Effects of Water Levels on Lock Demand Shifts

A Case Study of the Locks Weurt and Grave

by

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Style: TU Delft Report Style, with modifications by Daan Zwaneveld, and further modifications by Jelle Heetman

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Abstract

This study investigates the impact of lowered lock capacity on lock demand shifts within the Weurt-Grave system, a critical link in the Southeast inland waterway corridor of the Netherlands. It answers the following research question: ***What impact does a reduction in capacity, caused by low water levels, have on alternative locks within the inland waterway system, with a focus on the Weurt-Grave system?***

Understanding the interactions is important for improving waterway infrastructure planning. Lock capacity constraints caused by extreme water levels are becoming more likely to occur due to climate change. This increases the importance of being able to predict the effects these disruptions will have on the larger waterway system. This research shows from historical data how lock capacity decreases can affect other locks. This helps give insight in the scope that might need to be assessed when researching a single lock that is part of a larger system.

During dry periods, low water levels in the Waal limit lock Weurt's capacity, redirecting larger vessels to lock Grave. This redirection alters waiting times, fleet composition, and traffic patterns within the system. It shows the system's sensitivity to environmental conditions. Using lock usage and water level data from Rijkswaterstaat, the study applies statistical methods, including logit regression, time series analysis, and moving averages, to quantify water level impacts on lock utilization and traffic patterns.

The findings reveal redistributions in vessel traffic and load, primarily driven by vessel draught, origin-destination patterns. While the system shows adaptability, capacity constraints at Grave raise concerns about infrastructure durability under increased demand. Furthermore, the research identifies limitations in existing traffic models, such as SIVAK and BIVAS, which fail to capture dynamic interdependencies between locks under changing environmental effects.

This study shows that lock capacity constraints should not be viewed as an isolated problem. These constraints could be causing network wide effects, changing traffic flow and fleet compositions at other points in the system. By revealing how vessel behaviour responds to changing capacities, the research emphasizes the necessity of network wide approaches to lock modelling. Knowing of these possible system-wide effects is essential for modelling waterway infrastructure that need to handle the results of climate change and changing transport demands. This will improve the resilience and efficiency of the inland waterway network.

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1 Introduction

Inland waterway transport (IWT) plays a pivotal role in the Dutch freight landscape. This is shown by its significant contribution to the national freight movement. In the year 2021 the modal split of freight in tonne-kilometres for the Netherlands was 12.5% for the inland waterways (Eurostat, 2023). This is the second-highest percentage within the EU, only Romania has a higher percentage with 19.8%. The average for the EU is 1.8%. When looking at weight alone, in 2019, 324 million tonnes was shipped over inland waterways in the Netherlands of which 124 million tonnes was domestic transport, both being 17% of the total weight (CBS, 2023). When looking at the tonne-kilometres within the Netherlands, the percentage of inland waterway shipping is 35% compared to 53% for road shipping and 4% for railway shipping (Ministerie van Infrastructuur en Waterstaat et al., 2022). The difference between the percentage of freight tonnage (12.5%) and the percentage of freight tonne-kilometres (35%) show that transport over the IWT network is done in longer trips.

Compared to the other modes, IWT also performs a number of non-traffic related functions with both economic and societal benefits. The functions include the water management, and the touristic and recreational function it can have (Wiegmans and Konings, 2016)

The freight transport in the Netherlands can be divided into four different corridors (Rijkswaterstaat, 2021a). These corridors are:

- Corridor East: Area Rotterdam - Germany and beyond.
- Corridor South: Area Amsterdam/Rotterdam/Zeeland - Belgium and further
- Corridor North: Area Amsterdam/Rotterdam - North-Netherlands and further.
- Corridor Southeast: Area Rotterdam - Brabant/Limburg and further.

The regions that are contained in each corridor are visualized in Figure 1.1.

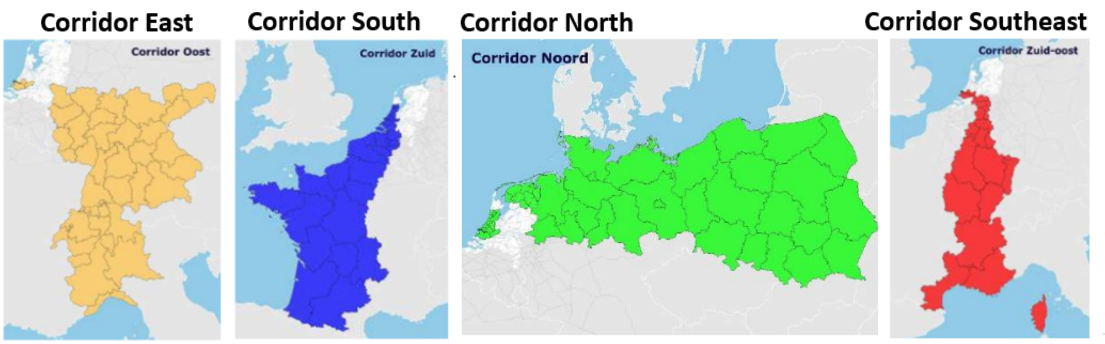

Figure 1.1: Corridors regions visualized (Rijkswaterstaat, 2021b)

The transport volume over these corridors is shown in Table 1.1. It demonstrates that the East and South corridors are approximately three times larger than the North and Southeast corridors.

Corridor	Total Transported Weight (tonnes)	Modal Percentage IWT	Weight IWT (tonne)
East	97 million	69 %	67 million
South	105 million	63 %	66 million
North	38 million	49 %	19 million
Southeast	33 million	51 %	17 million

Table 1.1: Transport numbers (road, rail, IWT) on the corridors in 2018 (**rijkswaterstaat_achtergron_2021**)

The inland waterways that are mainly used for the corridors are shown in figure 1.2.

Figure 1.2: Corridors IWT visualized (with some overlap) (Rijkswaterstaat, 2021a)

In the Netherlands, many hydraulic engineering structures, such as locks, bridges, pumping stations, and weirs, are nearing or have exceeded their designed life expectancy. To future-proof the main waterway network, a lot of financing is needed. While at the same time, the downtime of the infrastructure will increase (Rijkswaterstaat, 2020b).

Within the next 10 years, there will be 250 hydraulic engineering structures that reach their designed life expectancy. Furthermore, more than 800 will no longer meet their functional requirements. This combined will need an estimated €350 million per year for management, maintenance, and replacement (Kennisprogramma Natte Kunstwerken, 2023). Due to the high costs, efficiency can save significant amounts of money.

The downtime of hydraulic structures increases when they near the end of their designed life expectancy. Together with the downtime and reduced capacity created by maintenance and construction, a complex traffic problem is created.

A report that focusses on freight forecasts (the year 2030, 2040, and 2050) states that there are multiple locks that can become bottlenecks in their current form. A lock is seen as a bottleneck when there is an average waiting time that exceeds 30 minutes and when there is only one lock chamber for the design vessels (Rijkswaterstaat, 2021b). Figure 1.3 illustrates the locations of forecasted bottlenecks within the main waterway network.

Figure 1.3: Locks in the main waterway network that are a capacity and/or robustness bottleneck (Rijkswaterstaat, 2022)

Combining the ageing locks with those identified as capacity or robustness bottlenecks highlights a significant number of locks requiring construction or renovation. It is important to determine which locks require rebuilding and which can continue functioning with repairs, and to analyse its workings in the larger waterway system. Also, the order of these constructions needs to be determined to optimize the schedule.

Figure 1.3 shows where in the Netherlands the bottlenecks are located. These bottlenecks are in every corridor (Figure 1.2) Most of these bottlenecks are sequentially on the corridor. However, for the Southeast corridor, there are bottlenecks that lay parallel in the corridor. Making the rebuilding or maintenance likely impact another bottleneck.

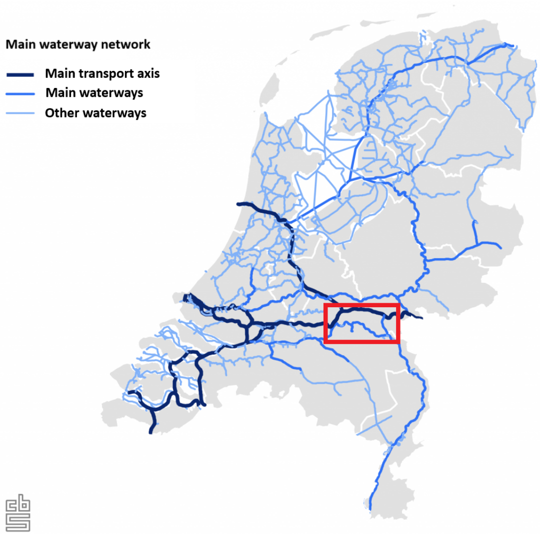

Figure 1.4: Main waterway network of the Netherlands, edited to show scope. original by: (CBS (Centraal Bureau voor de Statistiek), n.d.)

The Southeast corridor is connected to the rest of the Dutch waterway network with locks that are considered to be bottlenecks, These locks are Weurt and Grave. The location of these locks are shown in figure 1.4 and zoomed-in in figure 1.5. The vessels on the Southeast corridor that either come from or go towards Limburg or further south are likely to use either Weurt or Grave. Both of these locks are considered bottlenecks and are both in consideration of being rebuilt or renovated. This makes the Southeast corridor less reliable.

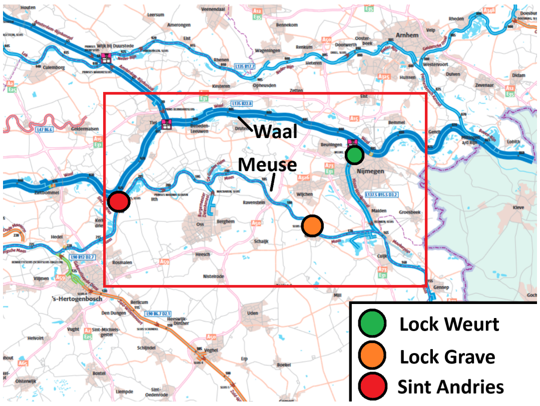

Figure 1.5: Waterway map of the Netherlands, zoomed in and edited original by: (Rijkswaterstaat, 2013)

For vessels coming from the South East there are two option, they remain on the Meuse and take the lock at Grave, or they take the lock at Weurt and continue their route over the Waal. It is also possible for vessels that took the lock at Grave to enter the Waal with the lock Sint Andries.

Water levels play a critical role for the IWT. High water can limit the height of vessels for certain bridges or locks. And low water can limit the draught of vessels for waterway sections or locks. the effects of water levels are highest in unregulated waterways (waterways without locks or weirs). However, even for regulated waterways, extreme water levels can strain the capacity by limiting the lock usage to reduce water loss in the waterway to keep it navigable.

A notable situation arises when water levels in the Waal drop. Unlike the Waal, the Meuse, regulated by weirs, maintains more consistent water levels even during reduced upstream flows. When the water level in the Waal becomes low enought that larger vessels can no longer take the lock at Weurt, vessels are then forced to use the lock at Grave. Figure 1.6 shows vessels rerouteing to the lock at Grave when water levels in the Waal decrease. Where the blue area is added there were low water levels in the Waal.

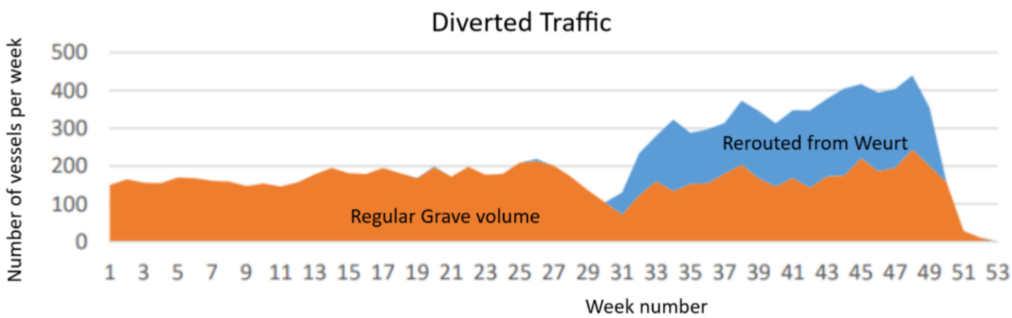

Figure 1.6: Vessels that reroute to the grave lock (Wouter van der Geest et al., 2022)

The extra traffic at the Grave lock in the second half of 2018 caused increased waiting times. During these dry periods the I/C ratio (intensity/capacity) increases to above 0.6 (de Jong, 2020). This could lead to very high waiting times. It could therefore be assumed that the vessels that rerouted from lock Weurt cause an increase in waiting times at Grave.

This can create interesting changes in the types of vessels that use each lock. When water levels decrease the larger vessels will first change their route to the Grave lock. When the water levels further decrease more and more vessels will change their route. The draught of the vessel (vertical distance from water level to the lowest point of ship's hull) is the limiting factor for the usage of lock Weurt. Since unloaded vessels have less draught, this means unloaded vessels of the same size might be able to use Weurt while loaded vessels of that same type may not. This rerouteing behaviour also impacts smaller vessels, which may shift from Grave to Weurt due to increased waiting times at Grave. This shift from Grave to Weurt under low water conditions in the Waal is referred to as a secondary effect of the reduced water levels at lock Weurt.

The Waal is the main distributary branch of the Rhine. The source of the Rhine is made up out of rain, snowmelt and glacier ice melt. Global warming affects these components, and this is expected to result in wetter winters and drier summers. Over time, it will result in more low-flow extremes (Kerstin Stahl et al., 2022). Figure 1.7 shows the estimated water flow (Q) in the Rhine at Lobith (where the Rhine enters the Netherlands). More periods with low water in the Waal are expected. Therefore, it is important to research the effects this has on the waterway network and the accuracy of modelling the waterway network. With a focus on areas where it is impacted the most, such at lock Weurt.

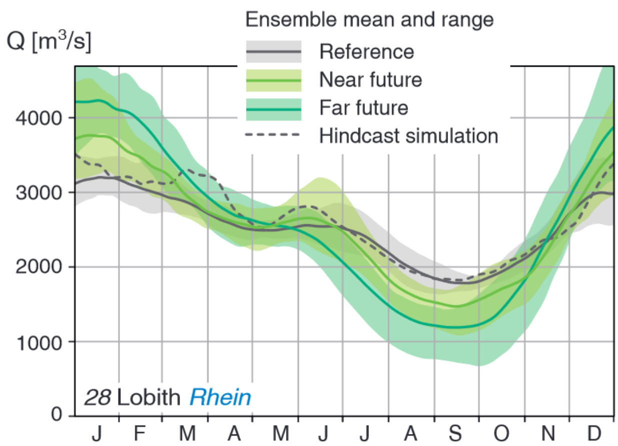

Figure 1.7: Changing streamflow regimes over time for Lobith, using a 30-day moving average of simulated mean daily streamflow (Reference is 1980-2010, Near future is 2030-2060, Far future is 2070-2100)(Kerstin Stahl et al., 2022)

Since IWT is vital for transport in the Netherlands, it is essential to assess the effects of policy and infrastructure changes, especially given the large amount of structures nearing the end of their design life. Modelling serves as a valuable tool to examine the effects of these changes. It provides a cost-effective way to evaluate complex systems and identify bottlenecks, and interventions to relieve those bottlenecks.

Currently, the Ministry of Infrastructure uses four models to simulate traffic over the inland waterways. These models are: BASGOED, BIVAS, SIVAK, and SIMDAS (Koningsveld et al., 2023). Figure 1.8 shows the scope of these models. BASGOED models the production and consumption of goods. It results in the amount of cargo per modal type for each origin-destination pair. BIVAS is a traffic assingment model that can use the output of BASGOED to estimate the traffic allocation on the inland waterway network. SIVAK is a simulation model that is used for traffic flows around bridges and locks. SIMDAS simulates traffic on waterway sections, incorporating vessel interactions.

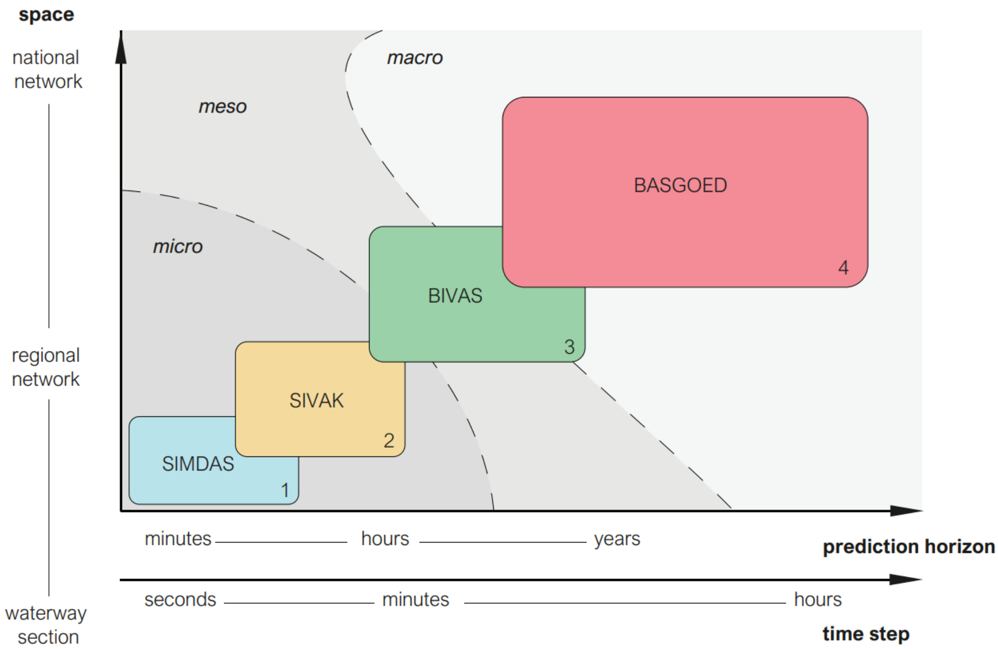

Figure 1.8: Waterways modelling landscape Rijkswaterstaat (modified from version by Tom van der Schelde, Rijkswaterstaat, by TU Delft – Ports and Waterways is licenced by CC BY-NC-SA 4.0)

The current waterway traffic modelling follows a linear process. First, the transported tonnes on an origin-destination pair is calculated with BASGOED. Then this is used to predict the number of vessels per waterway with BIVAS. Thereafter, these numbers are used to simulate the locks and waterway with either SIVAK and SIMDAS. This methodology assumes that the lower level details of lock modelling have a neglectable effect on the route choices made in BIVAS. However, BIVAS does not account for lock waiting times when allocating traffic. It is possible that the simulation of one lock can influence other locks. This can occur due to rerouteing because of low water levels. This research uses the Weurt-Grave system as a case study to illustrate these effects.

During low water levels on the Waal, there is a shift in lock usage, with some vessels diverting to lock Grave. This results in increased waiting times at lock Grave. Additionally, vessels with greater draught are the first to make this switch, altering the typical distribution of vessel types that usually pass through lock Grave.These dynamic, water-level-dependent effects are difficult to accurately capture using the BIVAS modelling method. A simulation of BIVAS uses fixed water levels. However, real water levels are not static. Small changes in water levels can impact what vessel can traverse past certain hydraulic structures. Since both water level extremes are estimated to become more frequent, it is becoming more important to model these situations well. Failing to do so can result in overestimating future lock capacity. Leading to more possible bottlenecks. Since both locks are nearing the end of their design life, it is important to gain insight in the future functioning of both locks. Since the Weurt-Grave system is affected by low water in the Waal, its inclusion in modelling this future functioning will be beneficial.

1.1. Research Gap

The replacement and repair of hydraulic structures requires planning to minimize disruptions, leading to a more efficient IWT. Accurate modelling improves this process by providing insight into traffic behaviour and the capacity of hydraulic structures. However, the current modelling methods might not capture the dynamic effects extreme water levels has on the inland waterway system.

As extreme water levels are expected to become more frequent, these limitations in the modelling methods are likely to have a greater impact. potentially leading to underestimated capacity constraints and overlooked bottlenecks. There is a need to evaluate whether current modelling approaches can accurately represent these effects and to determine the level of detail required for reliable simulation of lock interdependencies.

The extent of the effects that capacity reduction has on other locks is not sufficiently understood to conclude if the current modelling approach is valid in scenarios with capacity reduction. Therefore, there is a need to research the extent of the effects that capacity changes can have and if these effects can be captured with the current modelling approach.

1.2. Research Objective

This thesis will address the research gap by analysing the demand shifts at locks that are influenced by capacity changes at another lock. The research assess whether current modelling methods can accurately show the resulting demand shifts. Therefore, a deeper understanding of how these demand shifts occur is required. This study achieves this by analysing historical data to assess vessel behaviour under varying water level conditions. By examining observed traffic patterns, it evaluates whether existing modelling approaches remain valid or require improvement.

The study examines the effects of low water levels in the Waal on the waterway system surrounding Weurt and Grave, specifically evaluating:

- How low water conditions impact lock usage, waiting times, and vessel behaviour in the Weurt-Grave system.
- Whether current modelling methods can effectively capture these effects or require alternative approaches to better represent lock interdependencies.

Many existing models focus on individual lock performance or assume stable conditions, which may not fully reflect system-wide adaptations under varying water levels. This study provides insights into whether these models remain suitable for predicting inland waterway traffic patterns under changing environmental conditions.

While the primary focus is on the Weurt-Grave system, the results are designed to provide insights applicable to similar lock systems, supporting future planning and the development of more robust simulation models.

This thesis will help in making the waterway more climate resilient by identifying possible vulnerabilities in the current modelling methods for the Weurt-Grave system. It aims to help with improving the estimated needed dimensions for locks when it is modelled. Resulting in a more efficient waterway network.

This thesis evaluates current waterway modelling methods and proposes improvements for handling dynamic water levels, and interacting locks. While it focusses on the Weurt-Grave system, the findings can be applied to other lock systems and other environmental effects that influence lock capacity.

1.2.1. Research Question

This research aims to quantify changes in lock usage caused by capacity limitations at nearby locks. It will do this by researching the effect of low water levels in the Waal resulting in limiting lock Weurt usage and this causing demand changes at lock Grave. This is formulated in the following main research question:

What impact does a reduction in capacity, caused by low water levels, have on alternative locks within the inland waterway system, with a focus on the Weurt-Grave system? To answer this question, the following sub-questions are asked:

- ***What changes occur in the demand at alternative locks when the capacity of one lock is reduced?***
  In this sub-question, it will be researched if the reduction of usability of lock Weurt does result in demand change at Grave.

- ***To what extent do low water levels in the Waal impact the Weurt/Grave system?***
  for this sub-question, historical data will be used to find out how low water effects the route choice for Weurt-Grave. It will also try to prove the assumed change in vessel types at Grave occurs

and if there is a secondary effect for smaller vessels.

- ***Are the current modelling approaches sufficient for effects caused by extreme water levels?***
  for this sub-question, the current modelling approaches are assessed based on their ability to address the changes in capacity and demands shifts caused by low water levels.

1.2.2. Research Scope

This study will be limited to a specific part of the Dutch inland waterway network, centred around the locks Weurt and Grave in the Southeast corridor. The Weurt-Grave system is chosen because it has two locks in parallel where one is directly effected by extreme water levels. This results the ability to research the demand change due to low water and the demand shift. The research investigate the effects of low water levels in the Waal on vessel route-choice, lock usage, and traffic patterns in this region. The scope includes:

- Analysing the effects of reduced capacity at Weurt on demand at Grave.
- Understanding the changes in vessel types, waiting times, and overall traffic behaviour during low water periods.
- Evaluation of the ability of existing models to simulate these shifts accurately.

While the focus is on the Weurt-Grave system, the results will also offer insights into similar lock systems, particularly those impacted by external factors such as water level changes.

1.3. Methodology

This thesis aims to awnser the research question: **What impact does a reduction in capacity, caused by low water levels, have on alternative locks within the inland waterway system, with a focus on the Weurt-Grave system?** To answer this research questions 4 chapters are used. Each contributing to answering specific aspects of the main research question and its sub-questions.

1.3.1. Weurt-Grave System

This chapter provides an introduction to the relevant parts of the waterway network. It identifies the operational characteristics of both locks, including their capacities, vessel traffic, and responses to water level changes. These insights form the foundation for analysing the first two sub-questions.**What changes occur in the demand at alternative locks when the capacity of one lock is reduced?** and, **To what extent do low water levels in the Waal impact the Weurt/Grave system?**

1.3.2. Data Analysis

This chapter will analyse historical data to answer the first sub-question: **What changes occur in the demand at alternative locks when the capacity of one lock is reduced?** It does this by analysing the Water levels in the Waal, fleet composition in the system, transport patterns, lock performance, and route choice.

For the water level analysis and the transport pattern analysis, a time series analysis is done to gain insight in the yearly seasonality. Since the capacity of the lock in Weurt depends on the water level in the Waal it is important to understand the water level pattern. Since the water level in the Waal changes over the year, a time series analysis can show this seasonality. To see how the transport over the waterway network is impacted by the water level in the Waal, a time series analysis of the transport over the Waal is also created to see if the seasonality of both match.

The fleet composition will look at changes in the CEMT-class (a classification method for vessels) over time, and under differing water level conditions. This will show if there are changes in distribution of vessel types when the water level lowers.

The lock performance will be researched by creating a lock passage time distribution for normal and low water levels in the Waal. The lock passage time is the time from arriving at the lock to exiting the lock. Since the rerouting of vessels can cause congestion. If the congestion is higher during lower water levels, this will show in the lock passage time distribution.

For the route choice, a OD-matrix is generated from the historical data. This is used to see what types of vessels use each route under different water levels in the Waal. Showing if the impact the destination has on the effects of route choice for lower water levels.

1.3.3. Impact of Variables on Lock Utilization

This chapter will address the second sub-question: **To what extent do low water levels in the Waal impact the Weurt/Grave system?** This question will be answered by investigates how specific variables, such as water level, CEMT class, waiting times, and vessel route, affect the utilization of the Weurt and Grave locks.

First, the amount of vessels/load and their lock used is plotted with the water level to gain insight in the lock choice during different water levels in the Waal.

Moving averages are used to analyse the different variables and how they chance under different water levels. Moving averages are used because it can clearly show the changes of the variables for different water levels in the Waal. These plots can visually show the relation the variables have with the water levels.

To statistically assess the effects of the variables, logit regression is used. The logit regression models will show the effects each of the variables has on the lock choice for a vessel in the Weurt-Grave system. A logit regression is a good fit because there is a binary choice for each vessel. A vessel can take Weurt or Grave. The logit regression is done in separate regression models for each variable and variables together in one logit regression model. The regression models will the show the effects each variable has on the lock choice and if this effect is statistically relevant. And if these effects remain when all variables are assessed together.

1.3.4. Current Modelling Assessment

In this chapter, the third sub-question is adressed: **Are the current modelling approaches sufficient for effects caused by extreme water levels?** First the currently used models are explained then it is discussed if these are able to simulate the Weurt-Grave system for low water levels in the Waal. Also it is looks at different modelling methods that could be used to simulate the Weurt-Grave system.

1.4. Reading Guide

The thesis is organized as follows:

- **Chapter 2: Weurt-Grave System**
  In this chapter, the necessary information of the Weurt-Grave system is presented for answering the research questions.
- **Chapter 3: Data Analysis**
  This chapter analyses the historical data of the Weurt-Grave system from 2018 to 2023. It analyses water levels, vessel types and traffic patterns.
- **Chapter 4: Impact of Variables on Lock Utilization**
  In this chapter, the analysis is extended to examine variables and their influence on lock usage. This chapter shows how vessel behaviour changes due to low water levels and identifies patterns in lock usage.
- **Chapter 5: Current Modelling Assessment**
  This chapter reviews the current traffic models used for inland waterway systems. It focusses on the effects found in the previous chapters. It examines potential gaps in these models.
- **Chapter 6: Discussion**
  This chapter reflects on the findings. combining the results of the other chapters. It addresses practical implications, limitations, and areas for future improvement.
- **Chapter 7: Conclusion**
  The final chapter summarizes the conclusions of the study by answering the research questions.

It will also present the practical implications of the conclusions with recommendations for future research.

2

Weurt-Grave System

This chapter provides the necessary background information for the Weurt-Grave system, focussing on the characteristics of the locks and waterways in the system. It describes the locks in the system and explains their role. This chapter establishes the foundation necessary for analysing the impacts of low water levels causing reduced lock capacity and its impact on traffic patterns in later chapters. This chapter supports the sub research question: **What changes occur in the demand at alternative locks when the capacity of one lock is reduced?** and provides context for the analysis of later chapters.

2.1. Inland Waterway Network

The waterway network of the Netherlands is made up of several components (Koningsveld et al., 2023). These components are:

- Waterways (canals and rivers)
- Hydraulic structures (locks, weirs, and bridges)
- Inland ports and terminals
- Mooring facilities (places to dock)
- Service facilities (refuelling and maintenance)

This thesis focuses on the locks and waterways as the most relevant components. They directly affect traffic patterns. Their role is critical in understanding the impact of low water levels on capacity and demand shifts, which are central to this study. Additionally, since the research focuses on low water levels, height limitations due to high water are not applicable. In the next to sections, these will be further explained. Figure 2.1 shows the main waterways of the Netherlands.

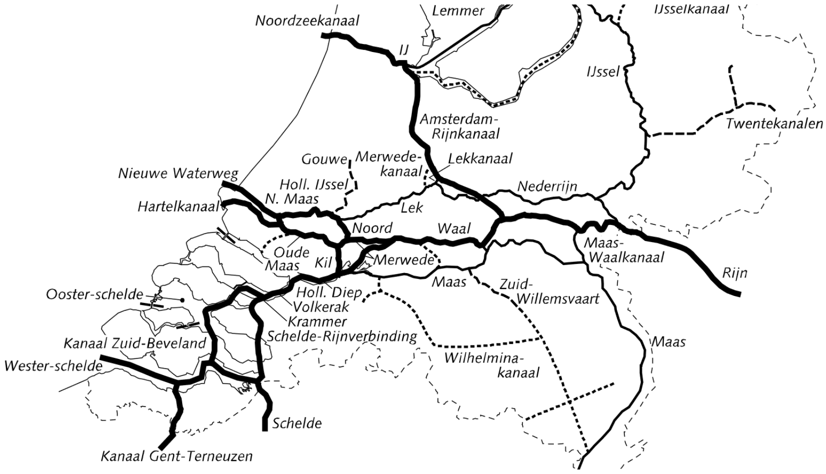

Figure 2.1: Main waterways of the Netherlands (Rijkswaterstaat, 2020a)

2.1.1. Classification

Inland waterways are classified by the largest design vessel that can safely navigate them. These design vessels are standardized into the CEMT-Classification. This classification helps standardize waterways across Europe, making it easier to plan and navigate. The CEMT-Classification groups waterways based on the size of vessels they can handle, focusing on key dimensions like length, width, and draught. This ensures that locks, bridges, and other structures are designed to meet the needs of the vessels using them. Table 2.1 provides the minimum values for lock dimensions by CEMT class.

CEMT-class	Usable chamber length	usable chamber width	Sill depth
I	43 m	6.0 m	2.8 - 3.1 m
II	60 m	7.5 m	3.1 - 3.2 m
III	80 - 95 m	9.0 m	3.1 - 3.3 m
IV	95 - 115 m	10.5 m	3.5 - 3.7 m
Va	125 - 150 m	12.5 m	4.2 m
Vb	210 m	12.5 m	4.7 m
VIa	160 m	23.8 m	5.0 m
VIb	215 m	23.8 m	5.0 m

Table 2.1: CEMT-class and corresponding lock dimensions (Richtlijnen Vaarwegen, 2020)

Vessels are also classified based on these dimensions. A vessel is assigned to the lowest CEMT class where it fits within all the dimensions. This ensures that a vessel of a certain CEMT class can always safely navigate a waterway of that same class.

2.1.2. Locks

There are several reasons for the waterways to be blocked by hydraulic structures (Koningsveld et al., 2023):

- To maintain a consistent water level in a specific section of the waterway.
- To store water in a reservoir.
- To manage differing water levels where canals meet rivers.
- To prevent saltwater intrusion

At Grave, the waterway is blocked to maintain the Meuse at a navigable level for vessels. At Weurt, the waterway is blocked where the canalized Meuse connects with the river Waal. At the Waal the water level fluctuates. Therefore, there are locks at Grave and Weurt to let ships pass these blockades in the waterway.

A lock works as follows:

1. Vessels enter the lock chamber.
2. The doors close, and the water level is adjusted to match the exit level.
3. The exit doors open, and vessels leave the chamber.
4. The process is repeated in the opposite direction once the chamber is emptied.

This process is shown in Figure 2.2. During this process, water can be lost depending on the difference between the two levels. This can have an effect on the number of passages possible and sometimes make locking impossible. For example, in September 2023 the Meuse was losing water due to a failure at Grave. To maintain the water level in the Meuse other branches were closed. The canal leading from the Meuse to lock Weurt was also blocked, locking at Weurt was not possible because the water level loss in the canal would be too large. As a result, eight vessels were stuck in the Meuse-Waal canal (Jelmer Bastiaans, 2023).

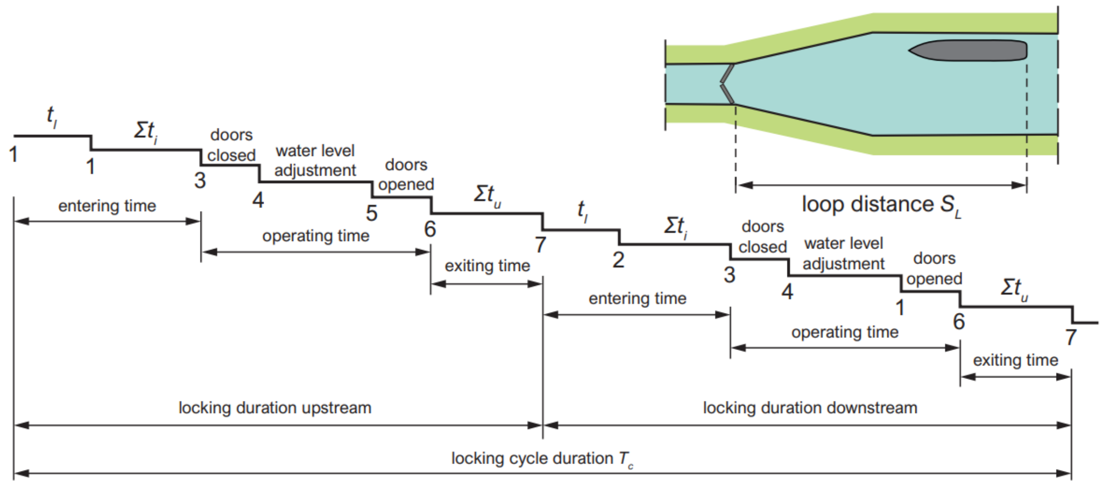

Figure 2.2: Phases of a locking cycle (bu TU Delft - Ports and Waterways is licensed under CC BY-NC-SA 4.0)

The locks in the Weurt-Grave system maintain water levels to ensure the Meuse waterways remain navigable for transport. However, they also introduce disruptions, such as delays caused by the locking process and waiting times, which can significantly impact travel times.

2.2. Weurt-Grave

The Weurt and Grave locks are indirectly connected within the waterway network. Vessels that traverse the Meuse have two options: Enter the Waal by going through the locks at Weurt, or continue and use the lock at Grave. Figure 2.3 shows the relevant waterways and the location of the locks Weurt and Grave.

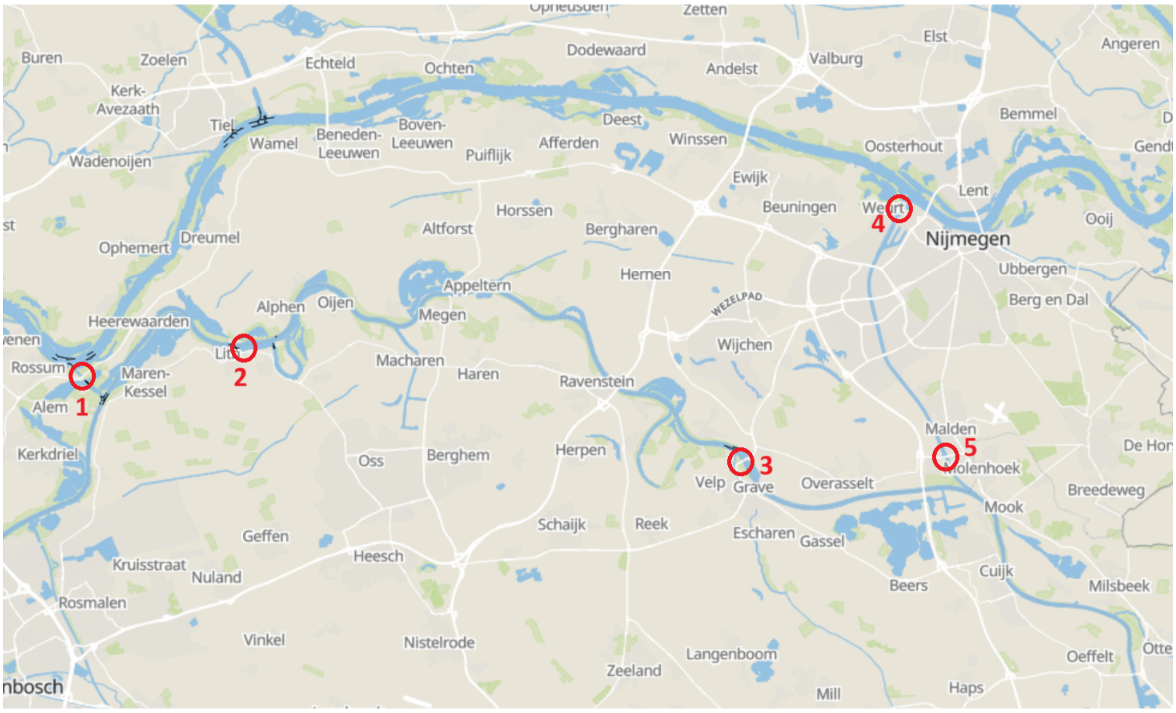

Figure 2.3: Location of locks around Weurt and Grave (map sourced from Rijkswaterstaat)

These are the names of the locks in area of the Weurt-Grave system:

1. St. Andries (connects the Meuse to the Waal further downstream).
2. Prinses Maxima locks at Lith (maintains water level in Meuse).
3. Grave (maintains water level in Meuse).
4. Weurt (connects the Meuse to the Waal).
5. Heumen (connects the Meuse to the Meuse-Waal canal).

For vessels travelling between the Meuse and Waal, there are two main route options. Consider a vessel departing from Maastricht downstream (bottom right of the figure). The first option is to use the lock at Heumen to enter the Meuse-Waal canal, then proceed through the lock at Weurt to access the Waal. The second option is to remain on the Meuse, passing through the locks at Grave and Lith. If the vessel needs to enter the Waal, it can use the St. Andries lock. The primary bottlenecks along these routes are the locks at Weurt and Grave.

2.2.1. Weurt

The Weurt lock connects the Meuse to the Waal. At one side is the Meuse-Waal canal and on the other side the Waal. This is shown in figure 2.4. The Weurt lock consists of two chambers, the West chamber and the East chamber, each measuring 260 meters in length and 16 meters in width. These dimensions allow CEMT-Class VII vessels to traverse the lock.

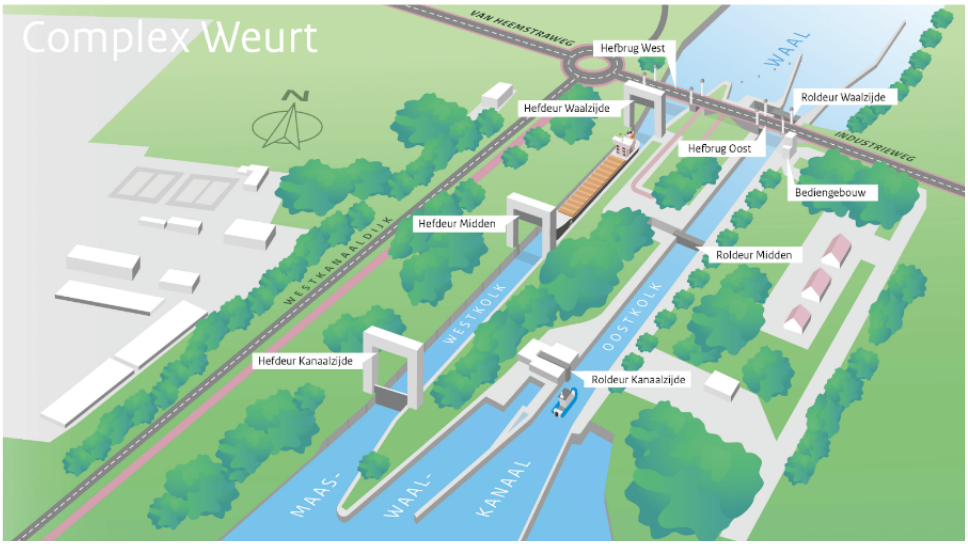

Figure 2.4: Infographic of lock Weurt (Rijkswaterstaat, 2023)

The East chamber cannot be used when the water level is lower than 5.85 m +NAP at Nijmegen. The sill depth of this chamber is +3.0 m NAP. For the West chamber, the sill depth is +1.5 m NAP. During periods of high water levels on the Waal, the lock at Weurt uses stepped locking. This involves adjusting the water level in multiple stages rather than in a single operation. This method helps manage the significant water level differences between the Meuse-Waal Canal and the Waal. In Figure 2.4, the multiple doors in the West chamber can be seen that are used for this purpose.

2.2.2. Grave

At Grave, there is a weir that is used to keep the water levels in the Meuse at a high enough level so that it can be safely traversed by vessels. To bypass this weir there is a lock next to it. This lock has one chamber. Figure 2.5 shows two chambers, however, one of those chambers is the old lock and is not in use.

Figure 2.5: Arial shot of Lock complex Grave (Rijkswaterstaat, 2017)

The chamber has a length of 142 m and a width of 16 m. These dimensions allow CEMT-Class VII vessels to traverse the lock. It has a downstream sill depth of 3.4 m. Grave only having one chamber makes it a robustness bottleneck. When the chamber is in maintenance or has a failure, the passage at grave is blocked. The water level difference between upstream and downstream of the lock is around 3 meters.

2.3. Dry Periods

Low water levels in the Waal limit the draught of vessels for lock Weurt. Since the Meuse is regulated by weirs, its water level remains relatively stable even during periods of low upstreams flow. This allows vessels with greater draught to continue on the Meuse when the route via Weurt is impossible because of the draught limit.

2.3.1. Waiting Times

Figure 2.6 shows the average waiting times from 2015 to 2020 of lock Grave. The yellow line shows the maximum average waiting time that RWS finds acceptable. Comparing this figure with the previous ones, it can be seen that the dry period in the second half of 2018 greatly affected the waiting times. Waiting times frequently exceeded three hours during this period. In the figure, this period is between the vertical red lines. This data was gathered for a report that researched the economic benefits of a second chamber at Grave commissioned by Rijkswaterstaat (Wouter van der Geest et al., 2022). It concludes that a second chamber at Grave will be economically beneficial.

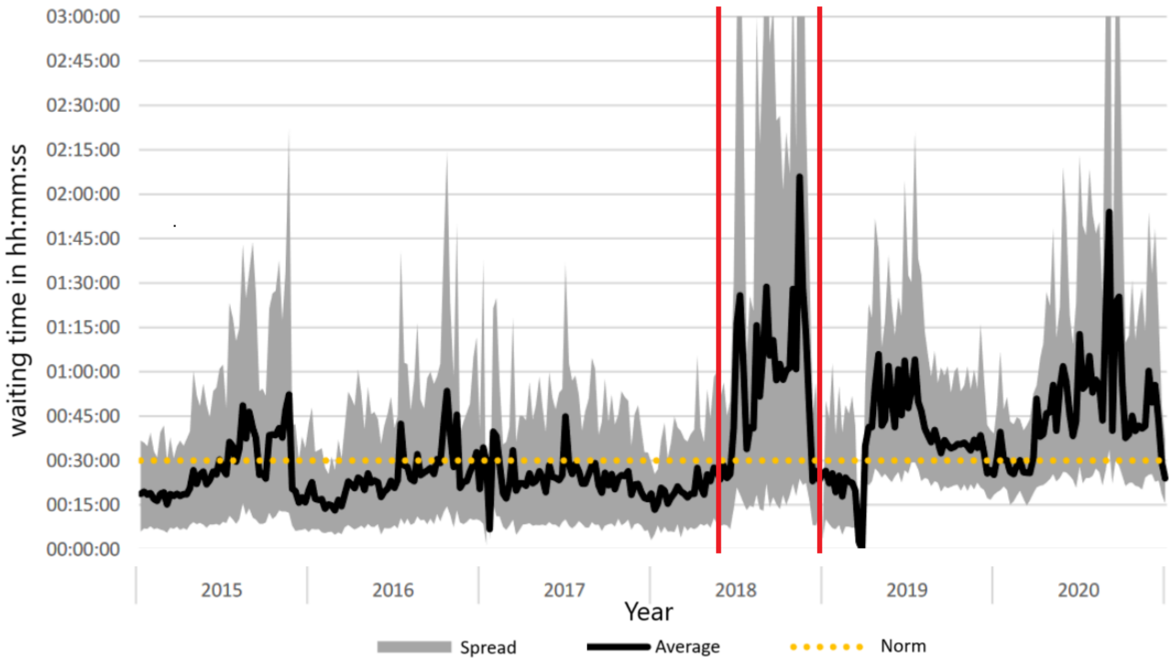

Figure 2.6: Average waiting times at lock Grave 2015-2020 (Wouter van der Geest et al., 2022)

The increased travel time likely makes the route via Weurt preferable for smaller vessels that would typically use Grave. Even the water depth of Grave favours that of the Waal on occasions. In figure 2.7 the number of days per year that the Grave lock can accommodate vessels with a larger draft than the Waal can. The red part of the bars would have been the amount of days if the Grave lock can accommodate a draught of 3.5 m instead of 3.2 m.

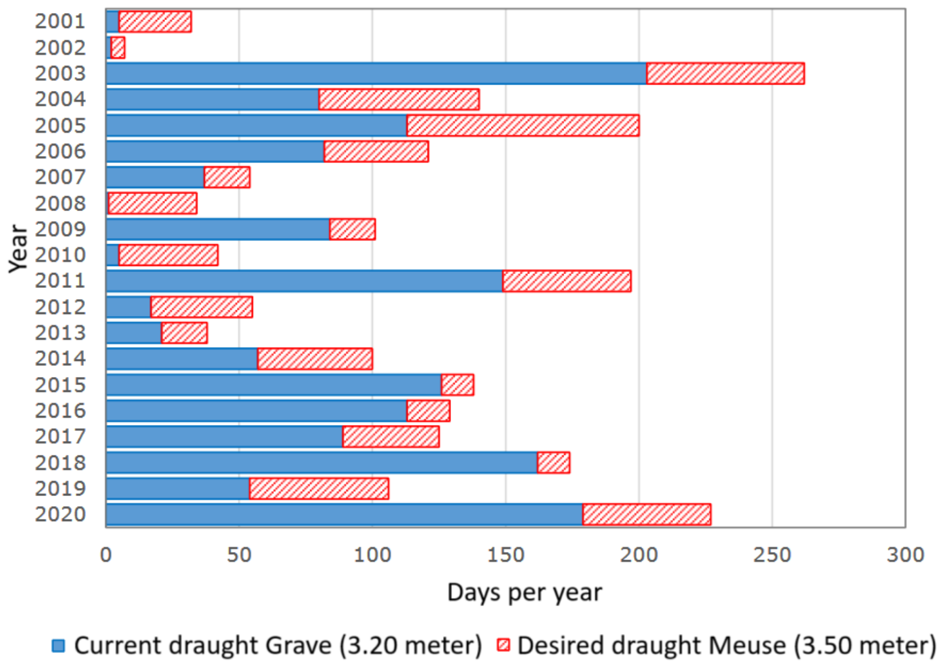

Figure 2.7: Amount of days per year when the route via Grave has more favourable nautical conditions then the route using Weurt(Wouter van der Geest et al., 2022).

During the low water period in 2022 a failure occurred at the West chamber. Due to the low water levels the East chamber could not be used. Vessels could reroute to Grave, but there were also issues with rocks lying in the path of the doors, causing waiting times of multiple hours (Hendriks and Mens, 2024).

2.4. Conclusion

This chapter has provided the background information for the Weurt-Grave system. Showing the two possible routes in the system. It described the roles of the locks in the Weurt-Grave system. The locks at Weurt and Grave were described and shown as bottlenecks within the system. Also, it was shown that there are connections between Weurt and Grave during low water levels in the Waal. This information will be used to analyse how reduced lock capacity influences traffic patterns and vessel behaviour. Helping to answer: **What changes occur in the demand at alternative locks when the capacity of one lock is reduced?**

3
Data Analysis

This chapter analyses the effects of low water levels on the Weurt-Grave system. Focusing on water levels, vessel behaviour, transport patterns, and lock performance. The goal is to answer the sub-research question: **What changes occur in the demand at alternative locks when the capacity of one lock is reduced?** This is done with the reduced capacity at Weurt during low water levels.

A structured approach is used to ensure the analysis captures the effects of low water levels. This will be done in the following order:

- **Water level analysis**
  Seasonal and extreme changes in water levels are analysed to gain insight in when the low water levels occur. A time series analysis is done to research if the water levels in the Waal follow a pattern. The variable that will be researched it the water level in the Waal in centimetres.
- **Vessel data Analysis**
  Fleet composition is analysed for the Weurt-Grave system during normal water levels and during low water levels in the Waal. This will be done with the CEMT-class of vessels. Vessels are categorised in a CEMT-class based on their length, width, and loaded draught. Larger vessels will be limited by lower water levels.
- **Transport pattern analysis**
  The Transport patterns in Weurt-Grave are analysed based on changes over time. A time series analysis is done to see if there are patterns over time. This will be done with vessel counts and loads over time. Here it would show if during low water there are changes in the load and count patterns.
- **Lock performance analysis**
  Passage times at the locks of Weurt-Grave are analysed for normal water levels and for low water levels. A distribution will be made of the passage times of the locks at Grave and the lock at Weurt.
- **Spatial transport analysis**
  The origin and destinations of vessels and their changes under low water levels are analysed. All the vessels counts will be placed in an Origin-Destination matrix. The differences in the matrix for different water levels and vessel draughts will be analysed.

By focusing on these analyses, this chapter describes in what ways low water levels affect the Weurt-Grave system.

3.1. Overview of Data Sources

The primary data sources include vessel records and water level data. Both datasets were retrieved from Rijkswaterstaat: Vessel observations are private data, while the water levels are public data. The vessel records are referred to as IVS, short for the Dutch 'Information and Tracking System for Shipping'. Each data row contains the following vessel data:

- The observation location
- The lock passage times
- The vessel type
- Origin and destination location
- Ship dimensions (length, width, draught)
- Ship load

the data has 265065 rows for three locations: Lock Weurt, Lock Grave and the Maximakanaal. The Maximakanaal, a potential rerouteing option for the Weurt and Grave locks, connects 's-Hertogenbosch to Maastricht. The locations of these measuring locations can be seen in figure 3.1. The analysis finds that during low water levels in the Waal the Maximakanaal is not significantly used as an alternative route.

Figure 3.1: Measurement locations (1:Maximakanaal, 2:Lock Weurt, 3:Lock Grave) map by Rijkswaterstaat

The second data set contains of the water levels of the port of Nijmegen. This measurement location is just outside the Weurt lock and measures the water level of the Waal. By combining these two datasets, water levels can be linked to each vessel passage at the measurement locations.

3.2. Water Level Analysis

The 2023 water level dataset contained measurement errors, there were short spikes with values above 100 meter. These data error were removed and interpolated to provide a more realistic representation of water levels during this period. The water levels in the data set were measured every 10 minutes from 2018 to 2023. The "dry" years are 2018 and 2022. During these years, the water levels got the lowest.

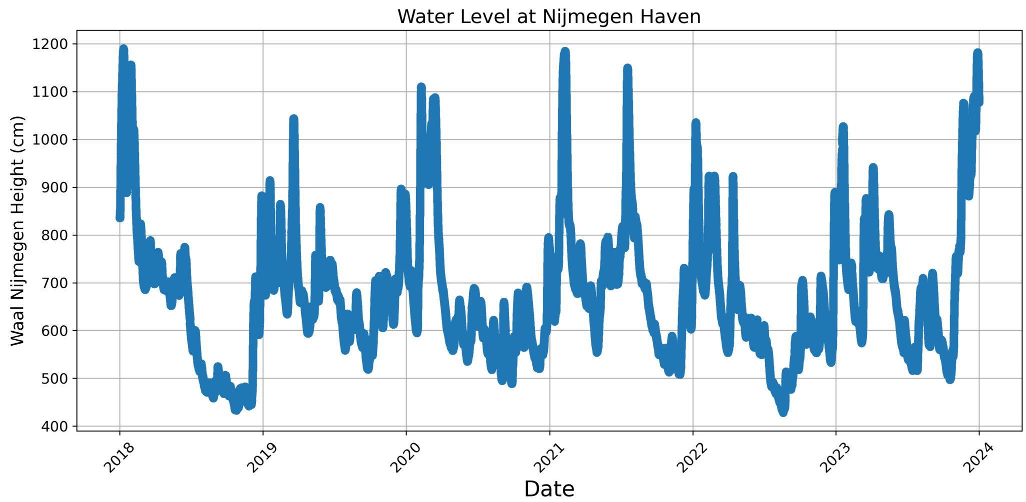

Figure 3.2: Water levels in the Waal measured closest to lock Weurt. Data requested from waterinfo.rws.nl

Figure 3.2 illustrates water levels in centimetres, highlighting the pronounced dry period in the second half of 2018. Also, there seems to be seasonality, the second part of each year there is a dip in the water levels. This is expected because the main source of the water in the Waal comes from Alp melt water (Uehlinger et al., 2009). Figure 3.3 shows the Rhine Discharge. The Waal is one of the branches of the Rhine.

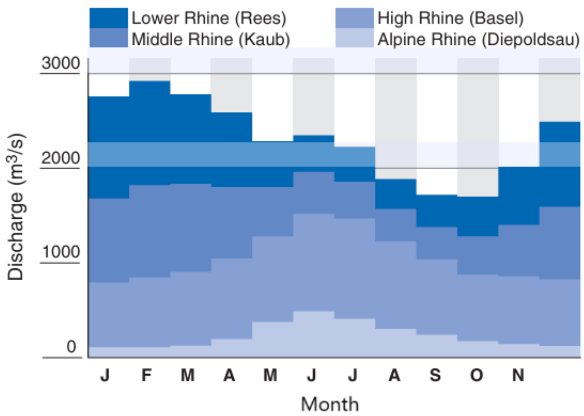

Figure 3.3: Rhine discharge, Rees is 20km upstream from the Dutch-German border (Uehlinger et al., 2009)

When looking at both figures, the effect of the average discharge can clearly be seen in the water level graph. In the beginnings of the years the water levels are higher than the second half of the year. An exception occurred in July 2021, when record-breaking precipitation was observed. The resulting river discharge in the Rhine catchment was the highest on record, caused by a slow-moving low-pressure system over Europe (copernicus, 2021). A time series analysis is done to more clearly show the seasonal effects in the water levels over time. The results are shown in Figure 3.4. The time series analysis done with the formula: $Y_t = T_t + S_t + R_t$. where:

- T_t: Trend
  The trend contains the long term changes in water levels. It is created by taking a moving average of the year.
- S_t: Seasonality component
  The seasonal variation shows the average trend for a yearly cycle. The seasonality is calculated

by subtracting the trend from the observed water level. Then these are averaged for each year into one yearly trend.

- R_t:Residuals
  The residuals are what cannot be explained from the trend and the seasonality. It is what is left when from the observed data the seasonality and the trend are subtracted.

To indicate the different years more clearly, red lines are used.

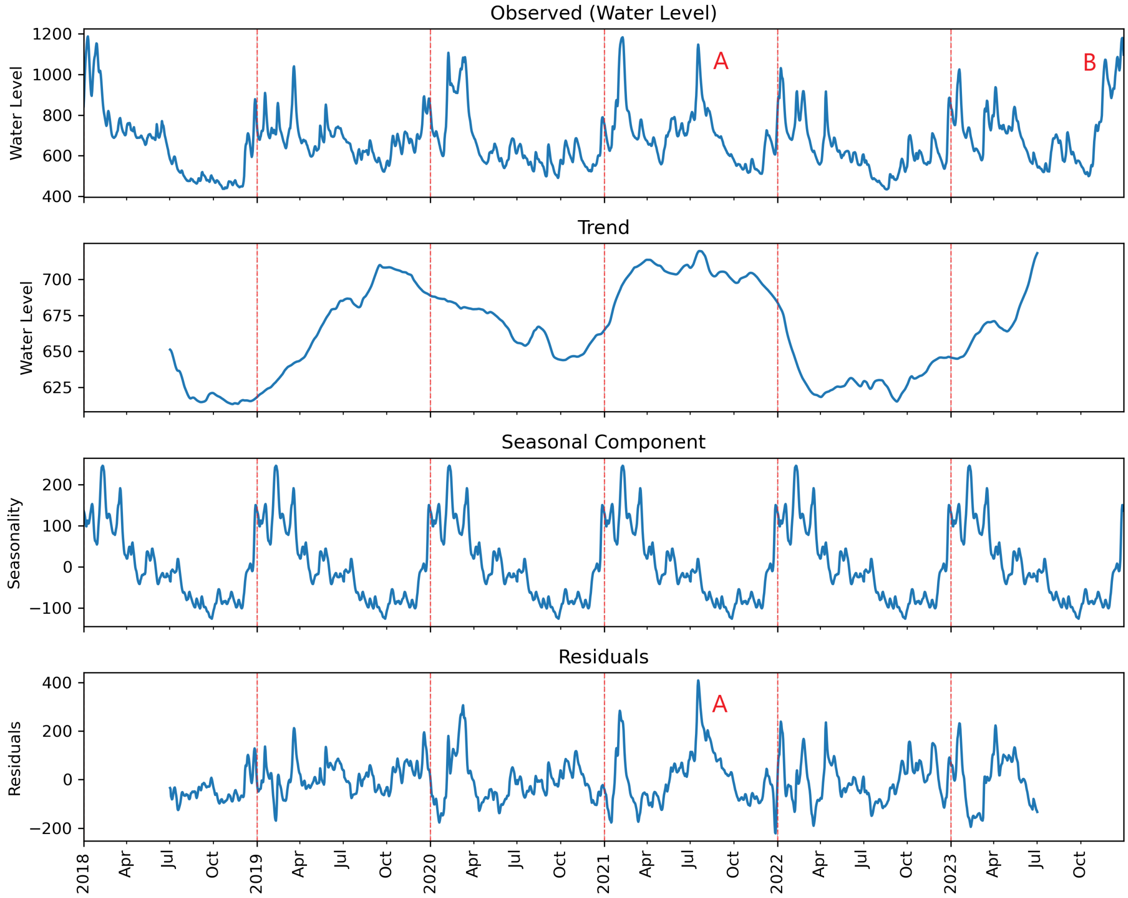

Figure 3.4: A time series analysis of waterlevels in the Waal using the seasonal_decompose from statsmodels.tsa.seasonal, it uses a additive function: $Y_t = T_t + S_t + R_t$ (A and B notate periods with peaks outside of the seasonality)

The seasonality does follow the shape of the Rhine discharge in figure 3.3. The seasonal range is 372 cm and the residual standard deviation is 90 cm. The residuals do show a high peak during the large rainfall in July 2021. There does not seem to be a seasonal component left in the residuals, meaning the seasonality successfully captures the recurring patterns, and the remaining residuals primarily reflect random variability and short-term hydrological events. The red A and B in the figure show periods where high precipitation in the Meuse catchment area caused large peaks outside the seasonality. The random variability is caused by variability of the precipitation in the catchment area of the Meuse and the variability in the melting rate of the snow in the Alps. The seasonal component does match with the Rhine discharge shown in Figure 3.3. Higher levels at the beginning of the year, a flatter lower water level between May and July, Then a decrease and concluding with an increase in November and December.

3.3. Vessel Data

In this section, the vessel data will be analysed on vessel type patterns between the measuring points and the vessel distribution changes over time.

3.3.1. Fleet Composition

To gain insight into the fleet, the vessels CEMT-classes are analysed per measuring point.The different CEMT-classes are listed in table 3.1 with their corresponding dimensions.

CEMT-class	Loaded draught	Load tonne
I	2.5 m	251-400
II	2.6 m	401-650
III	2.6 - 2.7 m	651-1250
IV	2.9 - 3.0 m	1251-2050
V	3.5 - 4.0 m	2051-4000
VI	3.5 - 4.0 m	4001-5600
VIb	3.5 - 4.0 m	6400-12,000
VIc	3.5 - 4.0 m	9600-18,000
VII	3.5 - 4.0 m	14,500-27,000

Table 3.1: CEMT-classes (Richtlijnen Vaarwegen, 2020)

Overall Distribution

To understand vessel types at each measuring point, the total distribution across all years is presented in Figure 3.5. It illustrates distributions for all vessels and at each location. It is expected that lock Weurt has a higher amount of large vessels types, due to it being the main connection from the Meuse to the Waal, and the Waal has at normal water levels preferable nautical conditions compared to the Meuse. Then the Grave because it is the continuation of the Meuse. And lastly the Maximakanaal since the waterway that connects it to Maastricht is of a lower CEMT-Class.

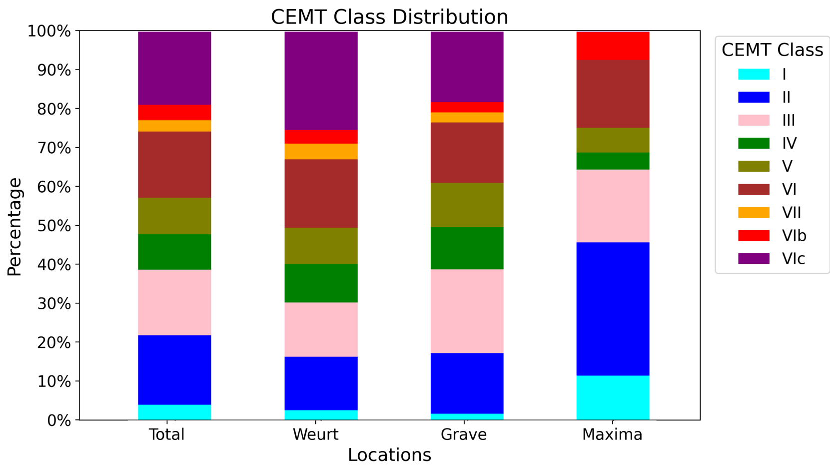

Figure 3.5: CEMT-Class distribution for each measuring location (Weurt, Grave and Maximakanaal)

The bar chart confirms the expectations. Weurt has the greatest proportion of larger CEMT-classes. About half are VI and larger. the Maximakanaal has predominantly smaller vessels, as the waterway connecting it to Maastricht is of a lower CEMT-class.

Trends over time

To gain insight on how these distributions change over time and the effects of dry years, the counts per vessel class are plotted for each year in figure 3.6. Since 2018 and 2022 were years of low water levels in the Waal, it is expected that a shift of the larger CEMT-classes from Weurt to Grave. If the Maximakanaal is also considered a reroute for low water levels, there should also be an increase in larger vessels there during these two years.

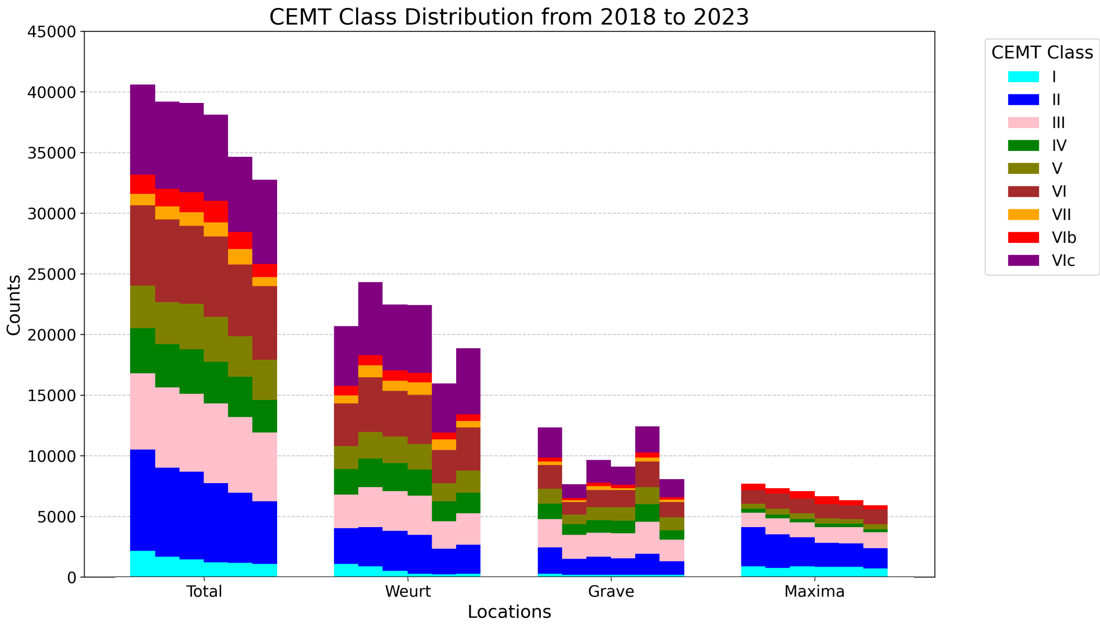

Figure 3.6: Number of vessels per CEMT-class for each year per measuring location (Weurt, Grave and Maximakanaal), left most bar 2018 right most bar 2023

There seems to be a downward trend in the number of vessels in the system. This matches the decrease in transport volume over the inland waterway in 2022 and 2023. In 2022 the volume decreased by 3.4 percent (CBS, 2023) and in 2023 it decreased with 5.2 percent (CBS (Centraal Bureau voor de Statistiek), 2023).

It can also be clearly seen that for both Weurt and Grave the counts in dry years (2018,2022) deviate the most from the rest. Here the number of vessels at Grave is clearly higher than the other years. At the same time they are lower at Weurt. This confirms the expected interaction between Weurt and Grave, with shifts observed not only in larger CEMT classes but also in smaller ones.

Also for 2019 there is a lower than expected number of vessels taking Grave, and an increase at Weurt. The cause for this is most likely that there was large maintenance needed at the locks at Lith (downstream from Grave on the Meuse). The North chamber was closed from September to November, leaving only the smaller South chamber (MdV, 2019).

To see more clearly how the fleet composition changes during the dry periods, a plot is made comparing the second half of 2018 with the second half of 2019. This plot can be seen in figure 3.7.

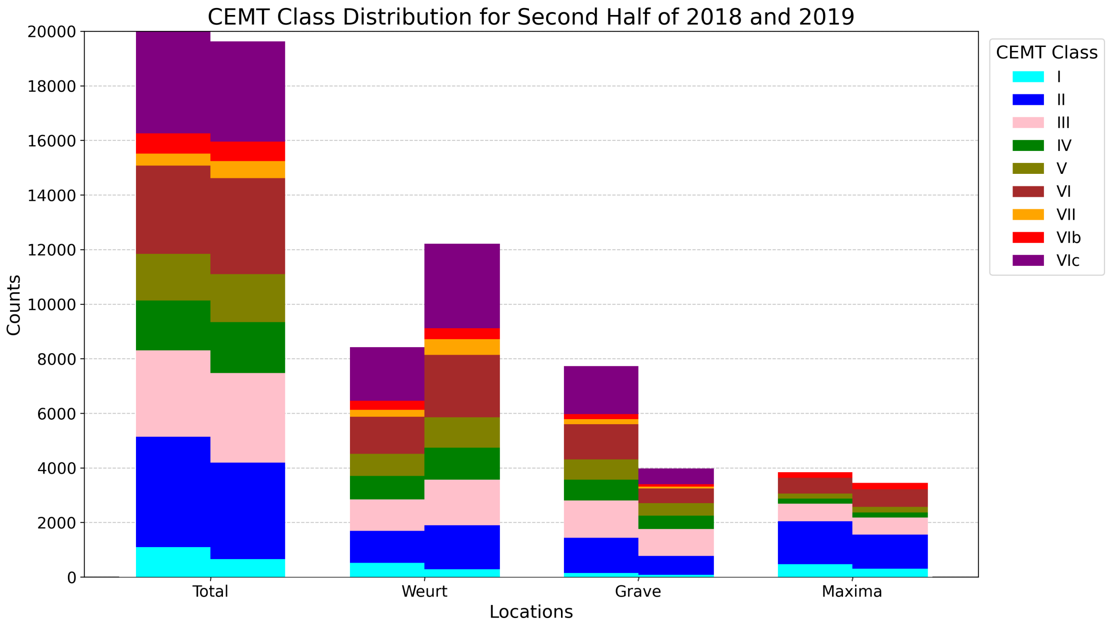

Figure 3.7: Left the vessel counts for the second half of 2018 (low water levels in the Waal) and right for the second half of 2019 (normal water levels in the Waal) for each measuring location (Weurt, Grave and Maximakanaal)

The figure indicates a significant shift in larger vessels. In the second half of 2019, large vessel types formed only a small part of the distribution at Grave, compared to their prominence in 2018. During low water levels, the share of large vessels decrease at Weurt while they increase at Grave, indicating a redistribution rather than a reduction. For the combined Weurt-Grave system, the overall share of larger vessels remains stable, suggesting that water levels in the Waal impact the distribution of vessel types between the two locks. The fleet distribution at Grave significantly changes based on the water levels in the Waal.

3.3.2. Transport Patterns

In this section, it is analysed how the vessel data evolves over time, including monthly, weekly, and daily patterns.

Monthly counts

It was visually confirmed that during dry years the vessel traffic for a part switches from Weurt to Grave. However, in both those dry years the first half of the year did not have low water levels. Therefore, the total monthly vessel counts per measuring location will be plotted over time. This is shown in figure 3.8. It is expected that the counts of Weurt mirror in reverse the counts of Grave. A peak is expected at Grave in the second halves of 2018 and 2022, with corresponding dips at Weurt. If the Maximakanaal is connected to the system, it will follow Graves line or peaks when Grave and Weurt dip.

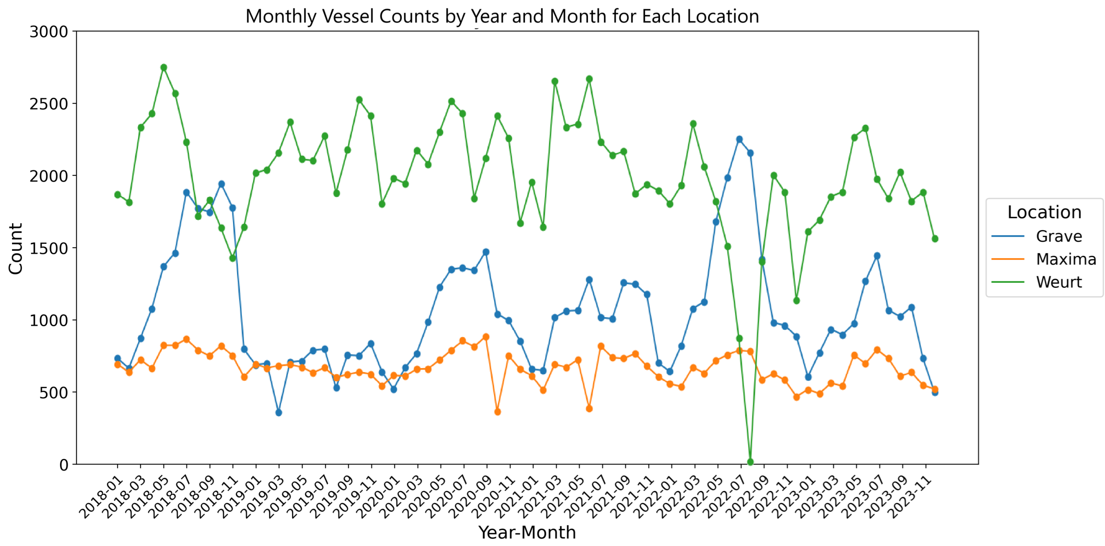

Figure 3.8: Monthly vessel counts over time for Weurt, Grave and Maximakanaal

The figure shows that when Weurt has large dips in 2018 and 2022. Grave indeed has a peak. However, this is not consistent for the smaller peaks. The largest peak at Grave occurs when there is no traffic at Weurt due to a closure that will be discussed later. There seems to be a yearly trend where the total vessel count peaks at the end of the summer. For the Maximakanaal, the trends appear to operate independently of the other locks. There are two clear dips in October 2020 and June 2021, but no consistent reactions to these dips are observed at the other locks. While the total monthly data gives a good insight in how many vessels pass each location, it does have month to month fluctuations since not every month has the same amount of days.

A time series analysis is done to more clearly show the seasonal effects of the vessel counts in the Weurt-Grave system. The results are shown in figure 3.9. Since the vessel counts of the Maximakanaal do not seem to be part of the Weurt-Grave system, the time series analysis is done for the total vessel count of Weurt and Grave added together. To take out the changes within a week, the weekly totals are used.

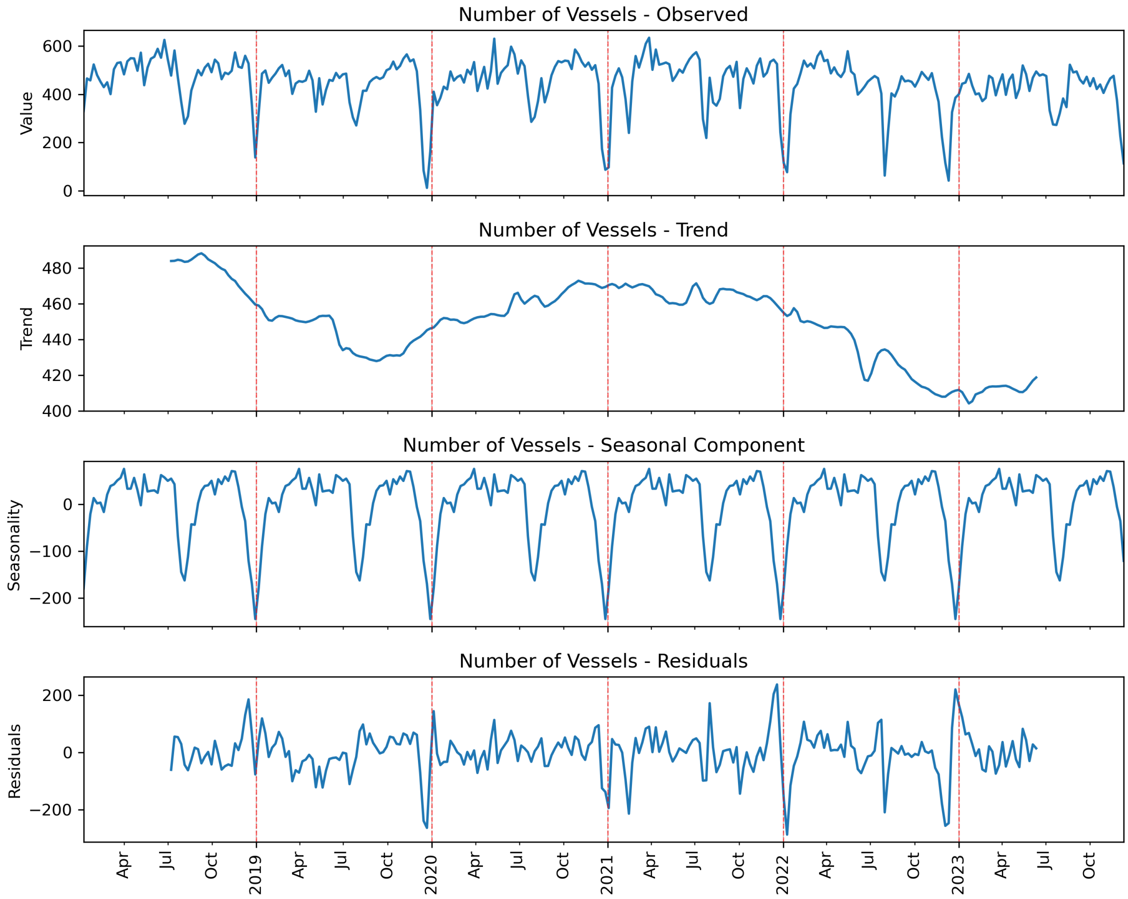

Figure 3.9: A time series analysis of the vessel counts in the Weurt-Grave system using the seasonal_decompose from statsmodels.tsa.seasonal, it uses a additive function: $Y_t = T_t + S_t + R_t$

When the vessel counts of Weurt and Grave are added together, the total number of vessels seems more stable. Because of the weekly data, the dips during the winter holiday and the assumed summer holiday are more clear in the value line. The seasonality also clearly shows these two. The trend line also show the decrease in number of vessels in the last two years of the data. The dip in the summer of 2022 will be addressed later.

Temporal Patterns of Lock Usage

To explore variations in vessel counts over different time periods, Figure 3.14 visualizes how these counts are distributed across months, weeks, and hours of the day. the daily averages are used per month to take away the fluctuations because of the different number of days in months. This analysis provides insight into the seasonal, weekly, and daily demand for the locks. It is expected that the traffic counts in the middle of the year are higher compared to the ends of the years, based on figure 3.8. For the weekly data, a dip in the weekend is expected, as people tend to work during workdays, and less in the weekend. For the daily distribution, it is expected that the there is a sharp rise in the morning and a sharp decline in the evening.

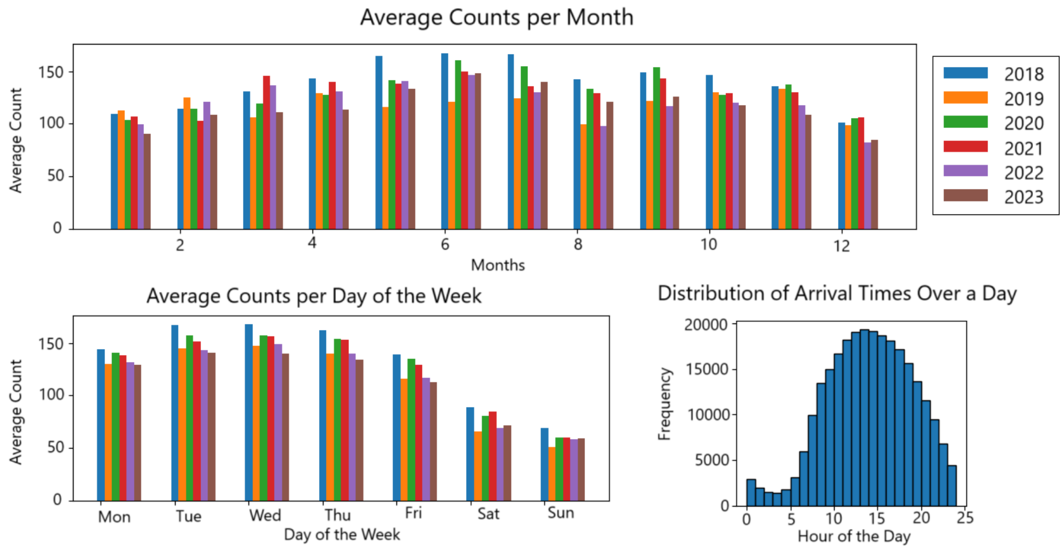

Figure 3.10: Temporal distributions of the vessel counts for the Weurt-Grave system, the averages counts are average daily counts

Midyear vessel counts appear higher, but a distinct dip in August likely reflects the summer holiday. for the distribution over the week the lower weekend counts are as expected lower. However, the Monday and Friday seem to be lower compared to Tuesday, Wednesday, and Thursday. This could be caused by vessels that have a trip over multiple days. For example, if a vessel leaves on a Monday and arrives on Tuesday. Depending on direction, half the time it passes the lock on Monday and the other half on Tuesday. Reducing the total values on Monday. Although, it might also because by people liking to add their free days against the weekend. The daily distribution is as expected, with a peak during the day and a dip at night.

To better understand the variations in vessel counts at Weurt, the data is isolated and visualized in Figure 3.11. It is expected that here the dry parts of 2018 and 2022 will result in lower counts and that in August 2022 the count is zero as seen earlier.

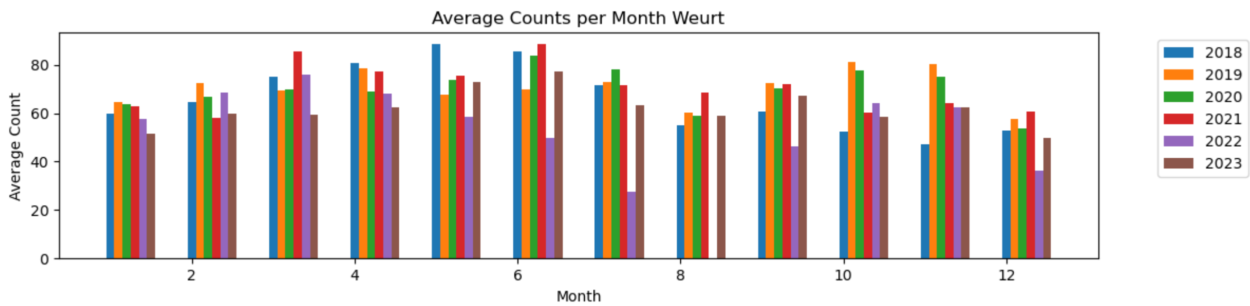

Figure 3.11: Average daily vessels at Weurt for each month from 2018 to 2023

The figures show that during the dry perios there are fewer vessels using Weurt. zero usage in August 2022 is also visible here.

Disruption at Weurt

Figures 3.12 and 3.13 show the beginning and the end of a streak where the lock at Weurt is not used. A news report, posted on the website of Rijkswaterstaat, states that: "The entire lock at Weurt is closed to shipping starting Thursday, July 21, 2022. We are closing the east chamber at 8:00 AM due to the low water level. The west chamber has been closed for a longer period for repair work." (Rijkswaterstaat, 2022). The report metnions that the duration of the closure is not yet know at the time, but the data shows that it reopened 1 September 2022. The small usage at the Saterday after the closure is explained by an event happening in Nijmegen, the "vierdaagse". For that event, the lock was shortly open for recreational ships.

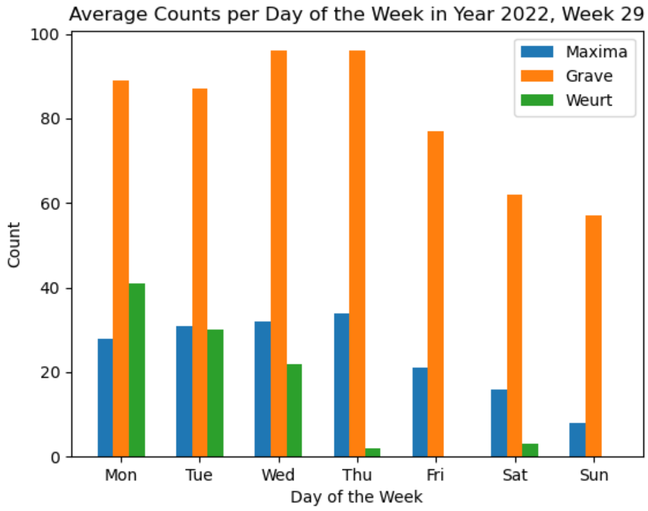

Figure 3.12: Daily counts of week 29 in year 2022 for Weurt, Grave and Maximakanaal

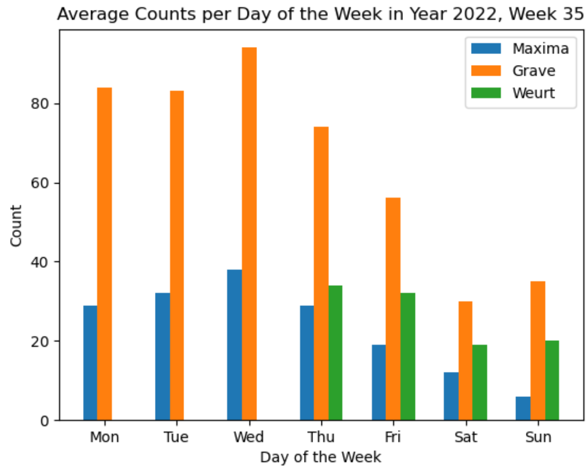

Figure 3.13: Daily counts of week 35 in year 2022 for Weurt, Grave and Maximakanaal

Because this happened during a dry period, the figures also show the that vessels counts at Grave before the closure are higher and Weurt and also when Weurt reopens.

Transported Load Trends

Since the weight of the load was also in the IVS data, this can also be plotted over time. This is done in figure 3.14. The load for each year is plotted monthly together with the load weight at each measurement location.

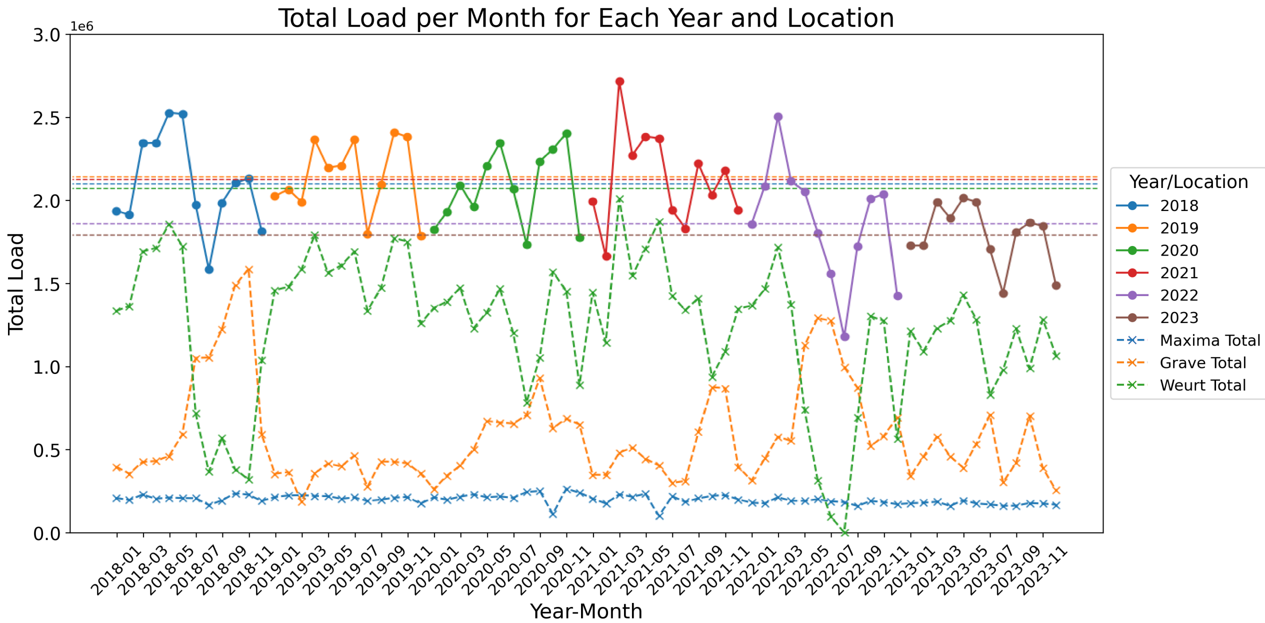

Figure 3.14: Load patterns over time for Weurt, Grave and Maximakanaal. With total load and total yearly load.

The graph shows that the expected decrease in transport volume in 2022 is likely also caused by the closure of lock Weurt. During the closure, the total load decreases sharply. The graph also clearly shows the correlation between Weurt and Grave. When Weurt is low, Grave is high. and in reverse. And since this mainly occurs in the second part of the year, when the water levels are lower, it can be concluded that when the water levels decrease a part of the transport volume switches from Weurt to Grave. Another important observation from this graph is that that correlation is not there for the Maximakanaal. This means that the amount of rerouting that might occur over the Maximakanaal in times of low water levels is neglectable.

A time series analysis is done to more clearly show the seasonal effects of the vessel loads in the Weurt-Grave system. The results are shown in figure 3.15. Since the Maximakanaal does not seem to be directly part of the Weurt-Grave system. The time series analysis is done for the total load of Weurt and Grave added togheter.

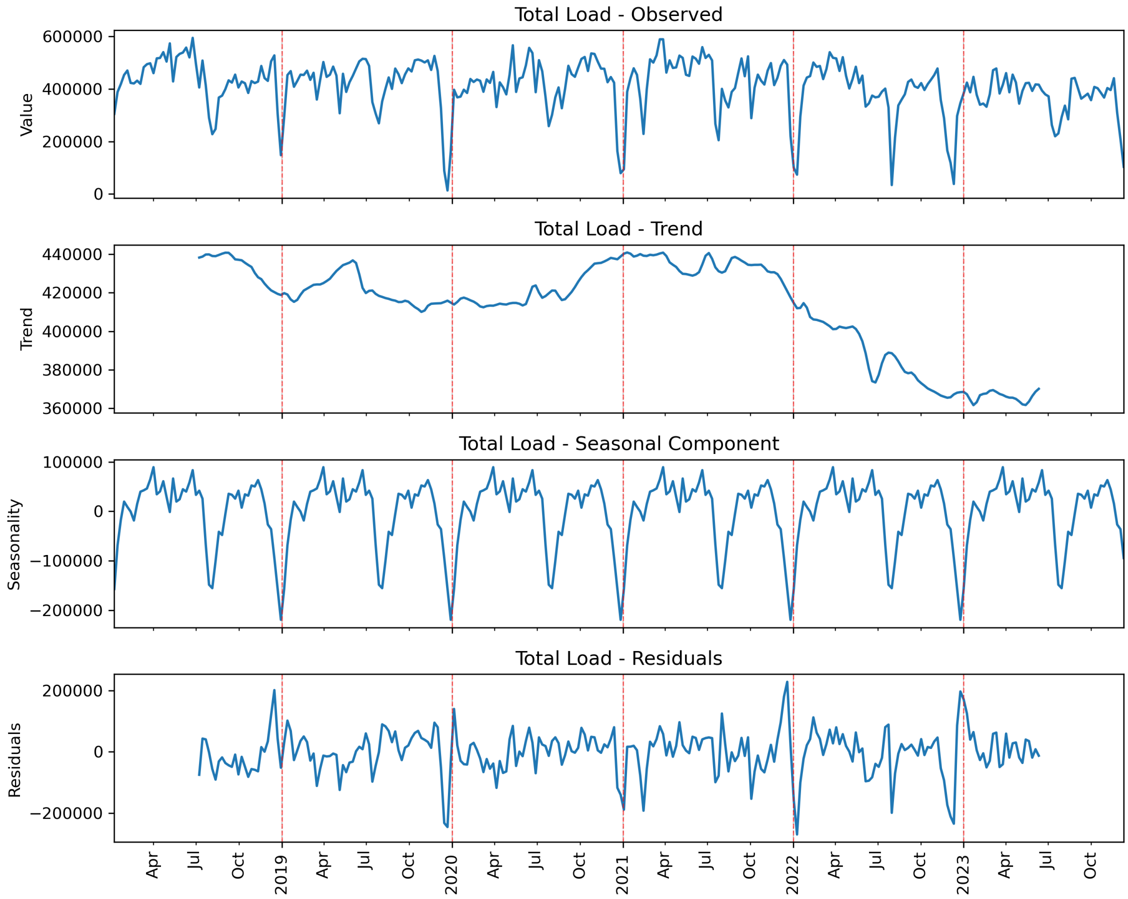

Figure 3.15: A time series analysis of the vessel loads in the Weurt-Grave system using the seasonal_decompose from statsmodels.tsa.seasonal, it uses a additive function: $Y_t = T_t + S_t + R_t$

Similar to the vessel counts, due to the weekly data the dips during the winter holiday and the assumed summer holiday are more clear in the value line. The seasonality also clearly shows these two. The trend line also show the decrease in load in the last two years of the data. The dip in the summer of 2022 was caused by a long disruption at Weurt.

3.4. Lock Passage Times

Since lock usage differs between dry periods and normal water levels, it is important to analyze lock performance under these conditions.

In figures 3.16 and 3.17 the distributions of the passage times are shown. The passage time is the time from arriving at the lock to leaving the chamber. The distribution at Weurt (top) and the distribution at Grave (bottom). The distribution for water levels lower than 520 cm in the Waal are depicted in left, and the ones higher than 520 cm are right. Next to the histograms is a IQR plot to better visualize the spread. It is expected that there is a large different between the low water periods for the lock at Grave.

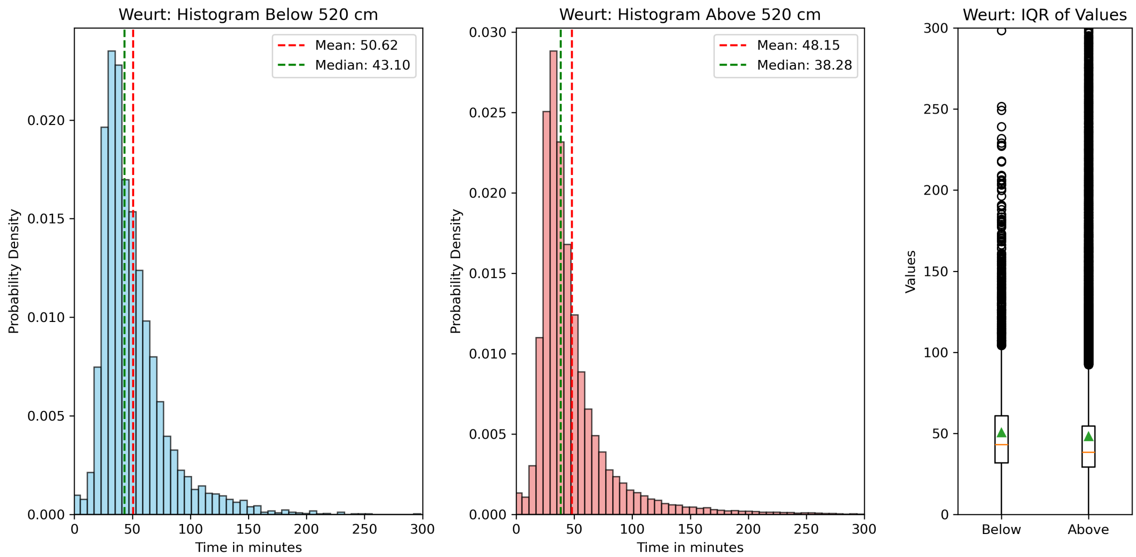

Figure 3.16: Histogram of Weurt + IQR lock passage with water levels below and above 520 cm

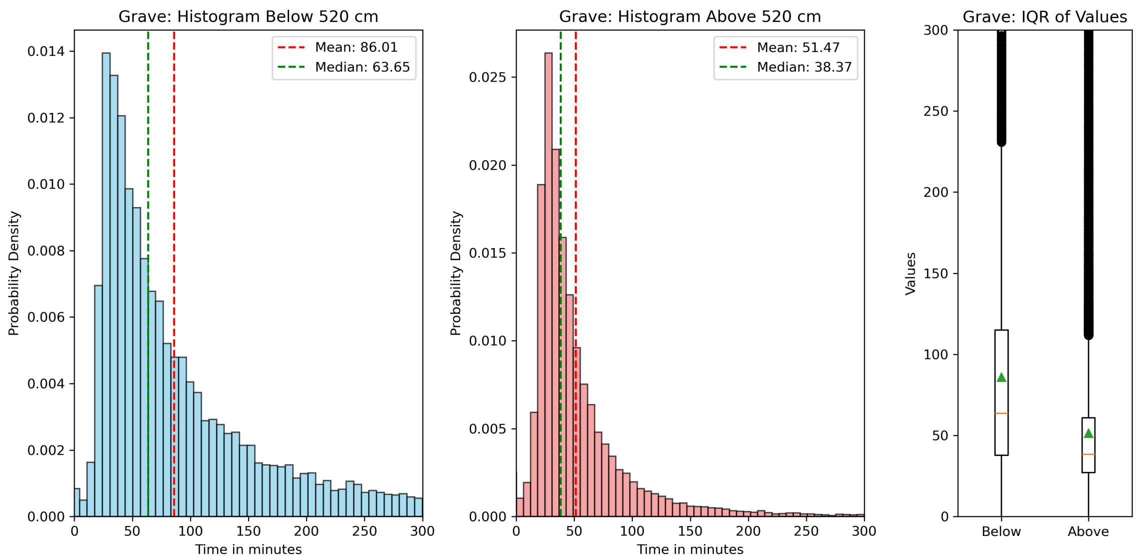

Figure 3.17: Histogram of Grave + IQR lock passage with water levels below and above 520 cm

As expected, there are large changers in the distribution of Grave. However, there are also some changes at Weurt. The distribution at Weurt seems to be shifted to the right at the low water levels. It is only a small change, too small to visually conclude that there is a difference between the two. There for two statistical tests will be performed.Since the distribution are not normal, the two test will be: The Mann-Whitney U test and the Kolmogorov-Smirnov test. The results are in Table 3.2.

The Mann-Whitney U test results suggest that the there is a significant difference for the Weurt and Grave distribution. The Kolmogorov-Smirnov (KS) test suggest the same. Since the KS test calculates the maximum difference between the cumulative distribution functions of the two datasets, the values of

Table 3.2: Statistical Test Results for Weurt and Grave

Location	Test	Statistic	p-value
Weurt	Mann-Whitney U Test	298751787.5	5.65×10^{-50}
Weurt	Kolmogorov-Smirnov Test	0.1020	1.13×10^{-48}
Grave	Mann-Whitney U Test	172954968.0	0.0
Grave	Kolmogorov-Smirnov Test	0.2742	0.0

Weurt and Grave can be compared. For Weurt this is a 10,02% and for Grave this is 27.42%. Meaning, the difference for Grave is greater, which matches the visual inspection of the histogram.

3.5. Origin-Destination Matrix

As most vessels have known origin and destination locations, an Origin-Destination matrix (OD-matrix) can be constructed using data from Weurt and Grave. For the Weurt-Grave system four entrance regions are used (Maastricht, Rotterdam, Amsterdam, Germany). Each vessel's origin and destination is put in one of those four regions. Details of the methodology are provided in Appendix B. In figure 3.18 the resulting OD-Matrix is given.

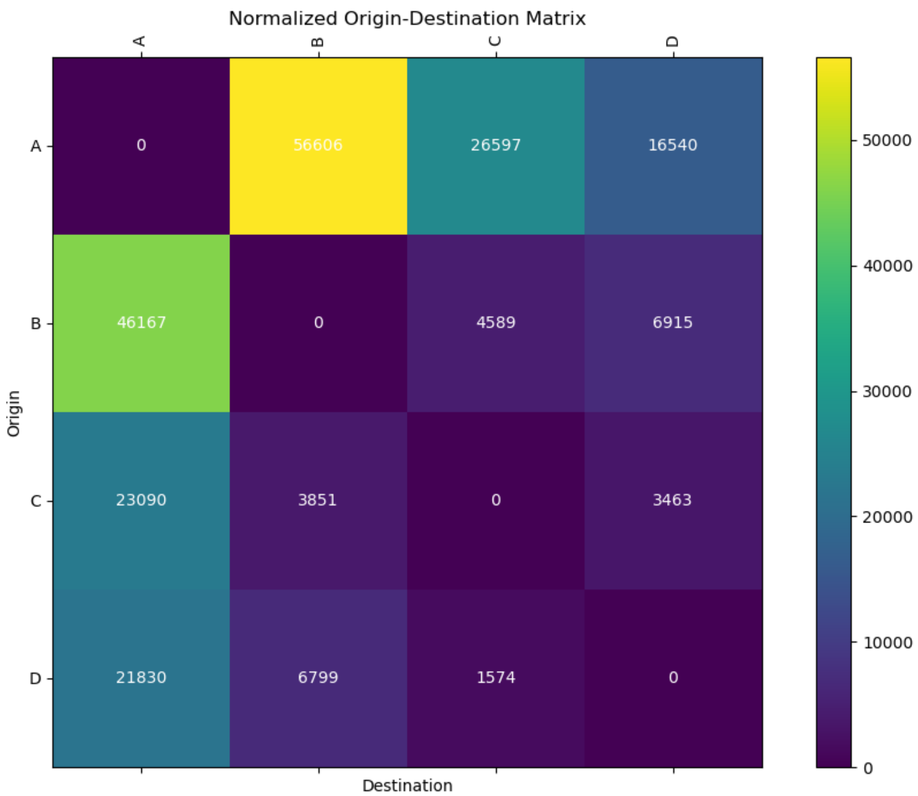

Figure 3.18: OD-Matrix for the Weurt Grave system for 2018 to 2022
The OD-matrix categorizes vessel traffic into four main directions, denoted by the following labels:
A: Direction of Maastricht,
B: Direction of Rotterdam,
C: Direction of Amsterdam,
D: Direction of Germany

As anticipated, most vessels travel to or from Maastricht, given Weurt and Grave's role in connecting the Southeast corridor to the Dutch waterway network. The pairing that do not contain A are possible. For example, if a vessel from Germany as a destination downstream from Grave it could take both locks. Vessels with the same origin and destination were redistributed across other pairing. A notable discrepancy is that the numbers are not mirrored, potentially due to data inaccuracies or non-returning trips.

3.5.1. Low water pattern

To evaluate the impact of low water levels on lock usage, IVS data was combined with water level measurements. To evaluate the vessel draughts of the vessels using Weurt under different water levels scenarios. Since the lock that is used depends on the origin destination pair, it is done for each direction. The traffic coming and going to Rotterman, Amsterdam, and Germany. It is expected that lower water levels in the Waal will force vessels with a larger draught to take Grave. In figure 3.19 this is plotted. The y-axis (depth groups) are the vessel draughts. The x-axis are the water levels in the Waal at Weurt. The colour shows what percentage of the vessels in that group chose what lock. Weurt for the top three plots, and Grave for the bottom Three plots. The data for this plot is limited to 2018 because during the dry period in 2022 there was a long lock closure at Weurt.

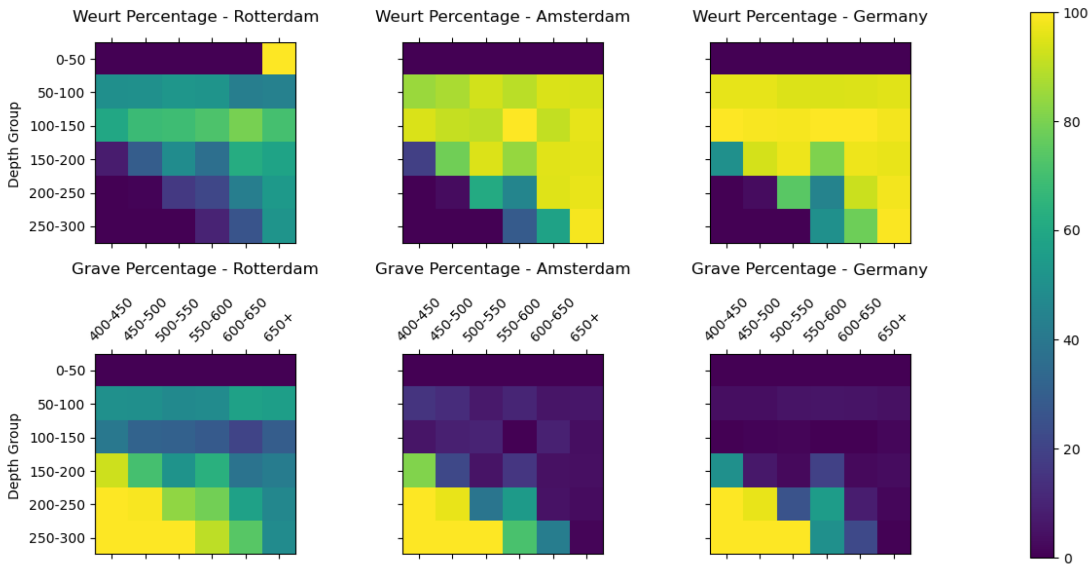

Figure 3.19: Weurt and Grave percentages under different low water conditions for different vessel draughts

As expected, vessels with low draughts are compelled to use the Grave lock. It also shows that under normal conditions, vessels traversing to and from Rotterman are the main users of Grave.

This demonstrates that varying water levels in the Waal influence the distribution of vessels draughts between the locks. Proving that low water levels in the Waal results in demand shift between the locks. This happens gradually. Proving the assumption that first the larger vessels change from Weurt to Grave and as water levels lower further the vessels with smaller draughts follow.

3.6. Conclusion

This chapter analysed how low water levels affect the Weurt-Grave system. It addressed the following sub-research question: **What changes occur in the demand at alternative locks when the capacity of one lock is reduced?** When the Weurt lock capacity is reduced by the water level in the Waal it causes changes in fleet composition, transport patterns, lock performance, and the OD-matrix. Below is a summary of the key findings:

- **Water Level Analysis:** The water level in the Waal changes during the year based on seasonal fluctuations in the Rhine discharge. The time series analysis confirms the seasonality in the Waal water levels between 2018 and 2023. with higher water levels at the beginning of the year and lower levels towards the end.

- **Vessel Data Analysis:** The fleet composition analysis showed that during, normal water levels in the Waal, the lock at Weurt has a larger share of vessels from a higher CEMT-class. During 2018 and 2023, coinciding with the low water levels, there is a sharp increase in vessels using Grave. During these times (second halve of 2018), the share of large vessels decrease at Weurt while they increase at Grave, indicating a redistribution rather than a reduction. For the combined Weurt-Grave system, the overall share of larger vessels remains stable.
- **Transport Patterns:** The transport pattern analysis revealed that during periods of very low water levels in the Waal, most of the load typically transported via Weurt shifts to Grave. Additionally, the analysis confirms that the total number of vessels in the system remains stable. A time series analysis further showed no significant dip in vessel traffic during the second half of the year.
- **Lock Performance Analysis:** The lock performance analysis highlights differences in passage times between normal and low water levels in the Waal. At Grave, low water levels result in a positive skew in the passage time distribution, an indication of longer delays. At Weurt the changes are minimal but also significant.
- **Spatial Transport Analysis:** The Origin-Destination (OD) matrix shows that the locks are mainly used for the Southeast corridor, most have the Maastricht either as their origin or destination. Splitting up the OD-matrix by water level and vessel draught show that vessels with larger draughts gradually shift to Weurt when the water levels in the Waal decrease.

In summary, a reduction of capacity at one lock (Weurt caused by low water levels in the Waal) causes a redistribution of vessels and load from that lock to another lock (Grave). What vessels change their route depends on their vessel draught. When this happens, there are increased delays at Grave.

4 Impact of Variables on Lock Utilization

This chapter addresses the sub-research question: **To what extent do low water levels in the Waal impact the Weurt-Grave system?** Using historical data it will be analysed how the water levels in the Waal affect the system. The analysis examines how low water conditions lead to shifts in vessel types at Grave, as previously assumed, and explores the possibility of a secondary effect where smaller vessels adjust their behaviour in response to these changes. Factors, including vessel characteristics (e.g., CEMT class), waiting times, and water levels, are analysed through logit regression.

First, the effects that the water levels have will be visually shown in plots. To show how the different variables interact with water levels and highlight points of interest. Then logit regressions will be used to statistically show the interactions of the variables with each other and low water levels. This will show the effect of low water levels and make this effect robust with the use of logit regression.

4.1. Extra Data Cleaning

The data used for this thesis consist of a large data set of vessels passing the locks at Weurt and Grave. For each vessel, multiple data points are collected. This is the same data from that was used in the previous chapter. However, in this chapter the dimensions of the vessels are also used. For some vessels, the passing at the locks is recorded with missing data points. Missing data points are marked as NaN (Not a Number) in the dataset.

There are also data points where the values are very unlikely. To remove these values, plausible ranges are defined based on the operational characteristics of the locks. Since these vessels did pass the locks. For the maximum length and width of the vessels the maximum size that can use lock Weurt is used. And the minimum are taken from the smallest possible vessel in the smallest vessel class.

For the load, the maximum value is constructed to be:

$$\text{Lading}_{\text{max}} = \frac{\text{Length (m)} \times 100 \times \text{Width (cm)} \times 100 \times \text{Draught (cm)}}{1000}$$

This function is used to calculate the mathematical maximum load a vessel of its size can have. Vessels with a load above this value are sure to have an incorrect stated load or incorrect stated sizes. These are removed from the dataset. In table 4.1 these ranges are stated.

Data column	Range maximum	Range minimum
Vessel Length	5 m	255m
Vessel Width	200 cm	1600 cm
Vessel Draught	30 cm	500 cm
Vessel Load	0	maximum possible volume

Table 4.1: Data Ranges

With these ranges for certain column, the data can be filtered. In table 4.2 the number of data points that are filtered out based on either NaN values or the range.

Data column	Number of NaN	Number outside range
CEMT Class	33,522	-
Vessel Length	23,047	5
Vessel Width	23,047	73
Vessel Draught	23,322	561
Vessel Origin	23,047	-
Vessel Destination	23,047	-
Vessel Load	94,761	299

Table 4.2: Table containing the missing data and probable false data

Rows with a NaN value in Vessel Length, Width, Origin and Destination, have a NaN value in every column. So not much besides the time that they passed the lock can be said about these vessels. In Appendix A these rows are analysed to see if values could be appointed to these rows. It is found that these vessels might correspond to lockage for recreational vessels. However, this cannot be proven, therefore these data rows are removed from the dataset. When these are removed this creates the left over NaNs that are shown in table 4.3. In this table the overlap is also shown.

	CEMT Class	**Vessel Draught**	**Vessel Load**
CEMT Class	10,475	42	9,089
Vessel Draught	42	275	258
Vessel Load	9,089	258	71,714

Table 4.3: Matrix of overlapping NaN values for vessel CEMT-class, draught and load

There are 10,475 NaN values in the CEMT-class column, of these, 9,089 rows also have NaN values in the load column, indicating a strong overlap with missing load data. This suggests that these rows likely represent vessels with incomplete or unreliable data, making them unsuitable for inclusion in this study.

The number of load NaN values is considerably higher than the other data columns. The raw data has 218,201 rows. with all the NaN load values deleted, it is reduced to 121,457. If the NaN values for load are kept, it is 183,628. So when all the vessels with NaN values are filtered out of the dataset, 44.3% is removed. If the NaN values for load can stay this is reduced to 15.8%.

4.1.1. Load NaNs

To decide if the NaN values in the load column need to be removed or not, the set of vessels with Load NaN values will be examined on two points. The distribution of the vessel classes and the draught. The vessel to find out if the distribution of the vessel types are similar. If they are, it could be that the NaN values are random and the data set with 44.3% might still be relevant. And the draught to examine if it can be assumed that vessels state NaN load if they have no load.

In appendix A the differences between the data rows with NaN values is compared with those with zero load. The appendix concludes that the data with NaN values for the load can be assumed to be zero load. With this information, only 15.8% of the data can be filtered out instead of 44.3%.

4.2. Patterns for Low Water Level Behaviour

The previous chapter concluded that there was a clear difference in lock usage under different water levels in the Waal. In figure 4.1 each day in the 6-year data timespan is plotted as a dot. Its position depends on how many vessels that day took Grave and Weurt. The colour depends on the water level in the Waal. Lower than 600 cm and the dot is red and higher and the dot is blue. In the right plot this is done for the loads that day.

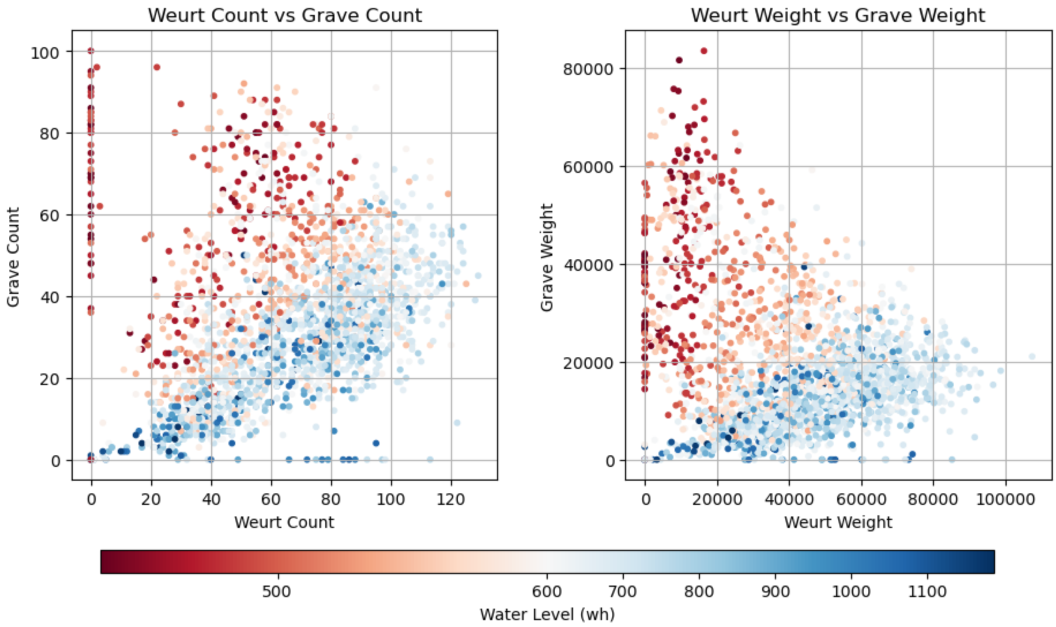

Figure 4.1: scatter plot of daily lock usage counts and load, with colour indication of water level at Waal

There seems to be a pattern in where the blue dots are located and where the red dots are located. Especially for the load plot. During low water periods, days are more likely to have higher Grave counts, and a higher amount of load is passed through Grave.

However, it is important to note that most of the time the water levels in the Waal are high enough to accommodate the larger vessels at lock Weurt. This can be seen in figure 4.2. This figure is a heatmap of the same data as in figure 4.1.

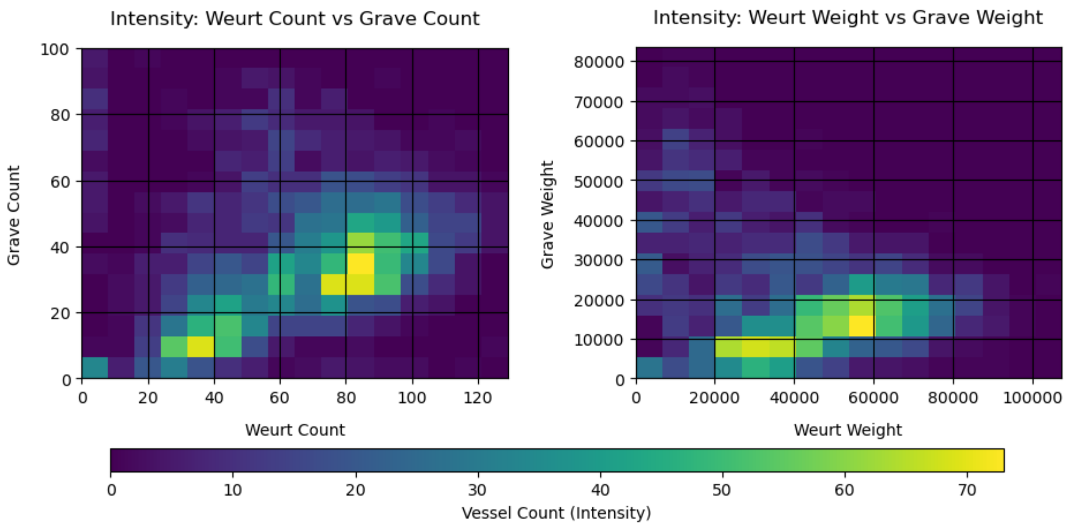

Figure 4.2: Heatmap depicting where the most point occur for the dots in figure 4.1

The heatmap shows that were the red dots are more prevalent in the scatter plot (figure 4.1) correspond to a smaller set of the data compared to the blue dots.

4.2.1. Low Water Level Effects for Vessel Dimensions

To visually show the continuous effect the water levels has on the lock usage, a moving average plot will be used. It will plot the percentage of vessels using Grave and to the right of it the load percentage using Grave. The moving average will be for 25 cm lower and 25 cm higher than the water level on the x-axis. This is done for all vessels, vessels with a draught of 0-200 and vessels with a draught of higher than 200. These two groups are chosen because these are around the same size. Also, the number of vessels within the 25cm bound are plotted under the name window size. This is shown in figure 4.3.

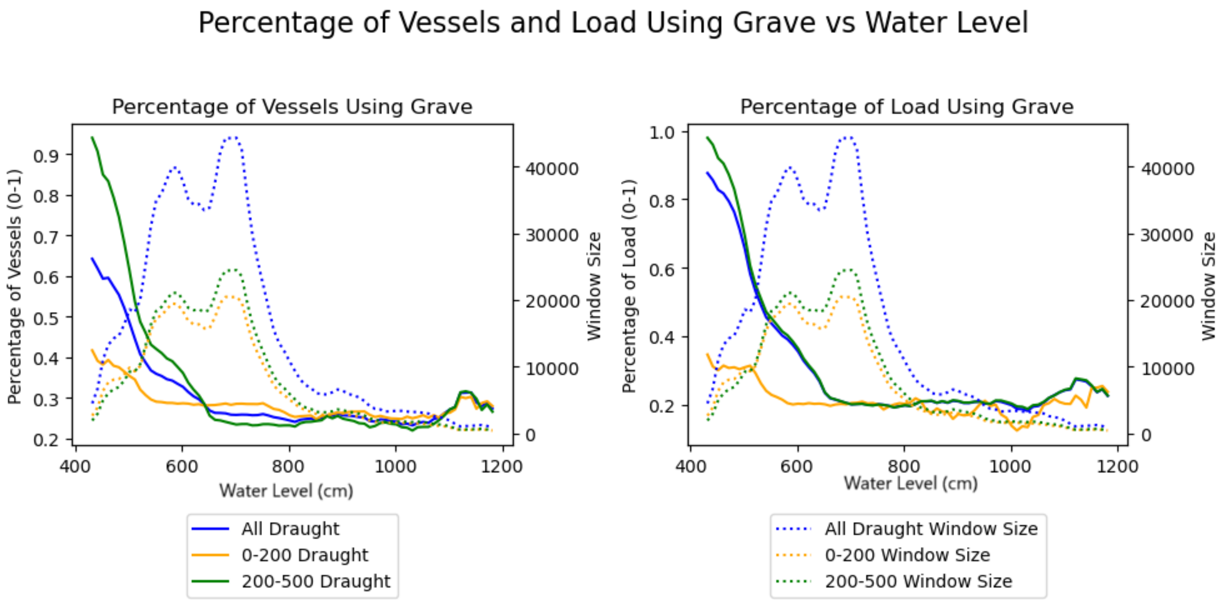

Figure 4.3: Moving average plot with -25 cm and + 25 cm bound for lock choice percentage and load usage percentage for Grave, for different vessel draughts

The figure indicates that vessels with draughts below 200 cm show an increased preference for Grave over Weurt during low water levels. However, this effect is nowhere near the change for vessels that sail with a larger draught (+200 cm). Those go from under 30 percent to above 80 percent.

In figure 4.4 the same is done. Except here it is the lines are shown for the different CEMT-Classes instead of draught.

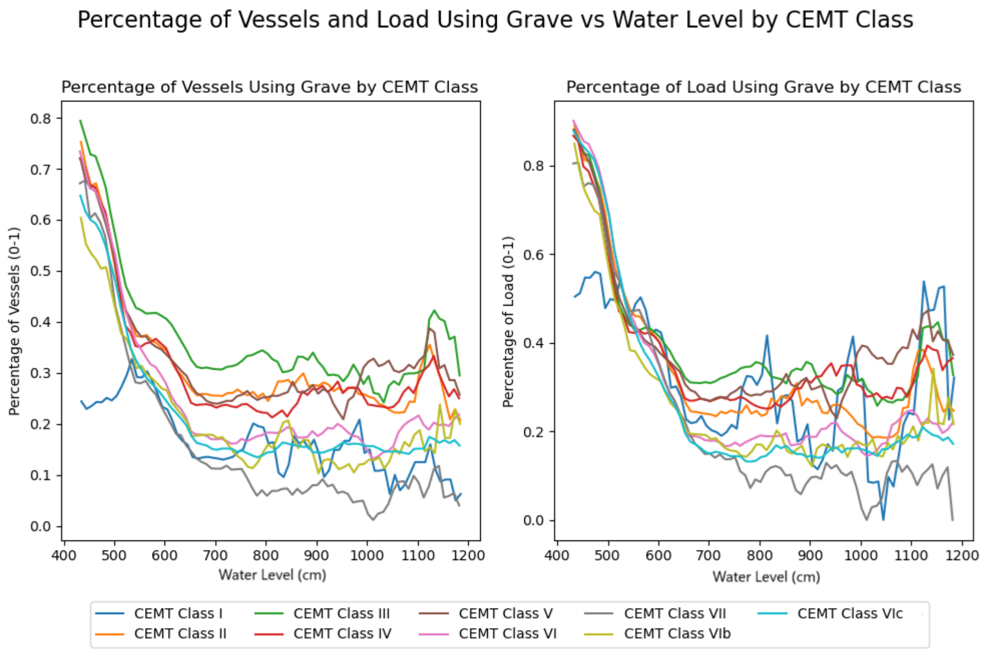

Figure 4.4: Moving average plot with -25 cm and + 25 cm bound for lock choice percentage and load usage percentage for Grave, for different CEMT-Classes

It can be seen that for all CEMT classes the percentage choosing Grave increases for under low water conditions in the Waal. It also shows that this change seems to happen gradually from 650 onwards. Even taking the smoothing of the moving average into account. Figures 4.3 and 4.4 reveal something interesting. At the lowest water levels the amount of 200+ cm Draught vessels taking Weurt nears zero percent. However, at the same water level the percentage of the larger CEMT classes stays below 80 percent. This also occurs at the load plot to a lesser exent. This means that unloaded vessels or less loaded vessels of the larger CEMT Classes stil use Weurt. Also, for the CEMT Class I there seems to be a reverse effect compared to the other classes at the lowest water levels. This might indicate that under those conditions the secondary effect occurs (vessels switch from Grave to Weurt because of the congestion at Grave).

Since the percentage gives less insight in the total numbers. The same style of moving average plots is done however instead of percentage now the average vessel count per day is given. This is shown in figure 4.5. Also, an additional plot is added for the average load per vessel. This will indicate if vessels are using Weurt more unloaded. It is expected for all plots, that at low water levels the usages and average weight goes up for Grave and down for Weurt.

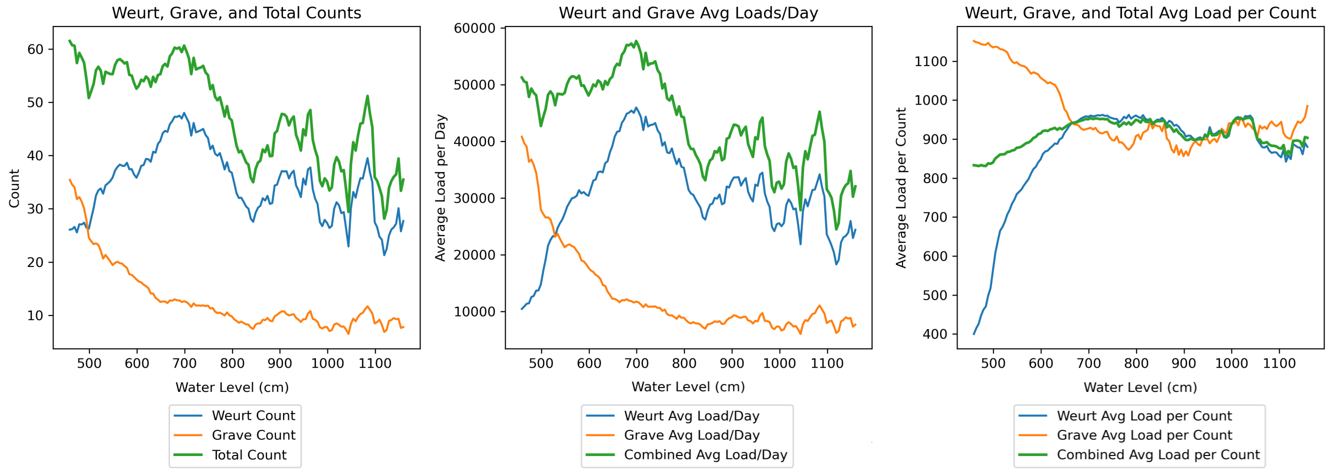

Figure 4.5: Moving average plots for daily counts, average load per day, and average load per vessel. For Grave, Weurt and total (Grave + Weurt)

The figure shows that when the lines go down for Weurt it goes up for Grave at low water levels. And also it shows that the total number of vessels does not change under low water level. However, the average load moved per day does seem to decrease. The third plot also seems to prove the assumption that for low water levels, vessels using Weurt are mostly unloaded or less loaded. This also explains that, for Weurt, the loads drop by three quarters compared to its peak, while the number of vessels only half. It also shows that for higher water levels the load and the usage seem to lower. This is most likely because the water levels are the highest in the winter months, that is when the number of vessels are lower compared to the other months.

4.2.2. Low water level effects on different OD-pairs

To better understand the impact of water levels on different OD-pairs, the previous plot was remade with data split by OD-pair.

OD-pair A-B represents traffic to and from Rotterdam, where the percentage of vessels using Grave is the highest due to it being the shortest route for most vessels.

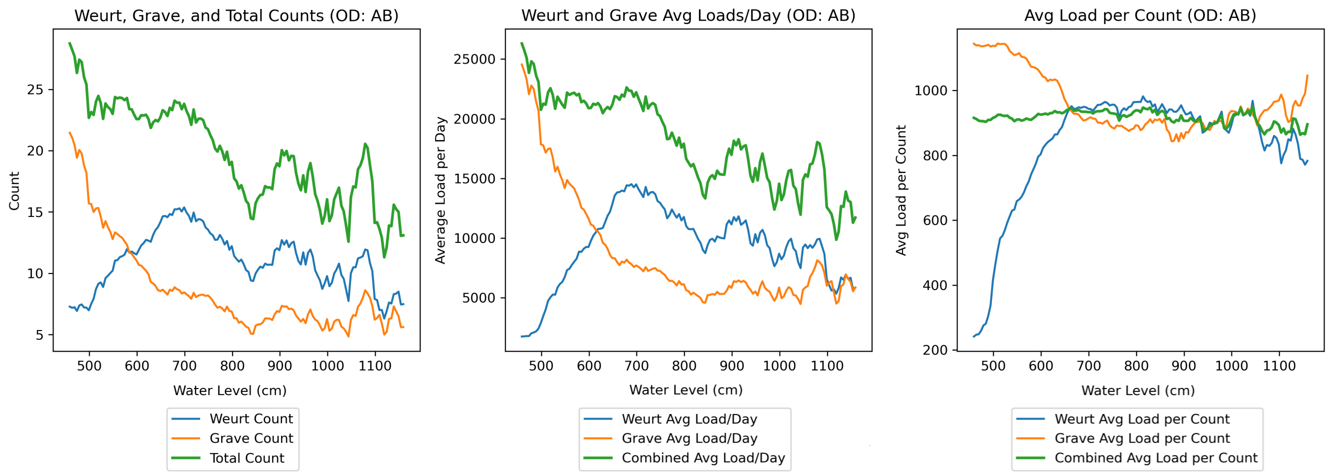

Figure 4.6: Moving average plots for daily counts, average load per day, and average load per vessel. For Grave, Weurt and total (Grave + Weurt). For OD-pair AB: Maastricht-Rotterdam

The results of the plots for the Rotterdam data is as expected. However, notable is that the for this OD-pair unlike the total data the average load per day seems to stay the same with a peak at the lowest water levels.

For the vessels from and to the direction of Amsterdam the results are shown in figure 4.7. It is expected that here there is a large shift to Grave. Since for this direction, Grave can be used as a reroute without too much extra travel time.

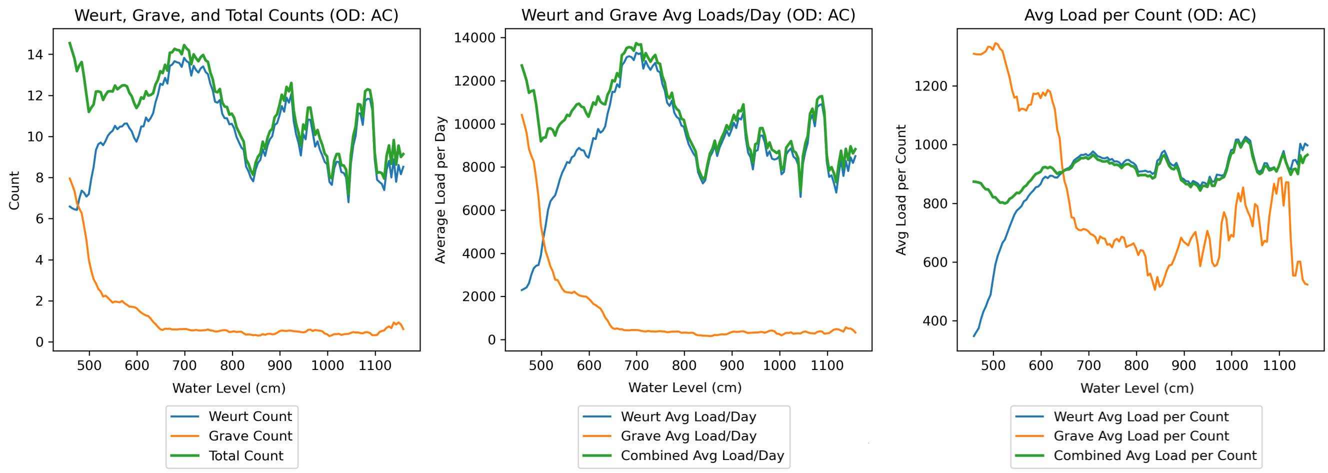

Figure 4.7: Moving average plots for daily counts, average load per day, and average load per vessel. For Grave, Weurt and total (Grave + Weurt). For OD-pair AC: Maastricht-Amsterdam

The figure shows something interesting. The increased usage of Grave seems to go in two steps. First at 650 cm and then at 530 cm. This might be because for the vessels in the first step, the rerouteing cost are not too large and therefore change their route, so that they don't have to reduce the load (see the up tick in the average load per vessel plot). For the second step, most vessels are no longer able to use Weurt, and therefore they switch to grave.

For the vessels going towards Germany, the results are shown in figure 4.8. For this direction, rerouteing at low water levels is likely unfeasible. Since these vessels will sail upstream on the Waal where the low water levels are also limiting the vessels that could traverse it. Therefore, it is expected that the number of vessels taking this route will reduce.

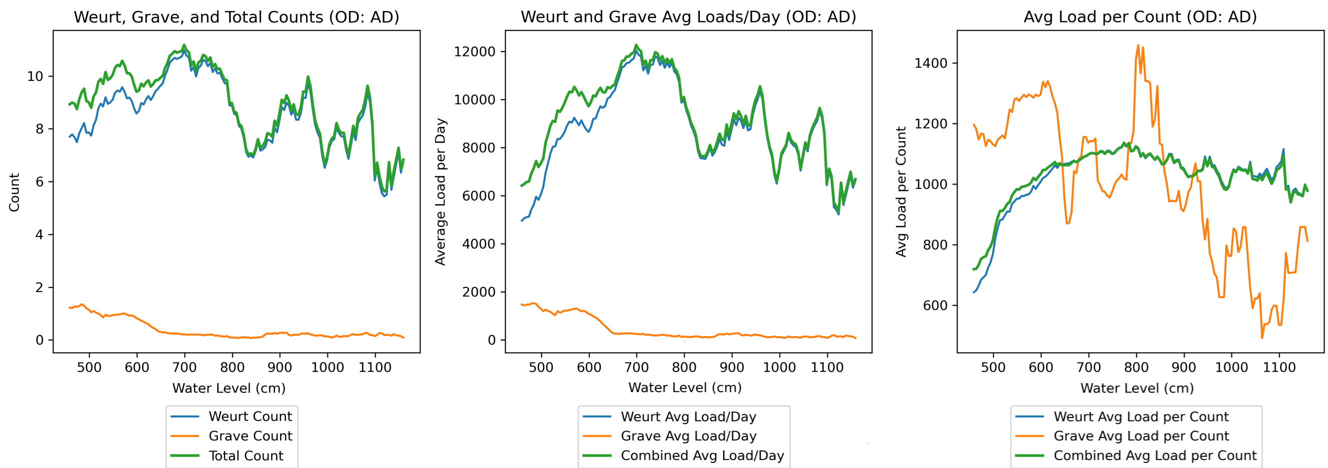

Figure 4.8: Moving average plots for daily counts, average load per day, and average load per vessel. For Grave, Weurt and total (Grave + Weurt). For OD-pair AD: Maastricht-Germany

The number of vessels that switch to Grave on this route is negligible. And the lower water levels limit the amount of load. However, the number of vessels per day does not decrease much. Meaning, these vessels take on less load than on normal water heights.

Analysing these figures together, it seems that the reduction in load to Germany at very low water levels (-530 cm) is compensated by an up tick for Rotterdam and Amsterdam at those levels. Figure 4.9 plots the totals for each OD-pair in one figure.

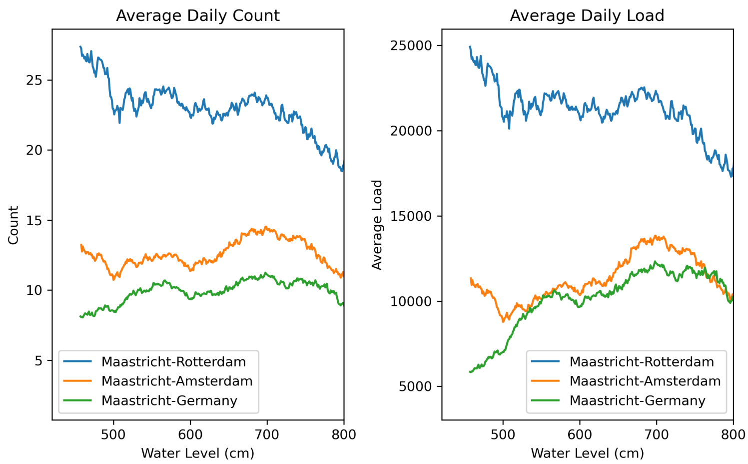

Figure 4.9: Moving average plots for daily counts, average load per day for the total of the locks Weurt and Grave

The figure shows that the decrease for the Maastricht-Germany pair at very low water levels coincides with an up tick in the loads for Rotterdam and Amsterdam.

4.3. Effect Water Level on Function Lock

Several factors can influence lock functioning, one of which is water level. Significant differences in water levels on either side of a lock can extend operating times, particularly during extreme low or high water levels. In the figures 4.10 and 4.11 the maximum number of vessels per week is plotted against the water level in the Waal. The median and mean are plotted together with the distribution of the maximum values. This is done to indicate if there is a relation between water level and operating times. This, however, assumes that once per week for an hour the cacity is reached. this is not true looking at the lowest maximum weekly values. However, with enough data point, it is assumed that the maximum weekly values reflect the highest observed operational throughput for larger window sizes.

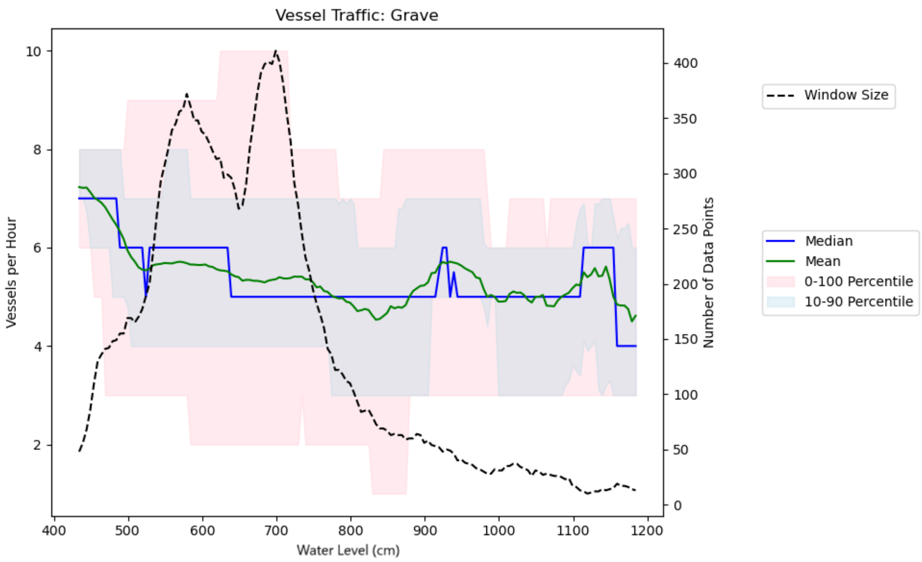

Figure 4.10: Weekly maximum vessels per hour for lock Grave over water level in the Waal

For Grave, it is notable that at lower water levels, the average maximum vessels per hour increases. This is most likely due to the higher demand, at lower water levels the maximum vessel per hours is more likely to be reached. This also explains the narrowing of the percentiles. Overall, the maximum vessels per hour stays relatively constant.

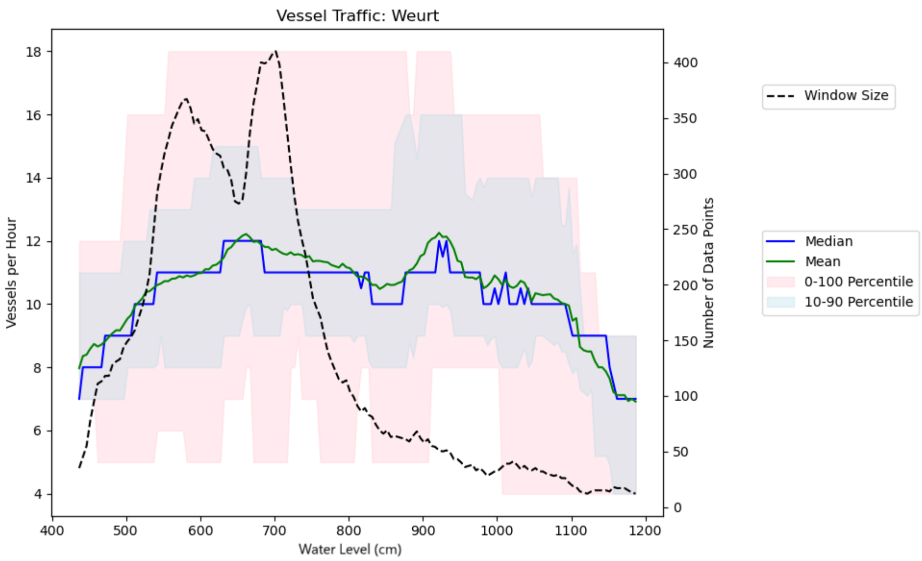

Figure 4.11: Weekly maximum vessels per hour for lock Weurt over water level in the Waal

At Weurt, a notable trend is observed: vessel throughput decreases at both low and high water levels. This could occur due to the increased locking times, but this is not significant because of the small window size there. At lower water levels, it does seem to decrease a lot. from a maximum of 18 to 12 vessels per hour. The cause could be the closing of the East chamber at lower water levels reducing the capacity of the lock. However, looking at how the mean values gradually decrease it is caused by fewer vessels being able to use Weurt, so there are fewer vessels at weurt. This shows that water levels affect both how the locks work and how vessels use them, making the relationship more complex.

To analyse what happens at the waiting times at the locks due to water level changes. The moving average of the waiting time is given. Together with the percentiles. This is shown in figure 4.12. For

Grave the Waiting times are expected to increase due to the increased demand. And at Weurt the waiting times are also expected to increase due to the closing of the East chamber.

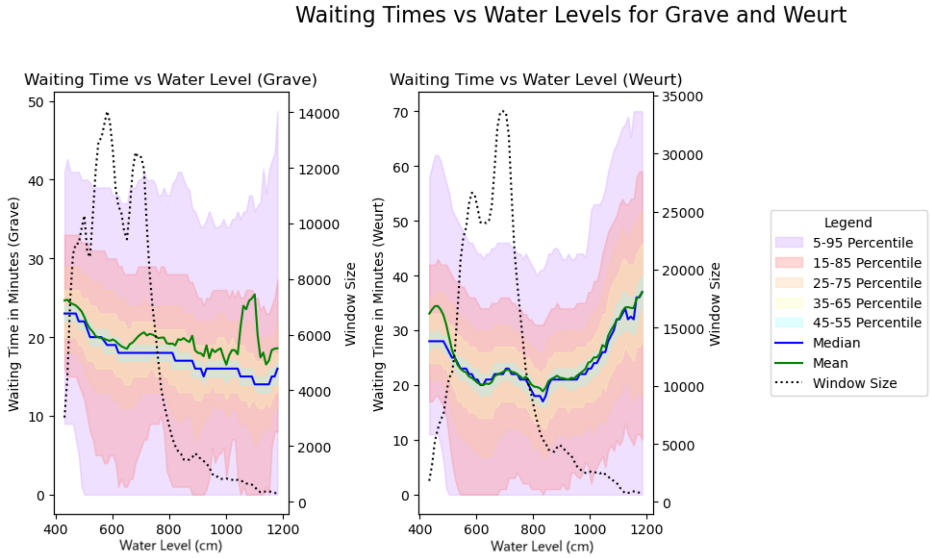

Figure 4.12: Moving average waiting times for Grave and Weurt in minutes, with percentiles

The increase in waiting time is there for Grave at lower water levels. The increase of the average is only around 3 minutes. But since the window size here is large, this is significant. Weurt also functions as expected for low water levels. However, for high water levels, it confirms that the locking takes longer at high water levels. This is most likely caused by the stepped locking at high water levels which takes place at Weurt, which makes the locking process take more time.

4.4. Statistical analysis

The effects of low water in the Waal are visually shown previously in this chapter. To further strengthen those results they will be statistically analysed. The data contains observed vessels that under differing situations and with differing characteristics chose either the lock at Weurt or Grave. This matches the use of a Discrete Choice model well. The model used will be a logit regression model (Juan, de Dios Ortúzar and Luis G. Willumsen, 2011). This method is often used to simulate choices in traffic models. It can be applied to this dataset to assess the effect each variable has on the route choice.

Since the changes in lock usage seem to appear around the water levels under 700 cm seem to appear, with another change in behaviour at 530 cm. Therefore, the statistical test will split the data in three water level groups: <530, 530 - 640, >640. for each of these groups, the following characteristics are tested on if they have a significant effect on the lock choice:

- Origin-Destination pairs
- Average waiting times
- CEMT class

To evaluate the different characteristics and their effect on the lock usage, multiple logit regressions will be used. Logit regression is a statistical method used to model the probability of a certain outcome based on one or more predictor variables. It is particularly suited for binary outcomes, such as a vessel choosing one lock over another lock.

A logit regression model estimates the probability P of a decision-maker selecting a particular alternative based on utility maximization. The probability of choosing alternative i follows the multinomial logit (MNL) formulation:

$$P(i) = \frac{e^{V_i}}{\sum_j e^{V_j}}$$

where:

- V_i is the systematic utility of alternative i.
- The denominator ensures that all choice probabilities sum to 1 by summing over all available alternatives j in the choice set.

For a binary logit model, where the choice is between two alternatives (e.g., choosing Weurt or Grave), the probability simplifies to:

$$P = \frac{1}{1 + e^{-(V_1 - V_0)}}$$

where:

- V_1 and V_0 are the systematic utilities of the two lock alternatives.
- The utility of each alternative is typically modeled as a linear function of explanatory variables:

  $$V = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k$$

  where $x_1, x_2, \ldots, x_k$ represent attributes such as *waiting time, water level, and CEMT class*.

The coefficients β indicate the impact of each variable on the **utility** of an alternative:

- A positive coefficient increases the probability of selecting that alternative.
- A negative coefficient decreases the probability of that alternative being chosen.

This will be done for multiple characteristics of vessels and the system to see what the impact is of them on the lock usage. Since it is binary, the lock usage for each vessel is set to 1 if it was Weurt and 0 if it was Grave. So negative coefficients increase the chance of Grave and positive increases the chance of Weurt.

To assess the fit of the model four performance metrics will be looked at:

- Log-Likelihood
  Fit of the full model to the observed data
- Null Log-Likelihood
  Fit of a null model (no predictors, intercept only)
- Pseudo R²
  Relative improvement of the full model over null model
- Likelihood Ratio Test (p-value)
  Significance of model improvement (p-value)

These metrics are calculated in the following way:

- **Log-Likelihood**: The measure of model fit for the full model. A higher (less negative) value indicates a better fit.

  $$\text{Log-Likelihood} = \sum_{i=1}^{n} \left[y_i \log(p_i) + (1 - y_i) \log(1 - p_i) \right]$$

- **Null Log-Likelihood**: The log-likelihood of a model with no predictors (intercept only). It serves as the baseline for comparison.

  $$\text{Null Log-Likelihood} = \sum_{i=1}^{n} \left[y_i \log(\bar{y}) + (1 - y_i) \log(1 - \bar{y}) \right]$$

- **Pseudo R^2 (McFadden's)**: Measures the proportional improvement in model fit over the null model.

$$R^2_{\text{McFadden}} = 1 - \frac{\text{Log-Likelihood}}{\text{Null Log-Likelihood}}$$

Interpretation: Low values are common in logit models. values > 0.2 indicate strong improvement.

- **Likelihood Ratio Test (p-value)**: Tests whether the full model significantly improves over the null model.

$$\text{LR Statistic} = -2\left(\text{LL}_{\text{null}} - \text{LL}_{\text{full}}\right)$$

Interpretation: A small p-value (e.g., $p < 0.05$) indicates that the predictors significantly improve the model.

4.4.1. Origin-Destination Pairs

First a logit regression is done to assess the impact the OD-pair has on the lock usage. The results are in table 4.5 and the model performance metrics are it table 4.4. It is expected that the OD-pair Maastricht-Rotterdam is the most Grave favoured and Maastricht-Germany the least.

Table 4.4: Summary of Logit Model Performance Metrics

Metric	Value
Log-Likelihood	-81,772
Null Log-Likelihood	-82,888
Pseudo R²	0.01346
Likelihood Ratio Test (p-value)	0.000

The model's **Log-Likelihood** shows an improvement over the **Null Log-Likelihood**, indicating that the predictors add explanatory power compared to an intercept-only model. The **Pseudo R²** value is low but typical for logit models, suggesting modest improvement over the null model. The **Likelihood Ratio Test** confirms that the model significantly improves fit over the null, validating the inclusion of the predictors despite the low Pseudo R². Overall, the model is statistically significant but explains a limited proportion of variation in the outcome.

Table 4.5: Logit Regression Results for Origin-Destination pairs

Variable	Coefficient	Std. Error	z-score	p-value
const (Maastricht-Rotterdam)	0.1860	0.008	21.955	<0.0001
Maastricht-Amsterdam	1.8686	0.020	93.454	<0.0001
Maastricht-Germany	2.7194	0.030	89.409	<0.0001

The results show that the OD-pair is significant and that Maastricht-Rotterdam is indeed the most Grave favoured, and Maastricht-Germany the least. The large coefficients for Maastricht-Amsterdam and Maastricht-Germany show that vessels on those OD-pairs use Weurt a lot more. In figure 4.13 the data for each OD-pair is shown and if the model will predict it correctly. Correct predictions are Weurt and incorrect are Grave due to all coefficients being positive.

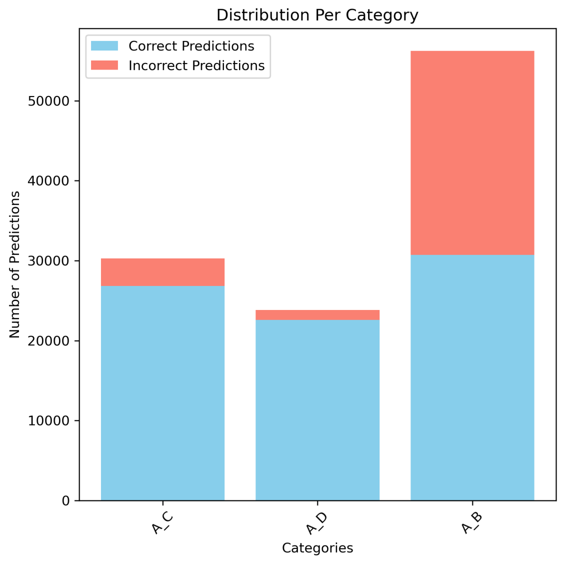

Figure 4.13: Distribution of correct and incorrect predictions per OD-pair (A_C = Maastricht-Amsterdam, A_D = Maastricht-Germany, A_B = Maastricht-Rotterdam)

The figure shows that only vessels coming or going towards Rotterdam have a large section of vessels using Grave. That is why the coefficient (0.1860) is close to zero. The other OD-pairs rarely have vessels using Grave, leading to high coefficients.

4.4.2. Waiting Time

the effect of the waiting times will be estimated with a logit regression. The expectation is that a high waiting time at Weurt will result in more vessels choosing Grave. A higher waiting time at Grave is expected to cause more vessels choosing Weurt. In table 4.7. The results of the logit regression are shown, and the model performance metrics are it table 4.6. To assess the waiting times, the most reliable data was the lockage duration, from arrival at the lock to exiting the chamber. In the table these are g_dur for the duration at Grave, and w_dur for the duration at Weurt.

Metric	Value
Log-Likelihood	-77,729
Null Log-Likelihood	-82,567
Pseudo R^2	0.05860
Likelihood Ratio Test (p-value)	0.000

Table 4.6: Summary of Logit Model Performance Metrics

The model's **Log-Likelihood** is substantially better than the **Null Log-Likelihood**, demonstrating that the predictors significantly enhance the model's explanatory power compared to an intercept-only model. The **Pseudo R^2** value is moderate, indicating a reasonable improvement over the null model and suggesting a stronger fit than typically observed in logit models. The **Likelihood Ratio Test** confirms the overall significance of the model, showing that the predictors are highly relevant in explaining the target variable. Overall, the model is statistically robust and provides a meaningful level of predictive accuracy for the data.

Table 4.7: Logit Regression Results for waiting times

Variable	Coefficient	Std. Error	z-score	p-value
`const`	0.4026	0.021	19.331	$<$0.0001
`g_dur`	0.0321	0.001	37.947	$<$0.0001
`w_dur`	-0.0081	0.001	-12.905	$<$0.0001

As expected, since a higher value means it has a positive effect on choosing Weurt, the waiting times affect the lock usage as expected. Figure 4.14 shows the logit regression curve with the moving average of the data.

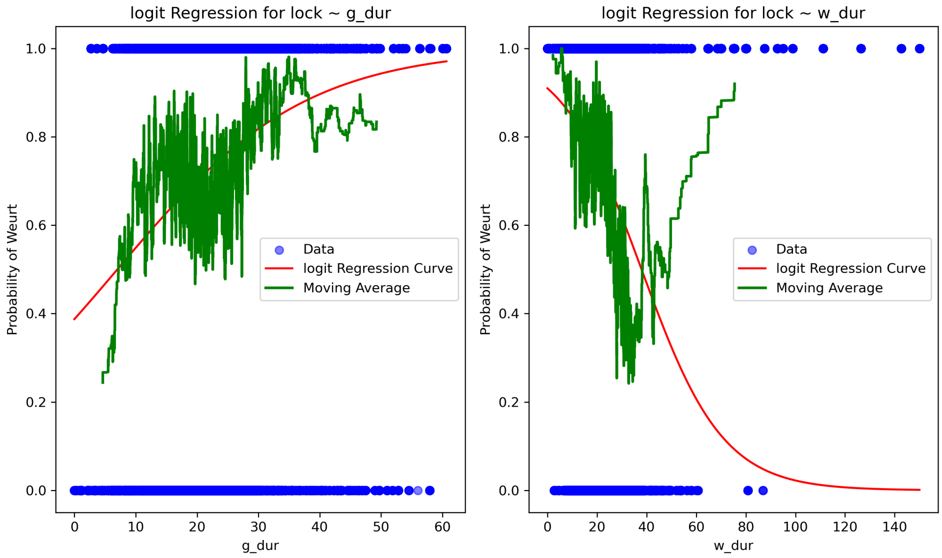

Figure 4.14: Logit regression curve for Grave and Weurt waiting times with a moving average (window size for moving average is 1000 data points)

The figure clearly shows that for most of the data, the waiting times at Grave has an opposite effect compared with the waiting times Weurt. However, for the Weurt waiting times at waiting times larger than 40 minutes, the moving average starts trending upwards.

4.4.3. CEMT

To find out the effect each CEMT class has on the lock usage, a logit regression analysis is done. The results are shown in 4.9 and the model performance metrics are it table 4.8. It is expected that most coefficients are negative since CEMT class **I** is taken as the constant, and that class is highly represented in the Weurt composition.

Metric	Value
Log-Likelihood	-81,772
Null Log-Likelihood	-82,888
Pseudo R^2	0.01346
Likelihood Ratio Test (p-value)	0.000

Table 4.8: Summary of Logit Model Performance Metrics

The model's **Log-Likelihood** indicates an improvement over the **Null Log-Likelihood**, confirming that the included predictors enhance the explanatory power of the model compared to an intercept-only baseline. The **Pseudo R^2** value is low, which is typical for logit models, particularly with large datasets. This indicates that while the model provides a modest improvement over the null, there is still unexplained variability. The **Likelihood Ratio Test** confirms that the model as a whole is statistically significant. Overall, the model demonstrates statistical robustness and a small but meaningful predictive improvement.

Table 4.9: Logit Regression Results for different CEMT classes

Variable	Coefficient	Std. Error	z-value	p-value
Intercept (CEMT I)	1.4816	0.049	30.054	<0.0001
CEMT II	-0.7338	0.052	-14.197	<0.0001
CEMT III	-0.9812	0.051	-19.126	<0.0001
CEMT IV	-0.6581	0.053	-12.465	<0.0001
CEMT V	-0.7141	0.053	-13.581	<0.0001
CEMT VI	-0.4163	0.051	-8.094	<0.0001
CEMT VII	0.0217	0.061	0.356	0.722
CEMT VIb	-0.2587	0.060	-4.281	<0.0001
CEMT VIc	-0.2690	0.051	-5.285	<0.0001

the VII class with a p value of 0.722 does not seem to be significant, meaning that being the VII class is not significantly different from being class I. The results show that CEMT class III is the most likely to take Grave. In figure 4.15 the data for each CEMT-class is shown and if the model will predict it correctly.

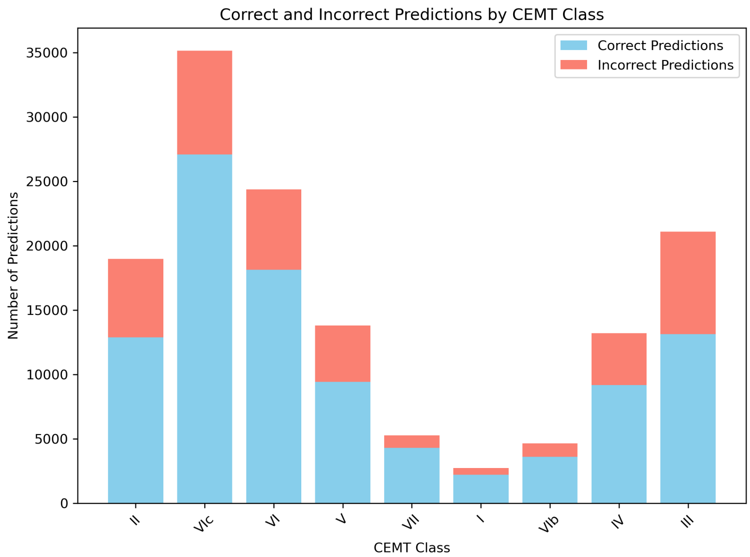

Figure 4.15: Distribution of correct and incorrect predictions per CEMT class

4.4.4. OD and Water Level

To research if within the different OD-pairs the water level has differing effects, the data has been split over the OD-pairs and a logit regression is done for the 3 main OD-pairs. The results are shown in table 4.11 and the model performance metrics are it table 4.10. Since there appears to be a stepwise reaction to the water level changes, the water level is categorized into three groups: Higher than 630 cm here the constant. between 530 and 640 cm and below 530 cm.

Table 4.10: Logit Regression Results for the water level for different OD-pairs

Variable	Rotterdam	Amsterdam	Germany
Log-Likelihood	-37,280	-9,210.1	-4,519.1
Null Log-Likelihood	-38,738	-10,716	-4,860.2
Pseudo R^2	0.03763	0.1405	0.07018
Likelihood Ratio Test (p)	0.000	0.000	7.209×10^{-149}

Across all OD-pairs, the **Log-Likelihood** values show substantial improvements compared to the respective **Null Log-Likelihoods**, indicating that the models effectively explain variations in the data. The **Pseudo R^2** values differ across OD-pairs, with Amsterdam (0.1405) exhibiting the strongest relative improvement, while Rotterdam (0.03763) and Germany (0.07018) show more modest but still meaningful fits. The **Likelihood Ratio Test** in all cases confirms that the predictors significantly improve the models' performance over the null models. Overall, the models are statistically robust.

Table 4.11: Logit Regression Results for water level for different OD-pairs

Variable	Coefficient	Std. Error	z-score	p-value
Maastricht-Rotterdam (n=56236)				
const	0.5524	0.012	46.110	<0.0001
between_530_640	-0.5593	0.019	-29.883	<0.0001
below_530	-1.4262	0.029	-49.015	<0.0001
Maastricht-Amsterdam (n=30275)				
const	3.0855	0.037	82.852	<0.0001
between_530_640	-1.2349	0.048	-25.925	<0.0001
below_530	-2.7138	0.051	-53.045	<0.0001
Maastricht-Germany (n=23820)				
const	3.8665	0.061	63.689	<0.0001
between_530_640	-1.4543	0.073	-19.874	<0.0001
below_530	-1.9582	0.086	-22.705	<0.0001

It can be seen that the constant, for Amsterdam and Germany, are heavily Weurt favoured. For both Rotterdam, and Amsterdam, there is a large difference between the two low water level groups. With the lowest more Grave favoured. However, for the Maastricht-Germany pair, the difference is small.

4.4.5. CEMT Class and Waiting Time

Since there might have been a occurrence of the secondary effect (smaller vessels rerouteing to Weurt to avoid delays at Grave due to low water levels at Weurt). To compare the CEMT classes with water level the data are split in CEMT class I (where the secondary effect might have happened) and the other classes combined. The results are in table 4.13 and the model performance metrics are it table 4.12.

Table 4.12: Logit regression performance metrics for CEMT Class I and All Other CEMT Classes for waiting times

Metric	CEMT Class I	All Other CEMT Classes
Log-Likelihood	-1,255.7	-80,673
Null Log-Likelihood	-1,306.7	-81,511
Pseudo R^2	0.03899	0.01028
Likelihood Ratio Test (p)	7.487×10^{-23}	0.000

The **Log-Likelihood** for both models indicates an improvement over the **Null Log-Likelihood**, confirming the inclusion of meaningful predictors. The **Pseudo R^2** value for CEMT Class I (0.03899) is modest but slightly higher compared to all other CEMT classes (0.01028), suggesting a better fit for this specific class. The **Likelihood Ratio Test** for CEMT Class I and for the others CEMT classes) confirms statistical significance in both models, indicating that the predictors significantly enhance model performance over the null. Despite the low Pseudo R^2 values, the models are statistically robust.

Table 4.13: Logit Regression Results for `g_dur` and `w_dur` on `lock` for CEMT Class I and Other CEMT Classes

Variable	Coefficient	Std. Error	z-score	p-value
CEMT Class I				
const	-0.0180	0.156	-0.115	0.908
g_dur	0.0649	0.007	9.648	<0.0001
w_dur	-0.0002	0.001	-0.283	0.777
Other CEMT Classes				
const	0.4564	0.021	21.737	<0.0001
g_dur	0.0321	0.001	37.658	<0.0001
w_dur	-0.0110	0.001	-17.439	<0.0001

First, the P values. For the "CEMT Class I" the P-value for the constant and the passage duration at Weurt is not significant. This means that both are not statistically different from zero. Meaning that only the passage duration at lock Grave is significant for the lock usage for the CEMT Class. Meaning it could be part of a secondary effect. For the Other CEMT classes, both are relevant.

4.4.6. CEMT Class and Water Level

To compare the CEMT class with the water level a logit regression. The results are shown in table 4.15 and the model performance metrics are it table 4.10

Table 4.14: Logit regression performance metrics for CEMT Class I and All Other CEMT Classes for water levels

Metric	CEMT Class I	All Other CEMT Classes
Log-Likelihood	-1,282.9	-78,682
Null Log-Likelihood	-1,306.7	-81,511
Pseudo R^2	0.01819	0.03471
Likelihood Ratio Test (p)	4.756×10^{-11}	0.000

The **Log-Likelihood** values for both models demonstrate an improvement over the **Null Log-Likelihood**, confirming that for both CEMT class groups. water level as predictors contributes to explaining lock choice. The **Pseudo R^2** values are modest: 0.01819 for CEMT Class I and 0.03471 for all other CEMT classes, with the latter showing slightly better model fit. The **Likelihood Ratio Test** for CEMT Class I and for all other CEMT classes indicates that the models are statistically significant. While the Pseudo R^2 values are low, the models are robust but do not fully explain the behaviour.

Table 4.15: Logit Regression Results for `water level` on `lock` for CEMT Class I and Other CEMT Classes

Variable	Coefficient	Std. Error	z-score	p-value
CEMT Class I				
const	1.8038	0.073	24.791	0.000
between_530_640	-0.7415	0.112	-6.635	0.000
below_530	-0.5452	0.136	-4.020	0.000
Other CEMT Classes				
const	1.2908	0.009	145.903	0.000
between_530_640	-0.5413	0.013	-40.587	0.000
below_530	-1.3502	0.019	-72.697	0.000

The results show that the CEMT I class indeed has a different usage pattern for very low water compared to the other classes. To find how significantly different these are the z score will be used. In table 4.16 the Z-score and p value is shown for the low water situation for CEMT class I.

Table 4.16: Z-Score Comparisons between CEMT Class I coefficients

Variable 1	Variable 2	Z-score	p-value
below_530	between_530_640	-1.114	0.265

The results show that the difference between the two coefficients are not significant. This means that it cannot be said that there is a difference between the two water level categories for lock usage. However, the extra shift to Grave at the lowest water levels that is there for the other CEMT classes is not there for CEMT class I.

4.4.7. Complete Logit Regression

To assess the predictive abilities, all characteristics are put together in a logit regression model. These results are shown in table 4.18 and the model performance metrics are in table 4.17.

Table 4.17: Logit Regression Results for All Variables Combined

Metric	Value
Log-Likelihood	-67,178
Null Log-Likelihood	-82,888
Pseudo R^2	0.1895
Likelihood Ratio Test (p)	0.000

The **Log-Likelihood** shows a substantial improvement compared to the **Null Log-Likelihood**, indicating that the combined variables significantly enhance the model's explanatory power. The **Pseudo R^2** value is relatively high for a logit model, suggesting a strong improvement over the null model. The **Likelihood Ratio Test** confirms the model's statistical significance. These results indicate that the combined variables provide a robust explanation of lock choice, with meaningful predictive power.

Table 4.18: Logit Regression Results

Variable	Coefficient	Std. Error	z-score	P-value
const	1.1077	0.057	19.292	0.000
w_dur	-0.0014	0.000	-7.531	0.000
g_dur	0.0388	0.001	40.395	0.000
cemtclass_II	-1.1400	0.056	-20.396	0.000
cemtclass_III	-1.1895	0.055	-21.496	0.000
cemtclass_IV	-0.9178	0.057	-16.087	0.000
cemtclass_V	-1.0644	0.057	-18.771	0.000
cemtclass_VI	-0.7480	0.055	-13.509	0.000
cemtclass_VII	0.0629	0.065	0.968	0.333
cemtclass_VIb	-0.9224	0.066	-13.900	0.000
cemtclass_VIc	-0.4698	0.054	-8.621	0.000
origin_destination_A_B	-0.4834	0.016	-29.869	0.000
origin_destination_A_C	1.5357	0.024	65.180	0.000
origin_destination_A_D	2.2490	0.033	68.482	0.000
water_lvl_below_530	-1.7637	0.022	-80.390	0.000
water_lvl_between_530_640	-0.5836	0.015	-40.100	0.000
Youden's Index		0.74		

Assessing the coefficients there are no major differences between the variables together in one logit function. All the signs are still in the expected direction.

There is a general preference for Weurt, seeing the constant is positive. The Weurt waiting times has a small decreasing factor on Weurt being picked. A higher waiting time at Grave increases the chance of Weurt. The effect of the CEMT classes remains the same. And for Maastricht-Rotterdam pair is still the most likely to pick Grave and Maastricht-Germany the least likely. And effect that Grave becomes more likely the lower the water level is in the Waal remains the same.

The model is only created to gain insight on the different variables that impact the lock usage. But to construct a confusion matrix for this model to assess how it functions, a threshold must be set. Since there is more Weurt data, it is unbalanced. To counter this the threshold is not set at the normal 0.5 but at Youden's index, which is a method to set the threshold to a value that is optimal for balancing sensitivity and specificity. Youden's index identifies the threshold that maximizes the difference between the true positive rate (sensitivity) and the false positive rate (1-specificity), ensuring the model's performance is less biased by the imbalance in Weurt and Grave data. Youden's index is:

$$J = \frac{\text{true positives}}{\text{true positives} + \text{false negatives}} + \frac{\text{true negatives}}{\text{true negatives} + \text{false positives}} - 1$$

In figure 4.16 model metrics are plotted for different threshold values. the Recall is the same as sensitivity. The Youden's index is the same as sensitivity + specificity - 1.

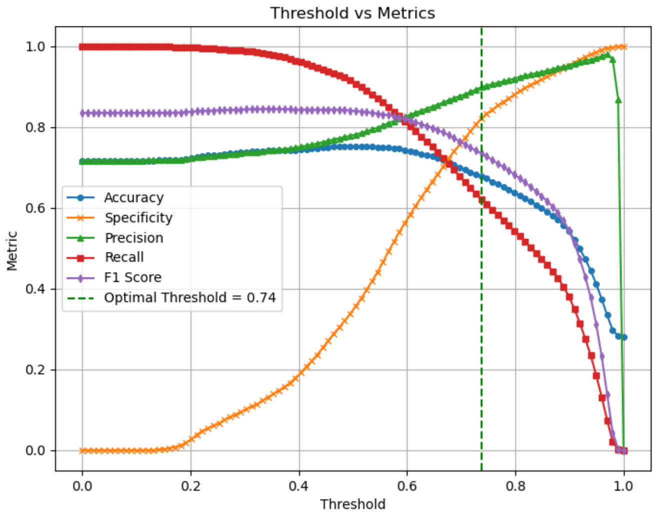

Figure 4.16: regression model metrics for different thresholds (Accuracy, Specificity, Precision, Recall, F1 Score)

A threshold at 0.74 results in the confusion matrix seen in figure 4.17.

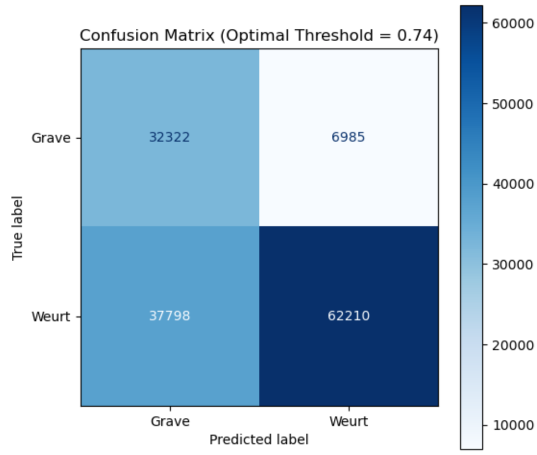

Figure 4.17: Confusion matrix

The corresponding Receiver Operating Characteristic (ROC) curve, shown in Figure 4.18, plots the true positive rate (sensitivity) against the false positive rate (1-specificity) for various thresholds. The ROC curve is a graphical representation of the model's ability to discriminate between the two classes (Weurt and Grave). A perfect model would have a curve reaching the top-left corner, indicating a true positive rate of 1 and a false positive rate of 0.

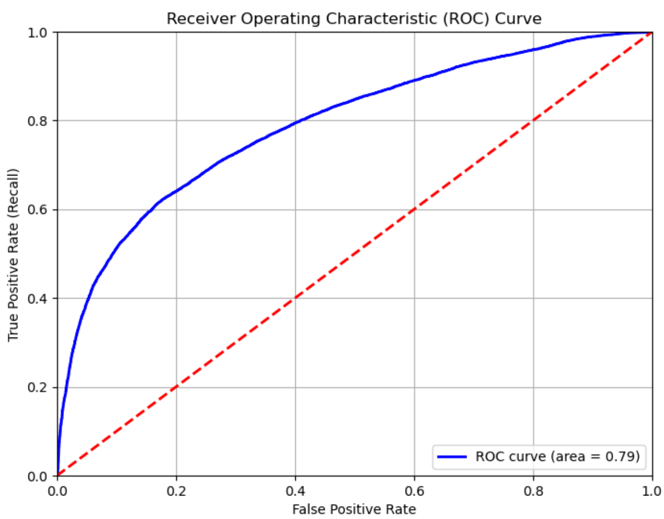

Figure 4.18: ROC Curve of the complete logit regression

The area under the curve is 0.79 this reflects good lock choices 79% of the time. his value is acceptable given the complexities and variability in the dataset.

4.5. Anomaly in Yearly Data

While researching the distributions for the four different options in the confusion matrix of the model, the differences in CEMT I class lock usage over the years stuck out. This is shown in figure 4.19.

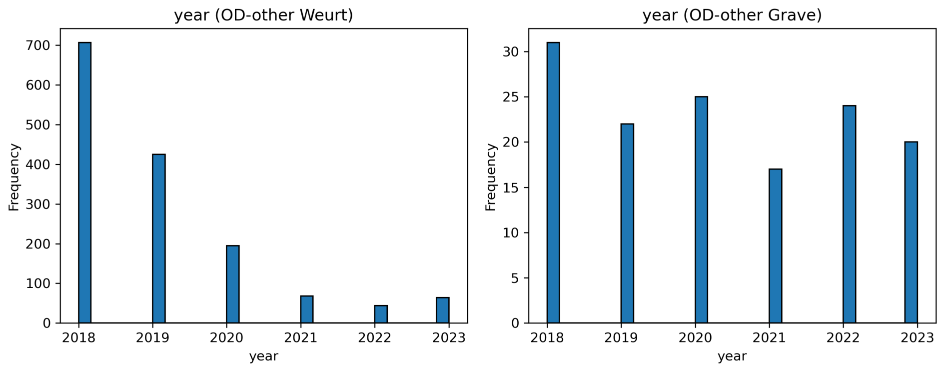

Figure 4.19: CEMT class I over the years for Weurt (left) and Grave (right) for the non main OD-pairs

This could have had an effect on the logit regression that was used to find if the secondary effect exists in this data.

To assess if this was the cause for the (not significant) secondary effect, the data is split in 2018 and 2019 and 2021-2023. This divides the data into a set with higher CEMT I values and one with lower ones. The results are shown in table 4.19

Table 4.19: Logit regression coefficients for different years periods

Variable	Coef (All)	Coef (2018-2019)	Coef (2021-2023)	P (All)	P (2018-2019)	P (2021-2023)
			CEMT Class I			
const	1.8038	2.1983	1.0011	0.000	0.000	0.000
between_530_640	-0.7415	-0.6595	-0.3675	0.000	0.001	0.032
below_530	-0.5452	-0.7298	-0.6581	0.000	0.000	0.029
			Other CEMT Classes			
const	1.2908	1.3346	1.2452	0.000	0.000	0.000
between_530_640	-0.5413	-0.2525	-0.6589	0.000	0.000	0.000
below_530	-1.3502	-1.5197	-1.0780	0.000	0.000	0.000

The results show that the effects mostly disappear. The coefficients for the 2018-2019 data are still not significantly different from each other. But now the below_530 coefficient is lower than the between_530_640. The P values for 2021-2023 being higher is the results of fewer vessels in that dataset. Since the datasets differ the values of the coefficients can not compare to each other. However, how the coefficients relate to each other in the dataset can be compared. The effect coefficient for below_530 are more negative for 2018-2019. This is probably a result from the percentage of vessels in low water levels being higher in the dataset from 2018-2019.

4.6. Conclusion

This chapter addressed the sub-research question: **To what extent do low water levels in the Waal impact the Weurt-Grave system?** The analysis confirmed that low water levels significantly influence lock utilization and route choices within the system. Vessels with larger draughts show a clear shift from Weurt to Grave under low water conditions, with this effect being gradual and more pronounced for specific CEMT classes. The reduction in load transported to Germany at very low water levels (-530 cm) appears to be offset by increased load for Rotterdam and Amsterdam, keeping overall system balance. Logit regression analysis highlights that waiting times at each lock are associated with changes in lock utilization. Longer waiting times at Grave correspond to increased usage of Weurt. For Rotterdam and Amsterdam-bound traffic, low water levels consistently drive shifts toward Grave, while Germany-bound vessels exhibit limited adaptability due to upstream constraints. The analysis also confirms that vessels with larger draughts shift to Grave during low water in the Waal. This shows the effect that vessel characteristics have one traffic patterns.

5

Current Modelling Assessment

This chapter takes a close look at how inland waterway traffic and lock demand are currently modelled, with a specific focus on the Weurt-Grave system during low water periods. It explains what the existing methods do well and, more importantly, where they fall short, to identify areas that need improvement for capturing rerouting dynamics and capacity constraints at locks during periods of low water. This will be used to help answer the sub-research question: ***Are the current modelling approaches sufficient for effects caused by extreme water levels?*** This is done by first focussing on the models that would be used for the Weurt-Grave system.

5.1. Current Modelling Methodology

he Ministry of Infrastructure and Water Management uses four main models for simulating inland waterway traffic:

- **Kooman-model**
  A spreadsheet-based tool that is primarily used to determine the I/C factor (Intensity/Capacity ratio) of locks.It uses a basis of empirical rules used to estimate waiting and passage times at locks (Kooman and De Bruijn, 1975). It's a basic tool that gives a static estimate of lock performance but doesn't adapt to real-time traffic changes or disruptions.
- **SIVAK**
  SIVAK is a simulation model used by Rijkswaterstaat to analyse ship traffic at locks, narrow waterways, and other water infrastructures. It is used to assess traffic composition, flow, operating strategies, and control measures. It can produce waiting times, waterway utilization, and costs per ship type. It is used to identify and prevent future bottlenecks for MIRT (Dutch Multi-Year Plan for Infrastructure, Spatial Planning and Transport) and used when developing new infrastructure (Ate Bijlsma and van der Schelde, 2019.
- **SIMDAS**
  SIMDAS is a model designed to simulate what happens along the waterways. It models waterway sections, bends and intersections. It can calculate congestion effects and capacity. It is also used for simulating interactions during encounters and overtaking manoeuvres. It can simulate congestion due to low water in waterways (Verschuren, 2020)
- **BIVAS**
  BIVAS is a static traffic assignment model designed to analyse the inland waterway network. It distributes traffic on the network based on route cost such as travel time, or travel distance, calculated from an Origin-Destination (OD) matrix (*BIVAS manual*, n.d.). The OD-Matrix contains transported goods. Provides information about optimal routes and traffic patterns based on predefined cost parameters.

When assessing the workings of locks, where route choice is important. The current methodology in the Netherlands will be: First, BIVAS will be used to calculate the number and type of vessels use that lock. Then SIVAK will be used to estimate the effects on the lock.

Since this research focusses on the effects of route choice changes combined with lock capacity changes, the two methods that normally would not be used are Kooman and SIMDAS. Therefore, the two models that will be assessed further are BIVAS and SIVAK.

5.1.1. Current Modelling Benefits

The main benefits of using SIVAK and BIVAS are:

- **SIVAK**
  - Can produce indicators of how well a lock functions, including waiting times, throughput, and operational efficiency.
  - Can change the dimensions and locking procedure of the locks under different scenarios.
- **BIVAS**
  - Generates network-wide traffic distribution.
  - Simulates large-scale changes, such as lock closures or increased capacity, to identify how these affect the overall waterway system.
  - Provides information about optimal routes and traffic patterns based on predefined cost parameters

While SIVAK and BIVAS each offer significant benefits for understanding and managing waterway traffic, they are not without limitations.

5.1.2. Current Modelling Drawbacks

The BIVAS and SIVAK models got drawbacks for modelling the waterway network.

- **SIVAK**
  - SIVAK simulates a single lock or section of the waterway.
- **BIVAS**
  - BIVAS assumes fixed conditions, such as constant route costs and vessel behaviour, and does not account for real-time changes like waiting times, temporary closures, or fluctuating water levels.
  - Bivas lacks the ability to model lock operations

When these models are used together, these drawbacks are greatly reduced. Using the model with more detail to simulate the lock operations, while the simpler BIVAS model has preassigned traffic. However, since this is used in a linear fashion, large waiting times or capacity drops during operation. cannot be captured.

5.2. Modelling Approaches for the Weurt-Grave System

The modelling approaches discussed in this section were selected based on the challenges of the Weurt-Grave system, particularly in relation to route choice, and lock capabitlity changes due to low water levels. The choice of these methods—Agent-Based Models, Traffic Assignment Models, and Event-Based Models—was informed by their ability to capture different scales and dynamics of the waterway network. The selected approaches are well-aligned with the research objectives and leverage existing tools such as SIVAK and BIVAS, which are grounded in these methodologies.

5.2.1. Event-Based Models

Event-based models simulate systems by representing operations and interactions as discrete events over time. Each event triggers changes in the system state. SIVAK is an example of an event-based model. Queueing models, a subset of event-based modelling, focus on representing traffic flows through queues and servers. In this context, vessels represent customers entering a queue, while the lock represents the server. After some time, the vessels are processed and leave the queue.

Compared to other models, queueing models abstract reality to a high degree. However, as Van Woensel and Vandaele (2007) point out, this does not make them inadequate for modelling traffic flows. Marsili et al. (2018) used a queueing model to simulate a series of locks and compared different maintenance methods to evaluate their effects on queue sizes. Although Marsili et al. (2018) acknowledged that their research was in its early stages, the results were promising.

Event-based models provide a structured approach to simulate lock operations and vessel interactions. They can be computationally efficient and can produce metrics such as waiting times and throughput. Queueing models, can excel at evaluating congestion and delays at locks by simulating the waiting queues. However, event-based models generally focus on localized sections. This makes them unsuitable for analysing route choice behaviours. The abstraction used in queueing models may simplify complex traffic behaviour too much.

5.2.2. Agent-Based Models

Agent-based models simulate traffic by treating each vessel as an independent agent that makes its own route choices and interacts with its environment. In agent-based models, traffic flows emerge from the local decisions of individual agents and their responses to environmental conditions Kaziyeva et al., 2023. These models are particularly effective for city-scale traffic simulations, where they can capture the complex behaviour of systems under various scenarios Zhao et al., 2019.

Huang et al. (2022) described agent-based models as ideal for analysing systems composed of agents that simultaneously interact and influence one another. Transport systems, being dynamic, stochastic, and heterogeneous, are well-suited to this modelling approach. Similarly, Nguyen et al. (2021) concluded that agent-based modelling is particularly useful for studying road traffic from an individual perspective.

Agent-based models allow for detailed simulation. It can simulate individual vessel interactions. This makes them well suited for localized systems like Weurt-Grave. However, due to their complexity it can be computationally demanding for larger networks and might be limited by the calibration. Reducing its practical applicability.

5.2.3. Traffic Assignment Models

Traffic assignment models distribute traffic flows across a network based on cost minimization criteria, such as travel time, distance, or fuel consumption. These models use an Origin-Destination (OD) matrix, which contains all traffic from each origin to each destination, to calculate optimal routes. For each OD pair, the optimal routes can be calculated using travel time, travel cost, and/or travel distance (Saw et al., 2014). The results of traffic assignment models include the flow distribution across network links. BIVAS is a static traffic assignment model.

Traffic assignment models are widely used for strategic transport planning and estimating future traffic flows and travel times to evaluate projects Bliemer et al., 2017. These models can be classified into two types: Static Traffic Assignment (STA), which loads traffic in one time step, and Dynamic Traffic Assignment (DTA), which uses smaller time steps to model time-dependent traffic flows. While STA is computationally efficient, it cannot capture dynamic interactions such as congestion at specific locks. DTA, on the other hand, provides a more realistic representation of dynamic conditions but requires significant computational resources.

Traffic assignment models are well suited to simulate network wide route choices. This fits well with the Weurt-Grave system. It can reroute the vessels from Weurt to Grave. However, these models tend to focus on flows and costs and may overlook detailed vessel behaviours and local operations, which is critical for the interaction between the locks.

5.3. Implications for the Weurt-Grave System

The Weurt-Grave system shows the limitations of current modelling methods during low water periods. While BIVAS, a Static Traffic Assignment (STA) model, is capable of creating low-water scenarios, it relies on static assumptions for route costs and vessel behaviour. This limits its ability to capture dynamic changes in lock usage or the cascading effects caused by water level fluctuations. The vessels that shift from Weurt to Grave depend on the water levels. For BIVAS to be effective, it should be run for numerous different scenarios. This cannot be easily done.

SIVAK (an Event-Based model) can analyse the effects of the low water levels well. However, it is not able to feed the results of the simulation back into a route choice analysis. It is unable to simulate two locks that influence each other from different routes.

These models are also not able to produce the secondary effect. Where capacity constraints at Weurt causes congestion at Grave which then causes smaller vessel to reroute to Weurt. That this occurs was not proven in the previous chapter. However, the ability for a model to handle such situations could be useful.

Event-based models, agent-based models, and traffic assignment models all offer advantages for addressing parts of the simulation needed at the Weurt-Grave system. The Event-based models are suited for the lock-specific analyses. Agent-based model will better capture the traffic behaviour locally. And traffic assignment models will provide network-wide route choices.

5.4. Possible Improvements

It is possible to improve the models to alleviate the limitations that they have for the Weurt-Grave system. This could increase the usability of SIVAK and BIVAS.

One significant improvement would be transitioning BIVAS from a Static Traffic Assignment (STA) model to a Dynamic Traffic Assignment (DTA) model. Traffic Assignment Models distribute traffic over a network by calculating the optimal routes for each Origin-Destination (OD) pair, based on criteria such as travel time, travel cost, or travel distance (Saw et al., 2014). The dynamic model would be a better fit for dynamically changing conditions in the system. This would increase the potential of BIVAS. However, this makes the model more complex.

The combination of SIVAK and BIVAS could also fix alot of the limitations that both models have. Replacing the linear modelling approach with a feedback loop between BIVAS and SIVAK. Using BIVAS to assign traffic to the system. Then using the resulting traffic to estimate the waiting times with SIVAK and then using those waiting times as costs in the BIVAS links. This approach would address the cascading effect, providing a more realistic representation of the Weurt-Grave system. Improving BIVAS and/or combining it with SIVAK will result in a more robust tool to model the waterway network.

5.5. Conclusion

This chapter showed the stregnths and limitations of the moddeling methods that are currently used for the Weurt-Grave system. While SIVAK and BIVAS provide valuable insights, SIVAK excels at lock-level analysis and BIVAS at network-wide traffic distribution, both models fall short in capturing the dynamic interactions between locks and the cascading effects of low water levels. Event-based, agent-based, and traffic assignment models could be configured to better model the Weurt-Grave system under low water levels. The shortcomings of the current modelling methods have to be taken into account when modelling the Weurt-Grave system. Since it will not be able to realistically simulate the system under changing low water levels in the Waal. The Rhine discharge in the future, is expected to increase in the beginning of the year and decrease in the second half of the year Kerstin Stahl et al., 2022) This will increase the amount of times the Weurt-Grave system will experience extreme water levels in the Waal. Increasing the importance of modelling it well.

6 Discussion

This research aimed to answer the following research questions: ***What impact does a reduction in capacity, caused by low water levels, have on alternative locks within the inland waterway system, with a focus on the Weurt-Grave system?*** And the sub-questions:

- ***What changes occur in the demand at alternative locks when the capacity of one lock is reduced?***
- ***To what extent do low water levels in the Waal impact the Weurt-Grave system?***
- ***Are the current modelling approaches sufficient for effects caused by extreme water levels?***

The findings of the study provide new insights in the cascading effects capacity constrains can have on the vessel redistribution between locks, and that those effects are not well simulated in the current modelling approach. The observed route change and fleet composition change show how inland waterway system responds to dynamic capacity changes in the form of water level changes. The results show that capacity constrains at one lock can greatly impact the traffic patterns of the whole system.

This chapter discusses the findings that address the research questions. Then, the implications for modelling such effects are explored. Next, the broader impacts of the Weurt-Grave system on related aspects beyond its immediate scope are considered. The discussion then extends to other locks where similar situations may occur and examines the applicability of these findings.

6.1. Interpretation of Results

The results of the thesis will be discussed here per sub-question.

What changes occur in the demand at alternative locks when the capacity of one lock is reduced?
The results show a redistribution of vessel traffic and load from lock Weurt to lock Grave during periods of low water levels in the Waal. This changes the fleet distribution at both Grave and Weurt, with larger vessels classes increasingly using Grave, while the overall vessel traffic in the system remains stable. The results also show that the transported weight shifts from Weurt to Grave during low water levels in the Waal. However, the total transported weight in the system remains stable. However, this shift leads to longer delays at lock Grave, whereas lock Weurt undergoes minimal changes in waiting times. These findings show the role of vessel size and lock accessibility in the traffic flows under constrained capacity conditions.

To what extent do low water levels in the Waal impact the Weurt/Grave system?
The findings show that low water levels in the Waal affect the utilization of lock Weurt and lock Grave. A gradual shift from Weurt to Grave is observed when the water level in the Waal lowers. This shift reflects the system's sensitivity to vessel characteristics and capacity constraints under low water in the Waal. The reduction in load transported to Germany during very low water levels is offset by increased

load for Rotterdam and Amsterdam, which helps maintain the overall balance within the system. Waiting times also have an effect on the lock utilization. At Grave, longer delays correspond to an increase in Weurt's usage. For Rotterdam- and Amsterdam-bound traffic, low water levels shifts traffic toward Grave, while Germany-bound vessels are less likely to change route. These findings show how water levels influence traffic patterns and lock performance in the system. A secondary effect, observed initially, involves smaller vessels rerouting from Grave back to Weurt due to increased congestion at Grave. However, it was not significant, and further analysis revealed the initial effect was strongly influenced by the presence of a larger number of the smallest vessel class, in the first two years of the dataset.

Are the current modelling approaches sufficient for effects caused by extreme water levels?
The results demonstrate that while SIVAK and BIVAS offer insights into lock-level performance and network-wide traffic distribution, they lack the capability to model the dynamic interactions and cascading effects caused by low water levels. Neither model can capture the redistribution of vessels between locks, together with changing constraints at Weurt. Projections of future changes in Rhine discharge patterns further increase the occurrences of the limitations of these models.

6.2. Results Implications

The observed traffic redistribution of vessel traffic from Weurt to Grave during low water levels increase the average daily vessels taking grave to above 30 vessels when the Waal has a water level of <500 cm. While under normal water levels the daily usage is around 10 vessels. When this happens the daily counts for Weurt are 27 vessels per hour compared to 45 vessels under normal condition in the Waal. For the load this is more pronounced. The load transported via Grave increased by four times and the load transported via Weurt decreases by 4 times.

So under low water conditions on the Waal the capacity of Weurt is lowered to such a extend that lock Grave becomes the main connection point from the Southeast corridor to the rest of the inland waterway network of the Netherlands. So there are two ways this problem could be elevated. The capacity at Weurt could be increased, lowering the sill depth. Making the system less reliant on Grave during low water. Or the capacity of lock Grave could be increased by adding a second chamber. Resulting in less delays at Grave when the traffic redistribution occurs.

The results show that not only is there an increase in the number of vessels taking Grave during low water levels, There is also a change in Fleet composition. This results in a increase of average load per vessels during low water at Grave. It increases to above 1100 tonne from 900 tonne at normal water levels. For Weurt it goes from around 900 tonne during normal water levels to less than 500 tonne during the lower water levels in the Waal.

The results show that in the Weurt-Grave system at low water levels. The traffic patterns change due to low water levels gradually. This dynamic effect of water levels has on the capacity of lock Weurt cannot be simulated well with the current modelling approach. The increasing the extreme water level scenarios in the future due to climate change increase the error of the current approach.

6.3. Applicability to Other Cases

The situation, observed in the Weurt-Grave system, can be generalized to other context within inland waterway network. The functional condition and system characteristics that could indicate similar interaction in other systems can be identified. By identifying these conditions, the applicability of this research increases.

For this research to be applicable, there need to be hydraulic structures that have different capacities based on environmental conditions. Like locks with low water levels, or height limits for locks or bridges for high water levels. The capacity changes could also be caused by a having a limited amount of water that is allowed to be lost during lockages. For that case, there is a hard cap on the number of lockages.

Further, there need to be dependency between the hydraulic structures. This can be that both structures are on other routes that could be taken. Forcing vessels to reroute when something happens at one structure. The other route that the loads take could also be on another mode. If there are no rerouting abilities on the waterway network the loads that need to be transported could switch to the road or rail network.

When a lock is under consideration for maintenance or construction, it is essential to evaluate whether its reduced capacity or temporary closure will affect other locks in the system. The results show that changes in capacity at one lock can cascade through the whole network. Failing to account for these interactions can lead to unintended bottlenecks or inefficiencies.

6.4. limitations

While this research provides valuable insights into the interactions between locks within the inland waterway system, several limitations must be acknowledged. These limitations are discussed in the following subsections.

6.4.1. Data Availability and Quality

The analysis relied on historical traffic and water level data from Rijkswaterstaat, covering the years 2018 to 2023. However, the dataset contained some inconsistencies and missing data points, particularly regarding the Origin-Destination (OD) matrix and cargo load values. For instance, certain OD pairs did not align with the observed lock choices, potentially due to errors in data entry or the aggregation of trip segments not captured in the dataset.

These data limitations impacted the robustness of the analysis. While assumptions were made to mitigate missing values (e.g., treating NaN load values as zero), this simplification may have introduced biases. As a result, the conclusions regarding traffic patterns and load distributions, particularly under low water conditions, may under-represent the true complexity of vessel behaviour. Future studies would benefit from more granular and complete datasets, including real-time vessel tracking and lock usage logs.

This study demonstrates what can be accomplished with operational data of a lock. However, it also highlights that using real time tracking data like AIS data could have increased the significance of the thesis by being able to more accurately construct an OD-matrix. However, the data size would have been greatly increased.

6.4.2. Limitations of the Logit Regression

The logit regression approach effectively identifies significant variables influencing lock choice, but has inherent limitations. Logit regression assumes a simple mathematical relationship between the independent variables (e.g., water levels, waiting times) and the likelihood of a specific lock being chosen. In reality, vessel behaviour is influenced by more complex interactions (e.g., Vessels can reduce their load to be able to pass Weurt). The best regression model could only produce the correct lock choice 79 percent of the time.

The application of logit regression used in this study faced several challenges. The smallest vessels where only a small part of the data set (CEMT-class I) this limited the research that could be done towards the proposed secondary effect. The logit regression did not take into account the progressive shifts in vessel behaviour over time. The other locks on the route could also have had an effect on either Weurt or Grave (e.g., maintenance of one of the locks downstream of Grave in the Meuse could have had an impact on the use of Grave).

The results of the logit regression show that there were likely missing attributes that influence the route choice. Also, the option of modal change was not incorporated. In periods of low water levels, transport could have switched to rail or road.

6.4.3. Focus on Specific Cases

This study focussed on the Weurt-Grave system as the representative case. Both locks in this system are considered bottlenecks, with limited capacity. This makes the Weurt-Grave system extra sensitive to the effect of capacity reductions. The observed redistribution of vessels and changes in fleet composition might be amplified because of this. Other locks, that are not bottlenecks, probably have reduced redistribution compared to Weurt-Grave.

6.4.4. External Factors

Since the data is over a period from 2018 to 2023 there are some differences between the years. external influences, such as weather conditions, seasonal variations, or policy changes (e.g., water management regulations), were not fully integrated into the analysis. These factors could significantly impact lock usage patterns and traffic flows, potentially altering the findings of this research. Including these variables in future models would provide a more comprehensive understanding of lock interactions.

6.4.5. Research Approach

The research approach could have been strengthened by modelling the data period (2018-2023) using the current modelling approach and showing where the gaps are. That the dynamic effects cannot be modelled is clear. However, simulation of the difference using BIVAS and SIVAK would have strengthened this thesis.

7 Conclusion

In this thesis the following research question was awnsered: *hat impact does a reduction in capacity, caused by low water levels, have on alternative locks within the inland waterway system, with a focus on the Weurt-Grave system?* This is done by awnsering the following sub-questions:

- ***What changes occur in the demand at alternative locks when the capacity of one lock is reduced?***
  The findings show a redistribution of vessel traffic and load from Weurt to Grave during low water conditions in the Waal. This shift is accompanied by a change in fleet composition for both Weurt and Grave, with larger vessels increasingly rerouted to Grave. Despite this redistribution, the total vessel traffic across the system remains stable, highlighting the adaptive capacity of the Weurt-Grave system.
- ***To what extent do low water levels in the Waal impact the Weurt-Grave system?***
  The findings show that low water levels in the Waal significantly affect the interaction between the Weurt and Grave locks. A gradual shift from Weurt to Grave is observed as water levels decrease. The variables that have effect on this process are:
  - **The water level in the Waal**
    When the water levels in the Waal become low the usage of Grave both in vessel counts and load increase. The shift for load from Weurt to Grave is more pronounced that that of the vessel counts.
  - **Fleet composition**
    Larger vessels, such as CEMT Class VI and higher, are more than half of the traffic at Grave during low water periods. While during normal periods they are only a quarter.
  - **Waiting time**
    There are significant increases in passage times at grave during low water in the Waal. Increased waiting times at Grave resulted from low water levels in the Waal correspond to a modest rise in usage at Weurt. And higher waiting times at Weurt increase the usage of Grave.
  - **Origin-Destination patterns**
    Rotterdam- and Amsterdam-bound traffic is more adaptable to changes in water levels, consistently shifting toward Grave under low water conditions. Conversely, Germany-bound vessels exhibit less flexibility due to possible upstream constraints (lower water levels in the Waal makes the Waal less navigable, even if the vessels reroute over the Meuse they need to finish their route over the Waal to Germany), and for this OD-pair the rerouting adds the highest cost (it is the longest distance).

  The proposed secondary effect (smaller vessels rerouting from Grave back to Weurt due to increased congestion at Grave) seemed to occur. However, this effect was not significant and was strongly influenced by the presence of a larger number of the smallest vessel class (CEMT Class

I) in the first two years of the dataset. When these years are modelled separately, the secondary effect disappears.

- ***Are the current modelling approaches sufficient for effects caused by extreme water levels?***
  The current modelling approaches, such as SIVAK and BIVAS, provide valuable insights into lock-level performance and network-wide traffic distribution separately. But cannot do both dynamically at the same time. These shortcomings limit their ability to model gradual traffic shifts and fleet composition changes observed during extreme conditions. Future projections of Rhine discharge patterns predict increased variability and more frequent extreme water levels, making it necessary to take this into account when modelling. Concluding that the current methods need to be adjusted or changed to be able to better simulate extreme water level situations.

The research question: ***What impact does a reduction in capacity, caused by low water levels, have on alternative locks within the inland waterway system, with a focus on the Weurt-Grave system?*** can be answered as follows:

Low water levels in the Waal reduce the capacity of lock Weurt, leading to a redistribution of vessel traffic and load to lock Grave. This redistribution is driven by a combination of factors, including vessel draught limitations, fleet compositions waiting times, and the Origin-Destinations of vessels. Larger vessels, which loaded cannot use Weurt during low water conditions, shift to Grave, resulting in increased traffic and delays at Grave while Weurt sees a decline in usage.

Despite the route changes that vessels make, the overall system remains stable in vessel traffic and total transported load. However, the change in fleet composition, with larger vessels dominating Grave during these periods, show the system's sensitivity to environmental conditions. The findings also show that while Rotterdam- and Amsterdam-bound traffic adapts more readily, Germany-bound traffic is less flexible due to higher rerouting costs.

Current modeling approaches, such as SIVAK and BIVAS, are insufficient to simulate these dynamic interactions and cascading effects of capacity reductions caused by extreme water levels. Future models should account for gradual traffic shifts, fleet composition changes, and locks affecting each other to better predict and manage such scenarios.

This study contributes to the understanding of lock interdependencies and vessel behaviour under constraining conditions. It used a data driven approach to show traffic patterns that are impossible to model with single lock models and hard to model with static models.

7.1. Practical implications

The most important implication of this research is that changes in capacity or demand at one lock can significantly affect the demand at another lock. This can also occur when these locks are not directly connected by the same waterway. The interaction between Weurt and Grave illustrates how limitations, such as low water levels, lead to shifts in traffic patterns and infrastructure strain across the inland waterway network.

With low water scenarios expected to become more frequent due to climate change, these effects are likely to increase in both frequency and magnitude. This raises concerns about the ability of existing infrastructure, particularly bottlenecks like Grave, to handle periodic heightened demand. Proactive maintenance and capacity upgrades can ensure these locks remain functional and efficient under changing conditions.

The findings show the importance of understanding vessel characteristics and the influence of Origin-Destination patterns on routing decisions. These dynamics play a critical role in traffic redistribution and should be integrated into future planning and modelling efforts to optimize lock operations and improve system resilience.

As many hydraulic structures in the Netherlands approach the end of their designed life expectancy, it is vital to evaluate their capacity to manage changing demand patterns. Locks like Grave, which absorb redistributed traffic, highlight the interconnectedness of the waterway network. Strategic planning for maintenance, upgrades, or replacement will be crucial to prevent inefficiencies and ensure the long-term sustainability of the inland waterway system.

The insights from this study apply to broader waterway infrastructure planning and waterway management strategies. Climate change will result in more weather extremes. Resulting in an increase of water level capacity restrains. When modelling these waterways, the interaction between water levels (or other constrains) can affect traffic patterns system-wide. The findings show that managing lock capacity should not always be seen as a local problem, but it can also be a system-wide problem. When this is overlooked, it could potentially lead to under-designing locks and unforeseen bottlenecks in critical transport corridors.

7.2. Recommendations for Future Research

While this research provides valuable insights into the interactions between locks within the inland waterway system. It revealed several limitations that could be addressed with future research.

7.2.1. Enhanced Data Collection and Validation

Future studies should explore the use of Automatic Identification System (AIS) data to validate and complement IVS data. AIS data provides detailed vessel tracking, which can help identify discrepancies in recorded Origin and Destination information and better understand route changes under varying water conditions. Combining AIS and IVS datasets would improve the reliability of vessel routing analysis and provide more robust insights into traffic flows.

7.2.2. Expanding to Other Lock Systems

To generalize the findings, research could investigate similar interactions in other lock systems. In the Netherlands locks with such interations are: the Amerongen and Prinses Irene locks or Hansweert and Kreekrak locks. Studying these systems can help determine whether the patterns observed in the Weurt and Grave locks apply to other waterways and under different conditions. A comparative analysis across multiple systems could identify common factors driving lock interdependencies and help refine modelling approaches.

7.2.3. Economic Analysis of Traffic Redistribution

This research addresses the distribution of vessels and cargo within the Weurt and Grave system. However, The broader effects of these traffic shifts remain unexplored. Future studies could investigate how low water levels impact emissions, transport costs, and the overall efficiency of the inland waterway system. This could help to prepare the inland waterway for the coming 50 years.

7.3. Concluding

In conclusion, this thesis provides a data driven examination of locks interacting due to capacity constrains. By researching the locks Weurt and Grave it showed cascading effects due to low water levels limiting the capacity at Weurt. This research shows the importance of incorporating these interactions into future planning and modelling efforts.

As waterway systems continue to experience varying environmental and operational conditions, the adaptability, and resilience of the inland waterway network will face increasing challenges. The findings show the importance of adjusting modelling approaches. This research provides a foundation for enhancing waterway management strategies, ensuring that systems remain efficient and reliable under changing environmental conditions.

This study shows that inland waterway networks do not function in isolated sections. A capacity constraint at a single point can cascade thought the network. Changing traffic patterns that the current modelling approach cannot capture. Knowing of these possible system-wide effects is essential for modelling waterway infrastructure that need to handle the results of climate change and changing transport demands. This will improve the resilience and efficiency of the inland waterway network.

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A
Nan evaluation

In this appendix, the decisions on what was done with the NaN values in the dataset is explained.

A.1. All data points NaN

The rows that had NaN values for all the data points are analysed here. First the in Figure **??** it is plotted in which months these NaNs occur.

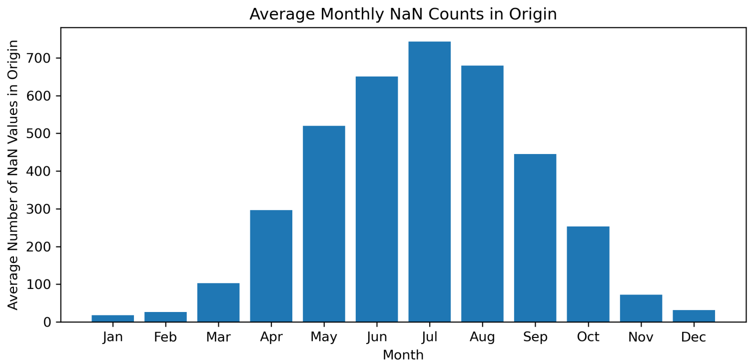

Figure A.1: Data rows that has NaN values in each column distributed over the months

It can be seen that there are minimal occurrences in the winter, and it peaks in the summer. This extreme fluctuation does not match with the seasonality of the other vessels, where there is a dip in the summer. The vessels with no data points might not be used for freight transport. To check this also the average of all NaN data points are plotted for the days of the week. This is shown in Figure A.2.

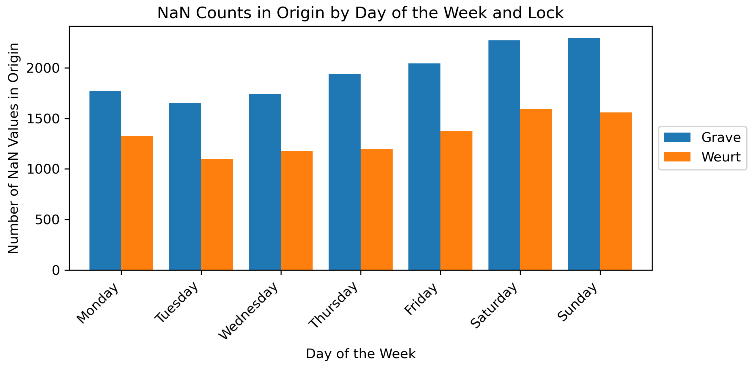

Figure A.2: Data rows that has NaN values in each column distributed over the days of the week

The figure also does not match with the other vessels. For the all NaN value rows, they are more prevalent in the weekend. These patterns might be partly explainable if they are lock opening for recreational vessels. However, this cannot be proven from the data. Normal data errors might also be mixed in. Therefore, it is concluded that these vessels cannot be assigned a value for the different data points. The best way to handle these is to remove them from the dataset.

A.2. Load NaNs

To decide if the NaN values in the load column need to be removed or not, the set of vessels with Load NaN values will be examined on two points. The distribution of the vessel classes and the draught. The vessel to find out if the distribution of the vessel types are similar. If they are, it could be that the NaN values are random and the data set with 44.3can be assumed that vessels state NaN load if they have no load.

In figure A.3 the distribution of the vessel classes is stated. First in the total counts and then in percentages. The no NaN values dataset size is 121,448 and the size of the NaN values is 62,170.

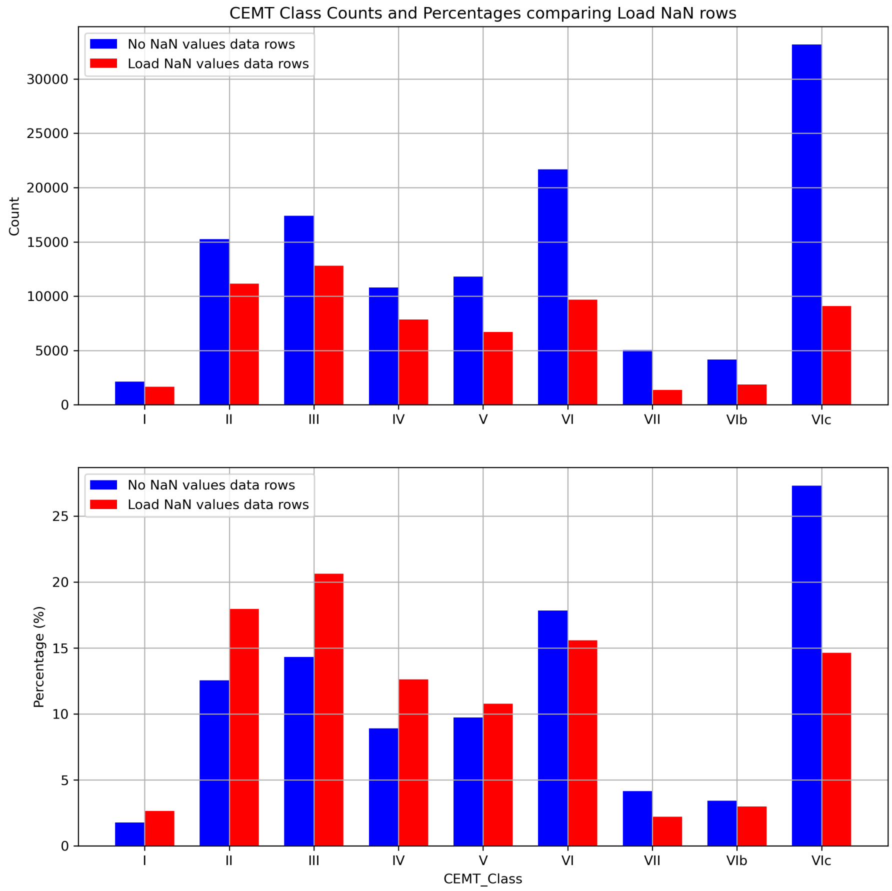

Figure A.3: CEMT class distribution of NaN values compared to no NaN values.

The vessel distribution do seem to be different. Especially for the larger vessel classes. Notably, the VIc class occurs considerably less in the dataset consisting of NaN load values. To a lesser extent, this also seems to happen for the VI class.

Next the same is done except instead of grouping them by class they are grouped by draught. this is done in figure A.4.

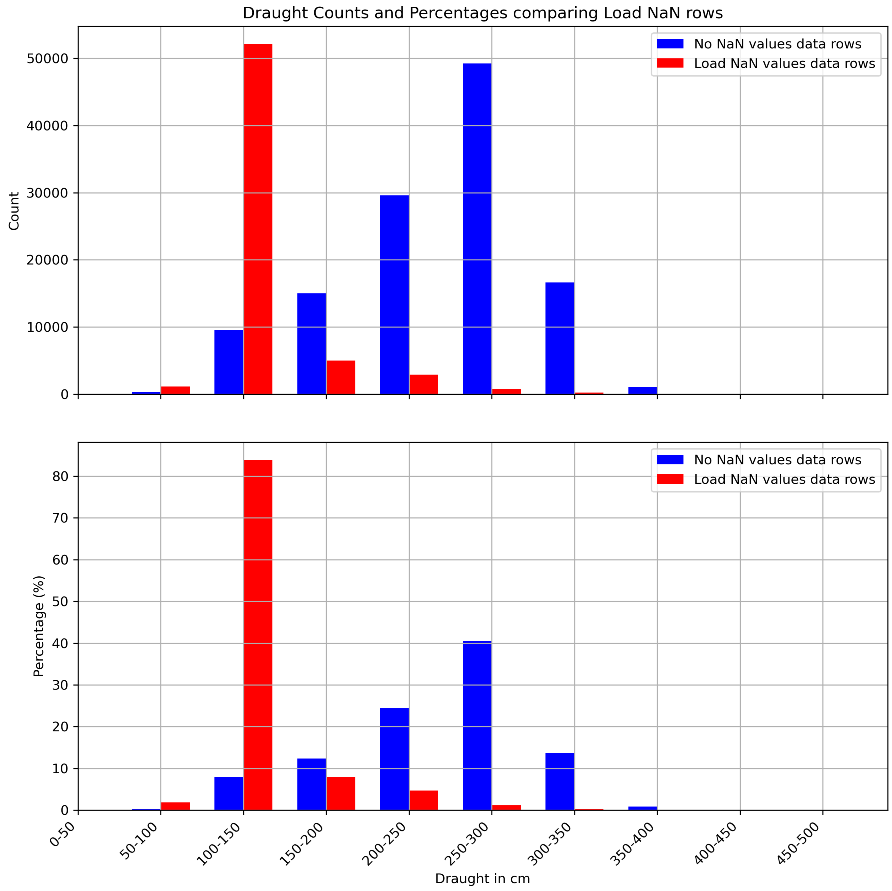

Figure A.4: Draught distribution of NaN values compared to no NaN values.

Figure A.4 clearly shows there is a difference in the set of data containing load NaN values. The draught of vessels having a load value is significantly higher than the draught of vessels stating their load. Since the CEMT class distribution from figure A.3 is relatively similar, it might be that most vessels having a NaN value can be assumed to have no load.

A.2.1. Assuming load NaN

To check if the vessels with a NaN load value can be assumed to be unloaded, the figures A.4 and A.3 are plotted again. However, this time the data set with no NaN values is split into values of 0 and bigger than zero. This is done to check if the load is 0 set is similar to the NaN set. In figure A.7 this is done for the CEMT classes.

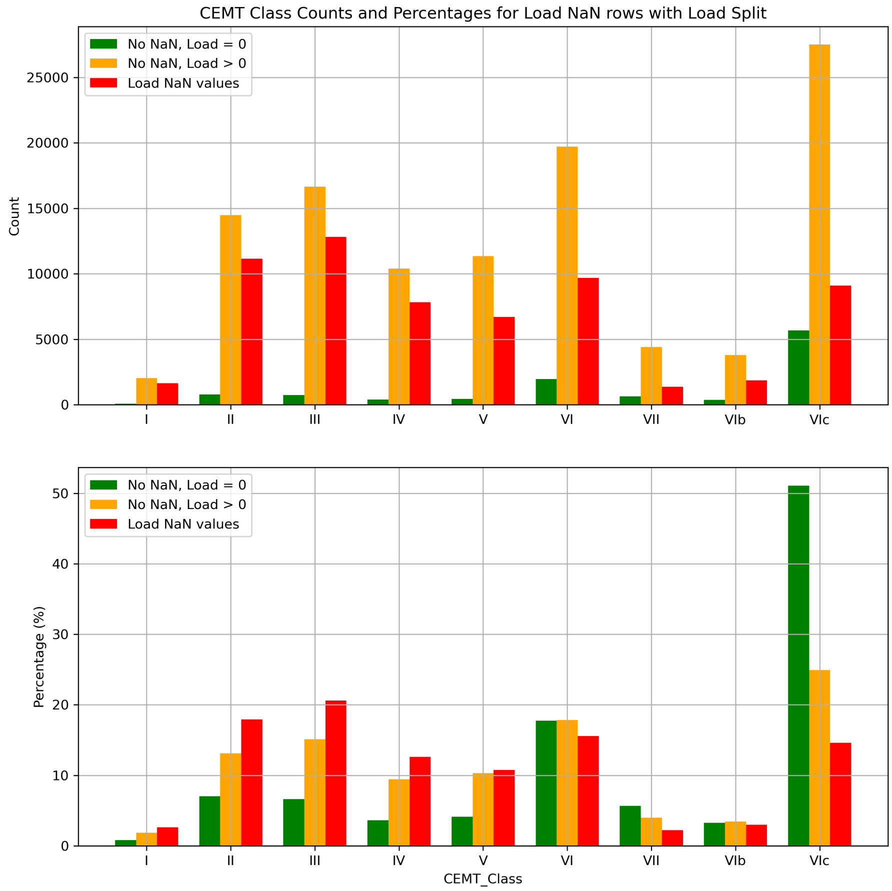

Figure A.5: CEMT class distribution of NaN values compared to no NaN values where the load is 0 and >0.

Figure A.7 shows that where the distribution differs the most, VIc and to a lesser extent VI, it also shows up in the unloaded data. It seems that the larger vessels state more often that they have 0 load. Since the VIc and VI are less in the NaN data set and more in the unloaded one, it might be countered. To check this the NaN data set is added to the unloaded one. This results in figure A.6

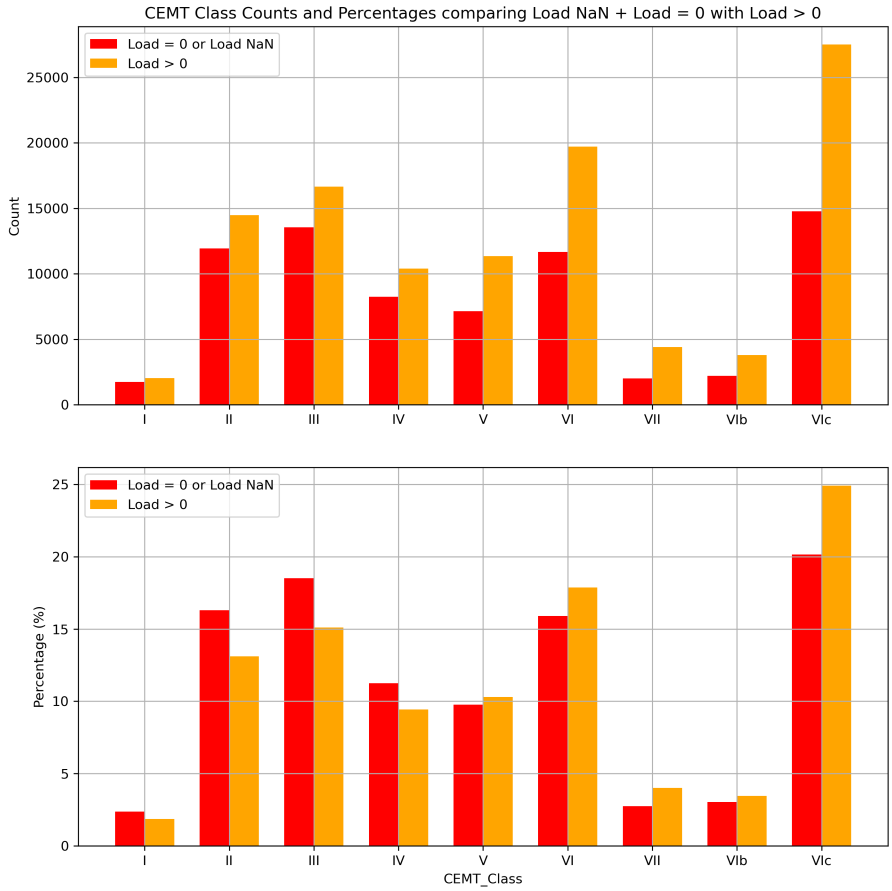

Figure A.6: CEMT class distribution of NaN values asumed to be 0 load.

examining figure A.6,It can be said that the distributions are now considerably more similar. If the NaN data set is assumed to be unloaded vessels, the only real differences is that smaller vessels are more likely to traverse unloaded than the larger vessels. This seems logical, since operating larger vessels is more expensive, so reducing the time spend with no cargo has financially more impact. As a final check, the draught distribution is also split into an unloaded class, loaded class and NaN class.

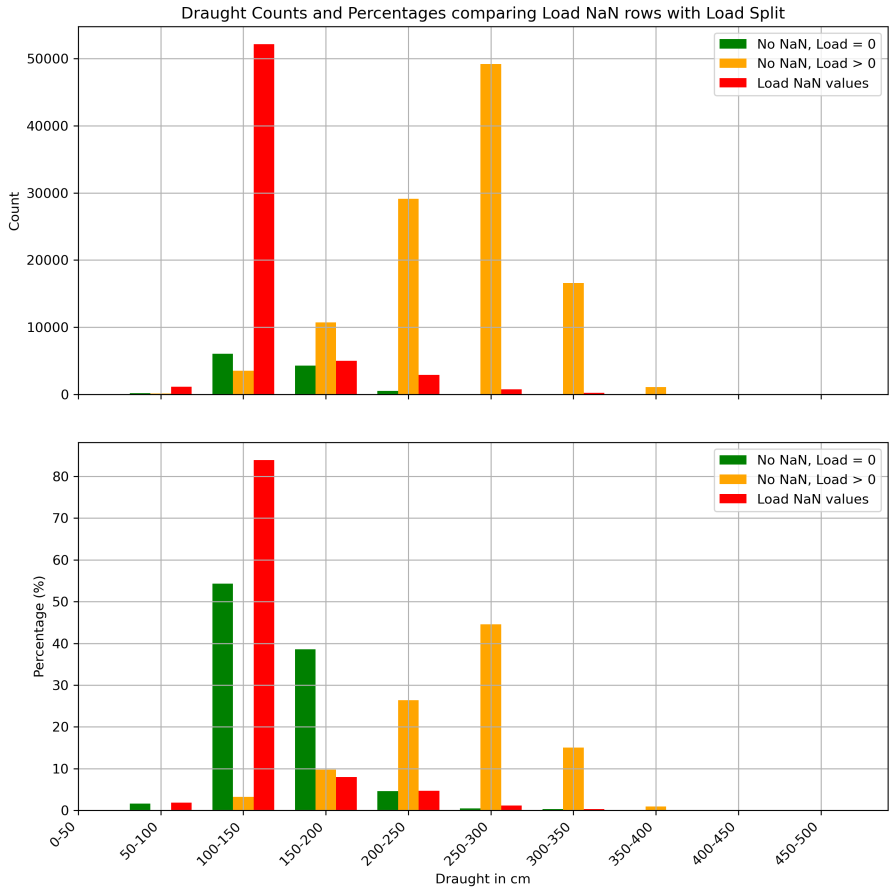

Figure A.7: Draught distribution of NaN values compared to no NaN values where the load is 0 and >0.

Figure A.7 shows that the draught distribution for unloaded vessels matches the one for the NaN values. The unloaded set is more weighted towards the higher draught bin, but this is expected because the figure A.6 showed that the larger vessel classes (VI and VIc) are more represented in the unloaded set. Therefore, it is concluded that there is enough evidence to assume the NaN load data points correspond with a load of 0.

With this information, only 15.8% of the data can be filtered out instead of 44.3%.

B
Origin-Destination Matrix generation

The origin and destination locations are mostly in the Netherlands. In figure B.1 the origin and destination countries are shown together with the percentage of vessel observations with missing location data. For all the other observations (the green in the figure) the location within the country is also known. Since the locking did occur for these ships they are all taken into account for the analysis for locks. However, for the construction of the Origin-Destination matrix these values are left out.

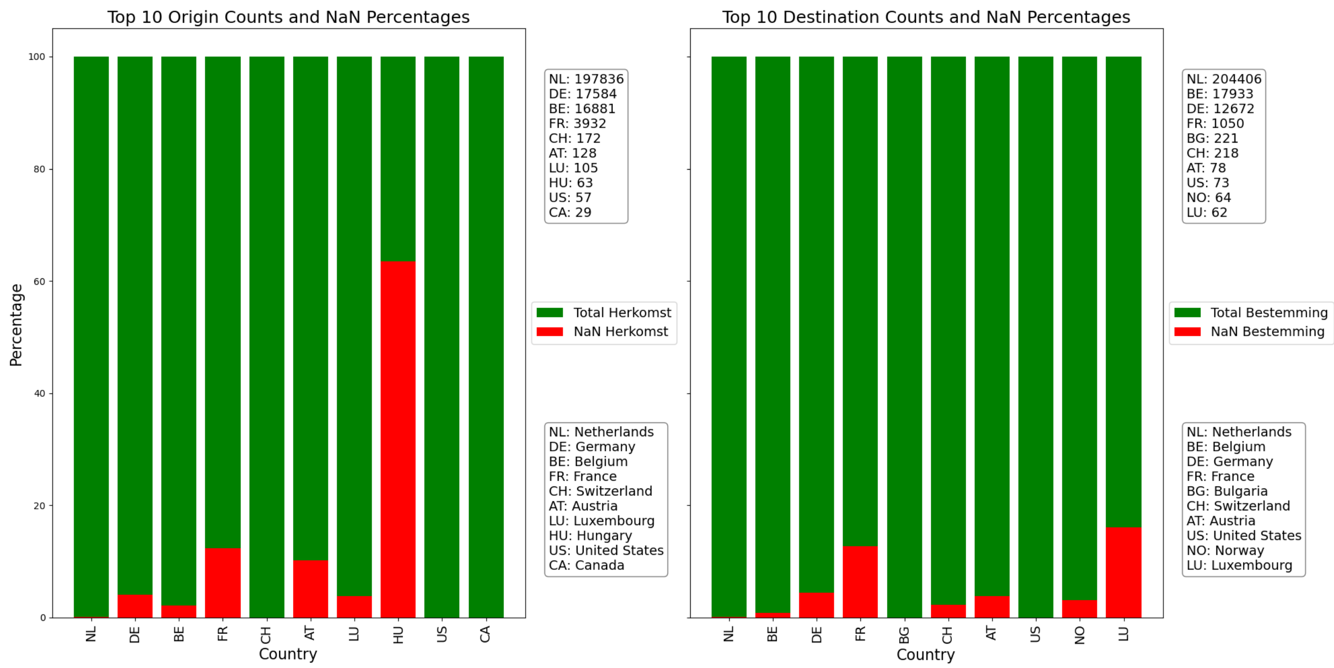

Figure B.1: Percentage of missing locations (NaN) in the data set

In figure B.2 the location of each origin and destination is given. For map of the Netherlands and that of Western Europe, the size of the dots log scale with the number of vessels. All these vessels pass either Weurt, Grave or the Maximakanaal.

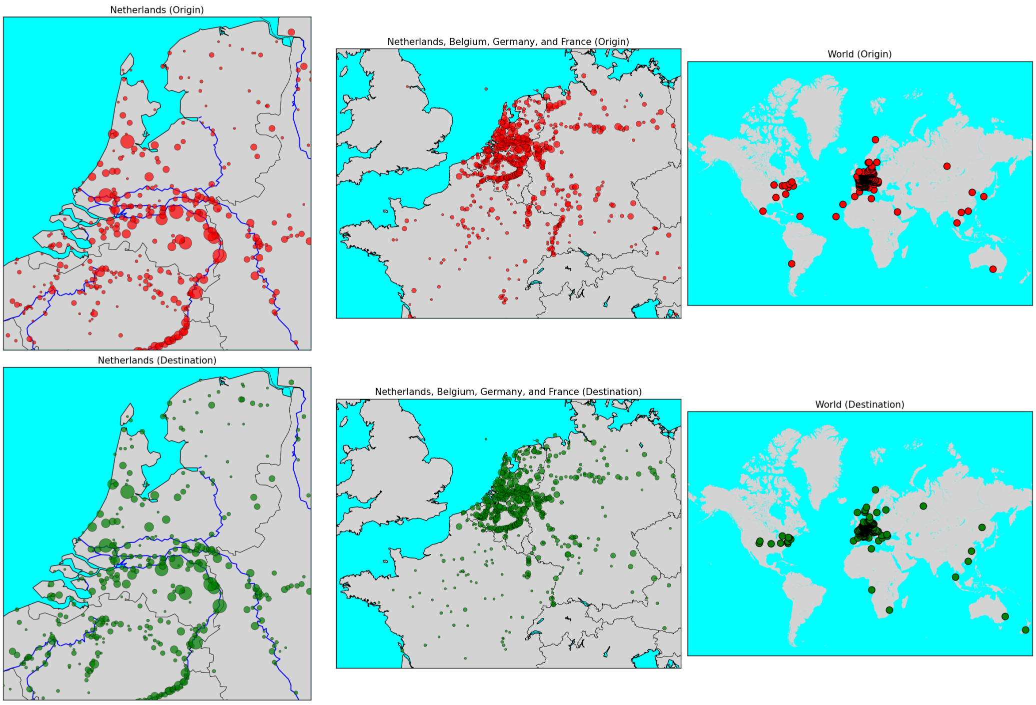

Figure B.2: Corridors regions visualized Rijkswaterstaat, 2021b

The dots that are outside the Netherlands but inside the corridors (shown in figure **??**) are assumed to leave the Netherlands via the inland waterway borders. While the dots outside that area are assumed to enter and leave the network in the direction of the Port of Rotterdam.

To go from the origin and destination locations to a OD-matrix each location should be connected to a Node. Since there are 4 main direction, the traffic can enter the system there will be four nodes. A for South, B for West, C for North, and D for East. The areas that were chosen, dividing main waterways are depicted in figure B.3

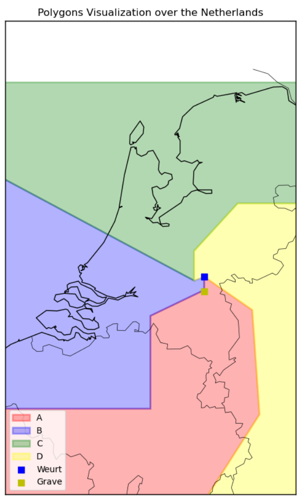

Figure B.3: Regions for each Origin and Destination

When using these borders to create a OD-matrix the OD-matrix as shown in figure B.4 is created. This is for all 5 years.

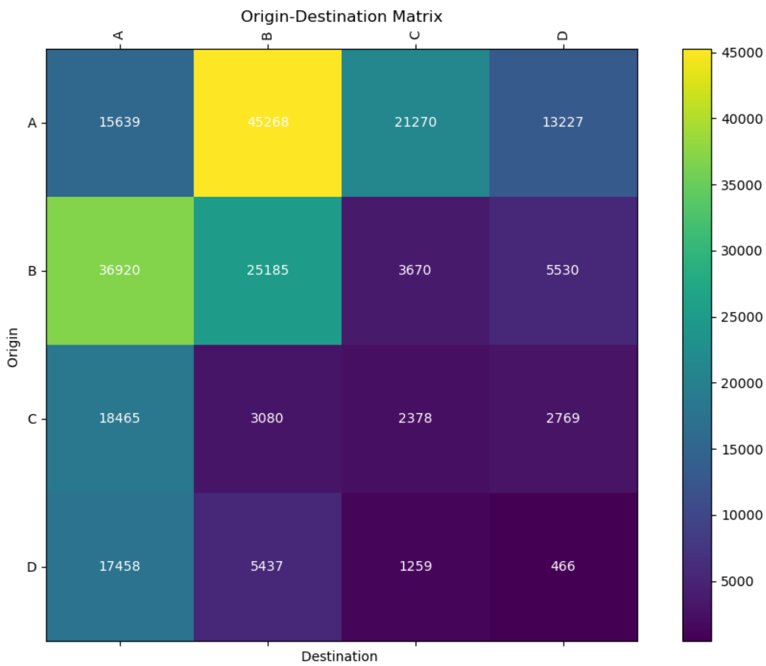

Figure B.4: Raw OD matrix

The high value between A-B A-C and A-D are expected because those are the main traffic streams. However, the high values for A-A and B-B seem unrealistic. Looking closely at the data, there are some weird occurrences. As an examples, ships in the south of France having it origin and destination in the south of France. But due to the data source, we know that this ship passed lock Weurt. To counter this, all he A-A, B-B, C-C, and D-Ds values are removed. But since we know these vessels did use the locks in the system, they are divided over the other OD pairs. The resulting OD-matrix is shown in figure B.5

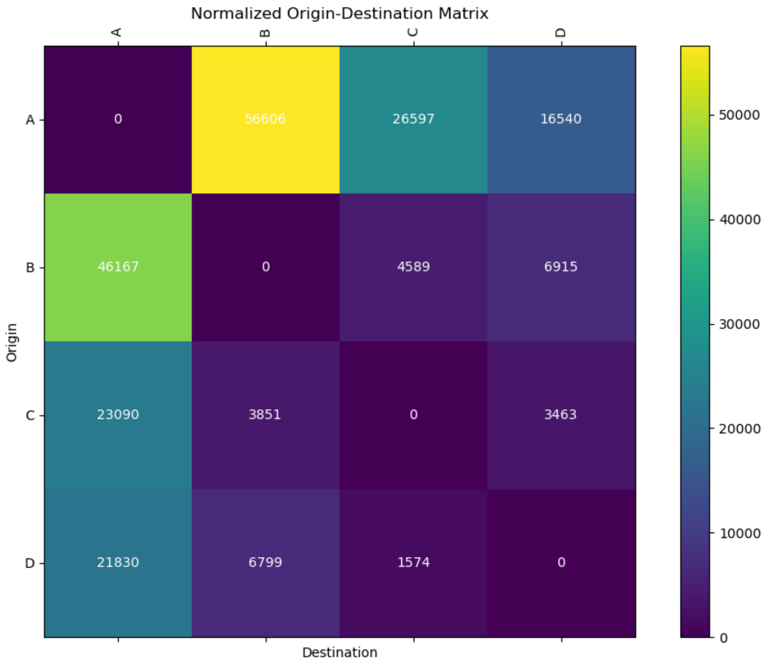

Figure B.5: Adjusted OD-Matrix