WLC = 750 million Euro

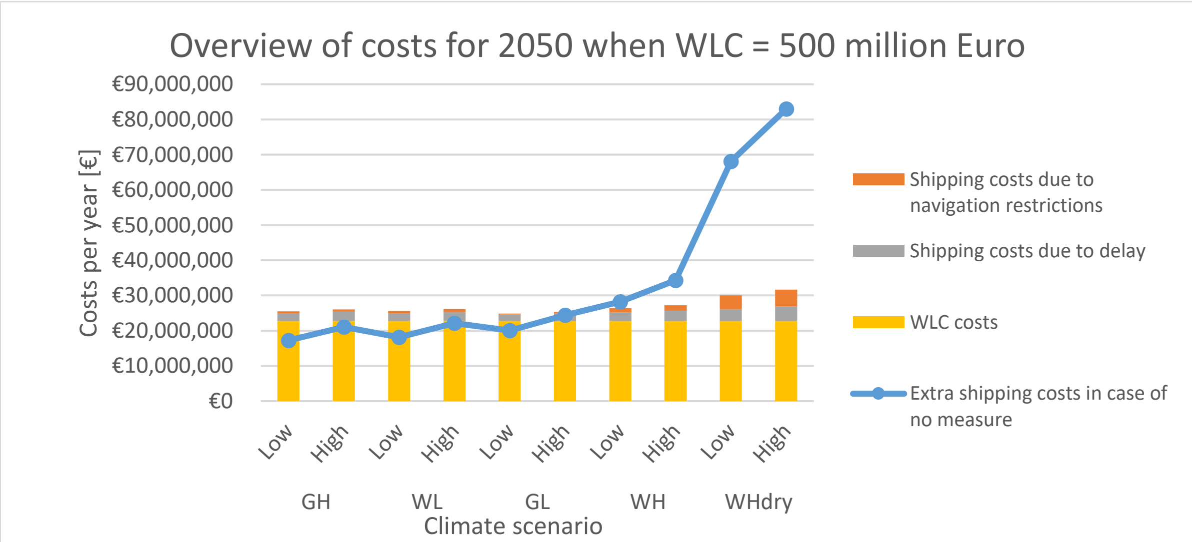


figure 101: Costs for 2050 in case of WLC = 500 million Euro

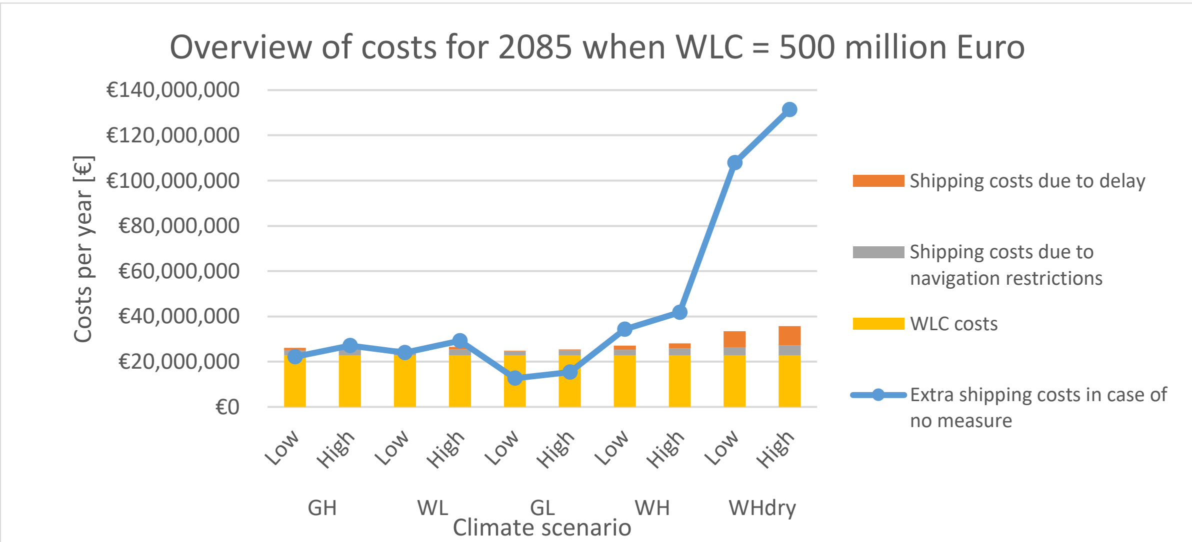


figure 102: Costs for 2085 in case of WLC = 500 million Euro

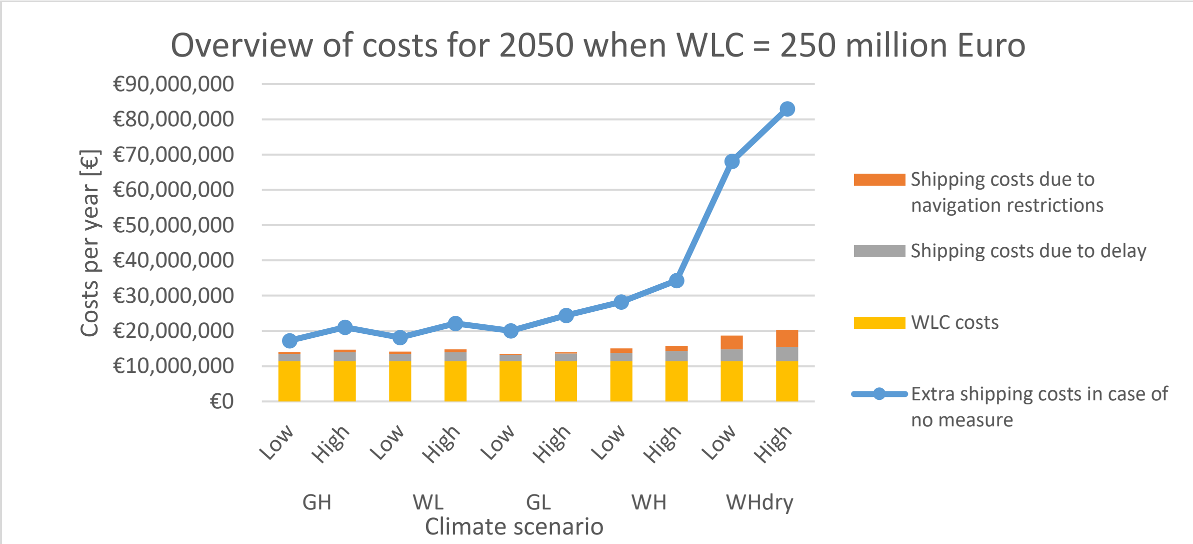


figure 103: Costs for 2050 in case of WLC = 250 million Euro

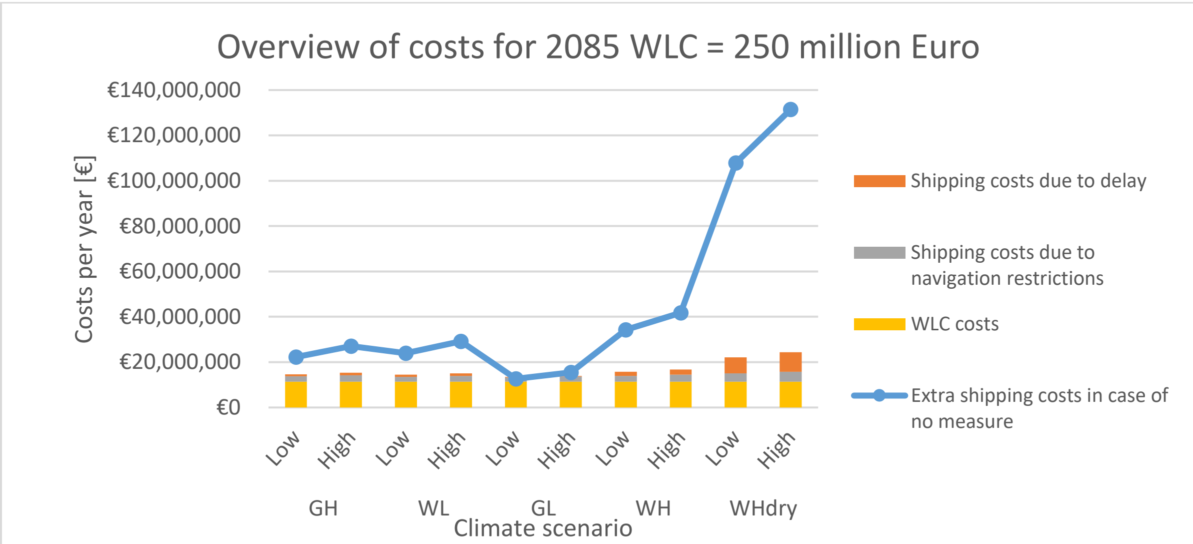


figure 104: Costs for 2085 in case of WLC = 250 million Euro

Climate scenario	*Economic scenario*	*Total WLC costs [mln Euro]*																						
		100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300
G_H	Low	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W_L	Low	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G_L	Low	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W_H	Low	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W_{Hdry}	Low	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Total		10	10	10	6	4	3	2	2	2	2	2	2	2	1	1	1	0	0	0	0	0	0	0
Feasibility		**100%**	**100%**	**100%**	**60%**	**40%**	**30%**	**20%**	**20%**	**20%**	**20%**	**20%**	**20%**	**20%**	**10%**	**10%**	**10%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**

table 90: outcomes feasibility inventory for the time horizon 2050

Climate scenario	*Economic scenario*	*Total WLC costs [mln Euro]*																						
		100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300
G_H	Low	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W_L	Low	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G_L	Low	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W_H	Low	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W_{Hdry}	Low	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
	High	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Total		10	10	10	8	6	6	3	3	3	2	2	2	2	2	1	1	1	1	1	1	1	1	0
Feasibility		**100%**	**100%**	**100%**	**80%**	**60%**	**60%**	**30%**	**30%**	**30%**	**20%**	**20%**	**20%**	**20%**	**20%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**0%**

table 91: outcomes feasibility inventory for the time horizon 2085