The impact of low river discharge levels on seaport terminal processes

A case study assessing the impact of Rhine low discharges on a dry bulk terminal using vessel movements data

R. F. den Brave

TU Delft

Royal HaskoningDHV
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by

R. F. den Brave

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Student number:	4581296	
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Thesis committee:	Prof. dr. ir. M. van Koningsveld,	TU Delft
	Dr. Ir. P. Taneja,	TU Delft
	Ir. I. Lambert,	Royal HaskoningDHV
	Ir. T.M. de Boer,	Royal HaskoningDHV & TU Delft
	Dr. Ing. M.Z. Voorendt,	TU Delft
	Ir. S.E. van der Werff,	TU Delft

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Cover image: EMO terminal, Port of Rotterdam (EMO, 2023)

Preface

This thesis marks the end of my master's degree in Civil Engineering with a specialisation in Hydraulic Engineering. The past years at TU Delft have provided me with the opportunity to acquire a profound understanding of Civil Engineering and to gain valuable international experiences. The completion of this thesis has been made possible through the collaboration with Royal HaskoningDHV which has afforded me the chance to undertake this project and expand my knowledge in the fields of Ports & Waterways and AIS data.

Conducting this research has been an enlightening journey, and I would like to express my gratitude to my committee for their support and guidance. I would like to thank Ingrid Lambert for all the weekly meetings at RHDHV. Her insights and feedback have provided me with many new perspectives and have been key in shaping this report. A major thanks to Solange van der Werff for always making time for me and assisting with the analysis of the AIS data and for her dedication to helping me refine the storyline through our meetings and calls. I would also like to thank Poonam Taneja for providing me with positive feedback and posing critical questions that fueled my motivation and energy. I would like to express my gratitude to Thijs de Boer for sharing his knowledge and enthusiasm, which greatly contributed to my understanding of port operations. I am appreciative of the clear comments of Mark Voorendt on the report. His suggestions have provided me with new perspectives on report writing and continuous opportunities for improvement. Finally, I would like to thank the chair of the committee, Mark van Koningsveld, for his great enthusiasm and for always driving me in the right direction.

Apart from my committee, I would also like to give a special acknowledgement to Frederik Vinke for sharing his knowledge on the topic and to Bas Turpijn for exchanging IVS data and helping me get it to work. Moreover, I would like to thank Peter de Klerk for granting me the opportunity to visit the EMO terminal, providing valuable information and sending fascinating drone photos.

Finally, I would like to express my gratitude to Roald and my family for their support throughout my studies and the process of writing this thesis. Your ability to discuss the project with me has been immensely valuable. Additionally, I would like to thank my friends and roommates for making this thesis period even more enjoyable and memorable.

R. F. den Brave
Rotterdam, June 2023

Abstract

The increasing severity of river drought poses a potential threat to the operations of ports using rivers as hinterland connections. River droughts have impacted navigation in various rivers worldwide, including the Rhine river where instances of low water levels in 2018 and 2022 caused disruptions in navigation. As a consequence, inland vessels were forced to reduce their cargo loads. Seaport terminals that serve as crucial links between sea vessels and inland vessels may be impacted by changes in fleet composition, thereby affecting a terminal's cargo handling operations and storage. However, there is a lack of research quantifying the effects of low river levels on seaport processes and determining suitable methods to assess this impact using vessel movement data.

To address this research gap, this study aims to quantify the impact of low river levels on seaport processes by focusing on the EMO dry bulk terminal within the Port of Rotterdam as a case study. Given the connection between this port and the Rhine, which is known for its vulnerability to drought and serves as a vital route for inland navigation, the analysis begins by examining the impact of reduced river discharge on the dry bulk fleet sailing from Rotterdam to Germany utilising Information and Tracking System for Shipping (IVS) data. Additionally, Automatic Identification System (AIS) data is employed to assess the service time, the number of vessels and the berth occupancy within the terminal to quantify the impact of low river discharge on the cargo handling process within the terminal. Specifically investigating the effects on vessels being loaded and bound to the hinterland and those being unloaded after arriving from the sea. Finally, the study analyses the impact on the storage capacity of the EMO terminal using monthly cargo data provided by the terminal, by studying the balance between the amount of cargo being unloaded and loaded.

The findings show that vessels sailing along the Rhine are required to reduce their load as discharge decreases, leading to an increased number of vessels. However, this compensation by more vessels does not fully offset the load losses, resulting in a decrease in the total load carried per day when discharge decreases. Consequently, more vessels arrive at the EMO loading berths during low discharge periods to compensate for the reduced load and therefore loading time for vessels at these berths is shortened. Due to the increased vessel arrivals, the berth occupancy at the loading berths increases to a maximum of 65%. On the contrary, the berth occupancy at the unloading berths remains unaffected. Cargo flow analysis shows that the lowest cargo loading into inland vessels occurs during months without low discharge, rather than during the months with the lowest discharge. Additionally, the share of rail transport increases during low discharge months but remains below maximum capacity, indicating sufficient slack to handle all cargo. The stockpile analysis reveals a small surplus during low discharge months, although not as significant as in months with normal discharge levels.

Overall, the findings indicate that the large size of the EMO terminal allows it to withstand the impacts of past periods of low river discharge. As the loading berth's occupancy is not at its maximum capacity and the unloading berths remain unaffected, there is sufficient slack to accommodate additional vessels. Accordingly, adequate vessels are loaded to transport cargo to the hinterland, ensuring no impact on the stockpile and thus maintaining the storage operations at the EMO terminal without disruption.

While this research provides valuable insights, it is important to acknowledge that terminals of varying sizes or handling different cargo types may experience different impacts and should be subject to further investigation. Additionally, the limited availability of AIS and cargo data, with only one year of extreme drought (2022) for analysis, prevents drawing definitive trends and making long-term assumptions for future scenarios. Nevertheless, this study's methodology can be adopted in related studies to analyse more terminals and gain further insights.

Contents

Acronyms

AIS	Automatic Identification System
ALD	Agreed Low Discharge
ALW	Agreed Low Waterlevel
CEMT	Conférence Européenne des Ministres des Transports
CDF	Cumulative Distribution Function
DWT	Dead Weight Tonnage
IMO	International Maritime Organization
IVS	Information- and tracking system for shipping (Dutch: Informatie- en Volgsysteem voor de Scheepvaart)
IWT	Inland Waterway Transport
LOA	Length Overall
MMSI	Maritime Mobile Service Identity
PIANC	World Association for Waterborne Transport Infrastructure
RWS	Rijkswaterstaat
RHDHV	Royal HaskoningDHV
TEU	Twenty-foot Equivalent Unit
UNCTAD	United Nations Conference on Trade and Development
WPI	World Port Index

1 Introduction

1.1. Motivation

Ports play a major role in international trade: they provide the connection between the sea and hinterland and drive economic growth. Over 70% of the global trade is handled by seaports worldwide (Hoffmann et al., 2017). Ports are thus the main hub of trade, but they are at high risk from the impacts of climate change. Since ports are located in coastal zones, low-lying areas and deltas, they are more frequently affected by flooding, rising sea levels, and storm surges. This will directly affect port operations and infrastructure, hampering trade (UNCTAD, 2021).

While the impact of flooding, rising sea levels, and storm surges on port performance is well-documented, river drought as an effect of climate change has not yet been considered much. Nevertheless, river drought causes lower discharge and water levels necessitating inland vessels to reduce load (Vinke et al., 2022). These reduced water levels impacting inland waterway transport (IWT) may affect port performances, potentially requiring port optimisation or expansion.

It is expected that the rivers will become drier and that low water levels will remain for longer periods in the future since the number and duration of droughts have already risen by 29% since 2000 (United Nations, 2022). The escalating severity of river drought and its consequential effects on IWT may raise significant concerns. Considering the important role that ports play in facilitating global trade, it is imperative to comprehend the implications of reduced river discharge on port performance, which is the aim of this study.

1.2. Problem analysis

Once freight arrives at seaports from overseas, it undergoes a series of operations including unloading from sea vessels, storage, and subsequent loading onto trains or inland vessels for transportation to the hinterland. During transport over waterways, river drought may enhance navigational problems. In addition, ships cannot sail fully loaded as a consequence of river drought. This was the case in 2018 on the Rhine. Vessels had to make more trips with less cargo to transport as much cargo as possible (Vinke et al., 2022). According to Van Hussen et al. (2019), the low water levels led to 30% higher freight rates and the demand for trains and trucks increased correspondingly, leading to higher prices for other modalities. In China, shipping routes along the Yangtze River had to be closed as a result of extreme droughts last summer (Waterways Journal, 2022). In 2020, Argentina experienced the worst drought in 77 years in the Paraná River region. Agricultural products, which are the main trade for this country, could hardly be shipped and an additional amount of 315 million dollars had to be paid for exporting these products. Moreover, the port terminal of Rosario along the Párana River had to extend the cranes to reach ships, to prevent ships from getting stuck (Politi, 2021).

Given that a seaport terminal with a connection to the hinterland handles both sea vessels and inland vessels, changes in fleet composition, such as an increase in the number of vessels with reduced loads, could potentially impact the cargo handling process for inland vessels within port terminals and thereby potentially affecting the storage. Consequently, it is anticipated that the Port of Rotterdam will experience a surge in demand for barge handling capacity during periods of low water levels in the Rhine river. This, in turn, will lead to an increased demand for storage capacity due to more cargo coming in than leaving the terminal, potentially necessitating the transportation of more cargo by truck or train (Krekt et al., 2011). It is crucial to investigate whether the current terminal design is equipped to manage these changes in port processes effectively or if adjustments are required.

The quantification of the impact of low river levels on seaport processes is lacking, as is the availability of a suitable method to determine this impact based on available vessel movement data.

1.3. Research objective and research questions

The objective of this research is to quantify the impact of low river levels on seaport processes, specifically focusing on cargo handling and storage capacity. This objective will be achieved by developing a method utilising vessel movement data to assess port processes, as no such methodology has been identified in the literature. This investigation will be carried out through a case study conducted at the EMO terminal, situated in the Port of Rotterdam and connected with the Rhine river. To achieve the aim of the research, the following research question is formulated:

What is the impact of low river discharge levels on seaport terminal processes?

In order to answer the research question, the study addresses the following sub-questions:

1. How can available data be processed and analysed to determine the effect of river drought on shipping at the river and port terminals?
2. How do low Rhine river discharge levels impact the amount of load carried and the number of vessels for the fleet navigating the Rhine?
3. How do low Rhine river discharges affect the cargo handling process for both loading of inland waterway vessels and unloading of seagoing vessels in the EMO terminal?
4. How do low Rhine river discharges affect the storage capacity of the EMO terminal?

1.4. Scope of the research

The logistical chain of a seaport with an inland waterway connection is depicted in Figure 1.1. Since river discharge is the driving parameter, the majority of the study focuses on inland waterway vessels and therefore the scope of this research encompasses the route of inland vessels along a river section, crossing the point of discharge measurement, between the port origin (Port of Rotterdam) and their destination. This ensures the incorporation of vessel movements within (1) inland waterway transport, (2) loading of inland vessels, (3) storage, and (4) the handling of sea vessels.

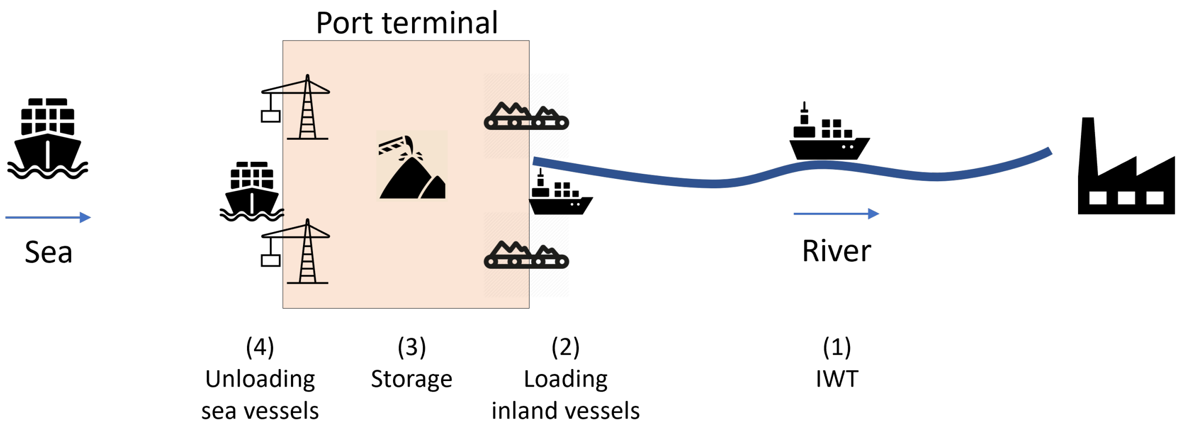


Figure 1.1: Schematic overview of the processes within the logistical chain of seaports with a hinterland connection

The selection of the Port of Rotterdam as a case study is based on the fact that cargo transported to the hinterland by inland waterway vessels passes through the Rhine, which is known to be affected by river drought (Krekt et al., 2011; Van Hussen et al., 2019; Vinke et al., 2022). Furthermore, there is available data on the movements of inland vessels specifically along the river Rhine. The research primarily centres on the dry bulk sector, as previous studies by Krekt et al. (2011), Van Hussen et al. (2019), Vinke et al. (2022), and Wienk (2021) have shown that the fleet shipping this commodity is mostly influenced by low river discharge levels and that it is less profitable to shift to other modalities.

1.5. Research approach

The research approach involves the development of a method based on vessel movement data to quantify the impact of low river discharge levels on seaport terminals. The comprehensive approach, as described in the following steps, addresses the four sub-questions outlined in Section 1.3, ultimately yielding an answer to the main research question.

1. A literature study is carried out to collect relevant data to analyse vessel movements in rivers and ports. This literature study also offers theoretical insights into the Rhine river corridor and identifies parameters suitable for quantifying terminal processes.

2. A method is devised utilising vessel movement data to assess the effects of reduced river discharge levels on both IWT and port processes, employing the identified critical parameters and aiming to answer the first sub-question.

3. The study quantifies the impact of low river discharge levels on IWT in the Rhine, denoted as (1) in Figure 1.1, using the background information and parameters as identified in the literature study. This approach step endeavours to address sub-question 2.

4. The study examines the influence of low river discharges on the cargo handling process, which is examined using the parameters found in the literature study, for vessels bound for the hinterland (2) and vessels arriving from the sea (4). Therewith aiming to answer sub-question 3.

5. The storage process, which relies on both incoming and outgoing cargo, is determined using data on the cargo flows of the terminal and provided by the terminal, indicated by (3) in the figure above. This step, therefore, aims to answer the fourth sub-question.

1.6. Report structure

To be able to reach the objective and to answer the research questions, with the above-stated approach, the report is subdivided into three parts with eight chapters, as listed below. Figure 1.2 outlines the report structure with the corresponding sub-questions addressed per chapter.

Chapter 1: Introduction

Part I **Literature, Materials and Method**
Chapter 2: Literature study
Chapter 3: Materials and method

Part II **Results**
Chapter 4: Impact of low Rhine discharge levels on inland waterway transport
Chapter 5: Impact of low Rhine discharge levels on cargo handling processes
Chapter 6: Impact of low Rhine discharge levels on the storage

Part III **Discussion, Conclusions and Recommendations**
Chapter 7: Discussion
Chapter 8: Conclusion and recommendations

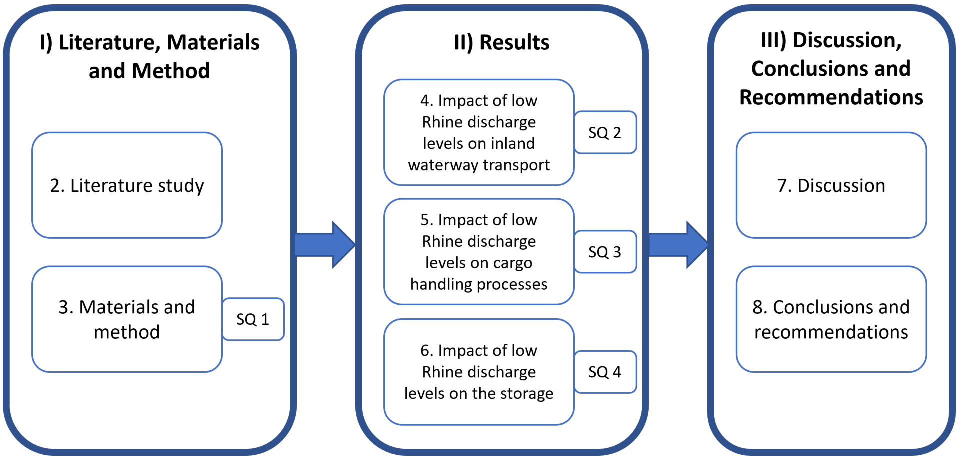
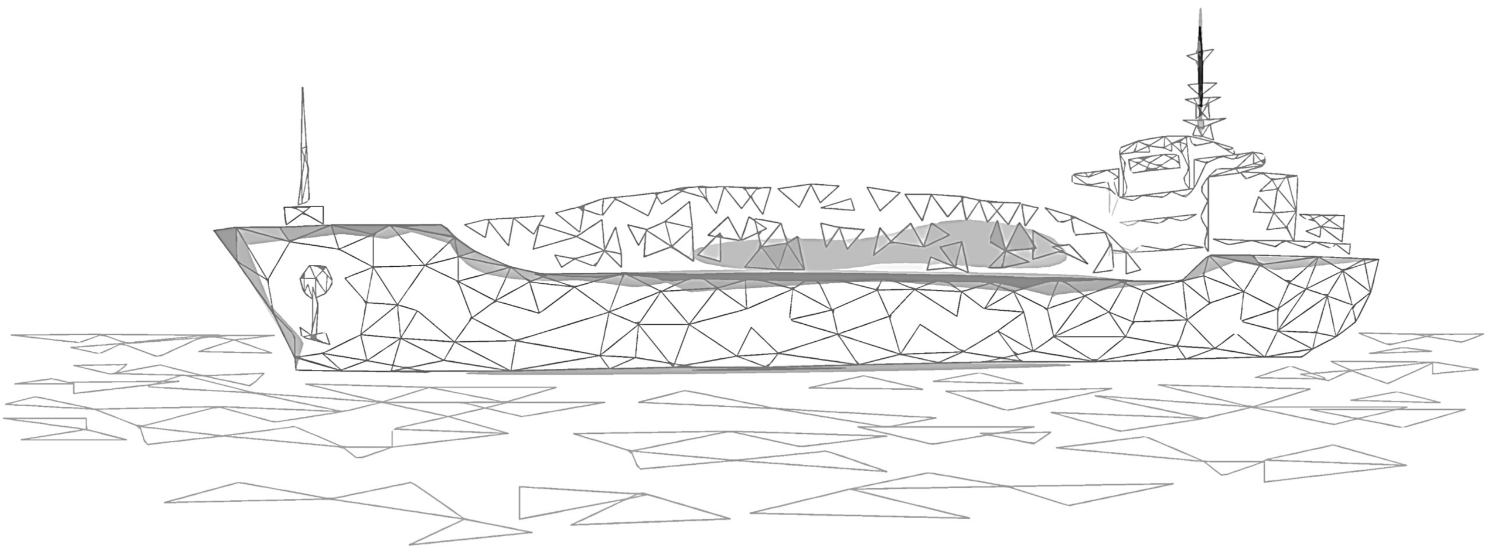


Figure 1.2: Overview of the report structure and corresponding sub-questions addressed in each chapter

I

Literature, Materials and Method



2
Literature study

This chapter presents the theoretical framework of this study, offering support for investigating the impact of Rhine discharges on seaport terminal processes, as outlined as the initial step of the approach in Section 1.5. The first section focuses on the global impact of river drought and its associated effects on ports to gain insights into the global problem. Subsequently, Section 2.2 provides an overview of the Rhine corridor, including the potential impacts of drought on the waterway system and fleet composition, as well as available data that can be used for analysing inland waterway transport. Section 2.3 further elaborates on port processes and the critical parameters that can be used to quantify port processes and furthermore outlines the available data that is used to analyse these processes. Finally, the key takeaways of this chapter are summarised in Section 2.4.

2.1. Rivers and ports affected by drought globally

2.1.1. Global drought issue

In 2022, 2.3 billion people were facing water stress as a result of drought (United Nations, 2022). Drought is a natural hazard that is characterised by multiple factors. The most commonly known one is the lack of precipitation. Global warming causes more water absorption in wet regions leading to more precipitation, while in dry regions, more water evaporates and they become drier (Denchak, 2018). Another effect of climate change is snow melting earlier in the year because of which water moves through the environment very quickly causing grounds to dry up. As a consequence of climate change, the natural pattern of drought is altered; making it more frequent, longer and more severe (USGS, n.d.). It is estimated that if global warming will reach 3°C by 2100, it could cause five times more social and economic losses than there are today. Globally this will affect 129 countries in the next few decades (United Nations, 2022). One of the four distinct types of drought, as identified by Huang et al. (2016) is hydrological drought. Hydrological drought refers to the lack of water in a hydrological system and, specifically, to the occurrence of drought in rivers. According to Van Loon (2015), hydrological drought has a significant impact on river navigation.

2.1.2. Inland waterways affected by drought

A considerable number of rivers across the globe serve as transportation routes. According to Marine Vessel Traffic (2022), 93 rivers around the world have live ship traffic tracking AIS maps, indicating their navigability. Of the 93 rivers identified, 65 are classified as main river streams, with the remaining 28 being tributaries. Additionally, the study only includes rivers that have significant hinterland connections, resulting in the exclusion of 12 rivers, of the 65 main river streams, leaving 53 navigable rivers for further analysis. Recent news articles show that 20 of these rivers have suffered from drought. For instance, in 2022, drought conditions resulted in an abandoned ship being uncovered in the Dnieper River, while water pollution was witnessed in the Oder River. Nevertheless, the effect of these droughts on the navigability of these particular rivers remains unidentified. Appendix A.1 provides further details on these 20 rivers.

Contrary to the situation where the drought does not affect the navigability of the 20 rivers, news articles have confirmed that the drought could indeed impact the navigability of some other rivers (bne IntelliNews, 2022; Bove, 2022; MAERSK, 2021; Poel, 2023; Politi, 2021; Vietnamnet, 2017; Waterways Journal, 2022). As previously mentioned, the Rhine, Yangtze and Paraná River encountered problems during the drought of 2018, 2022 and 2020, respectively. Similarly, vessels had to queue at ports and transit stops along the Bulgarian section of the Danube River in 2022 (bne IntelliNews, 2022). The red river in Vietnam also caused difficulties with waterway transport due to its low water level in 2017 (Vietnamnet, 2017). According to Bove (2022), the Mississippi River was experiencing drought in 2022, resulting in barges getting stuck and causing traffic jams due to the increased use of vessels. Moreover, the river drought results in cargo owners being required to pay a fee charged by carriers to offset the limited freight utilisation. Fees are charged not only on the Rhine and Mississippihaven but also on the Saint Lawrence River for vessels unloading cargo in Montreal and for vessels crossing the Amazon to load cargo at the port of Manaus as a result of the drought in 2022 (MAERSK, 2021; Poel, 2023). These 8 rivers, mentioned in this paragraph, are indicated with the blue line in Figure 2.1, which displays only the mainstream of the rivers.

2.1.3. Ports potentially affected by drought

As previously noted, the processes of a port may be influenced by low river discharge levels. In an attempt to gain insight into which global ports may be affected by droughts, the ports along the 8 previously described rivers affected by drought are identified by the World Port Index (WPI). This WPI consists of a dataset with 3,699 major ports worldwide including their characteristics, however, smaller inland ports are not included in this data. After having this data, only ports lying around the 8 previously described rivers with sizes ‘Medium’ and ‘Large’ are included, and an exception is made for the ports mentioned by news articles such as Manaus and the only port along the Hong red river: the port of Hai Phong, which have port size ‘Small’ as indicated by HDX (2019). As a result, 17 ports, seaports as well as inland ports, are detected as potentially being affected by drought, which are indicated by the red dots in Figure 2.1. It should be noted that seaports and inland ports exhibit distinct logistical chains, as these seaports handle both vessels coming from sea and vessels sailing to the hinterland, while inland ports are used for import or export to land and handle only vessels sailing on inland waterways. Furthermore, it is observed that nearly all ports facilitate the handling of dry bulk and containers. More details about the specific ports, including their maximum length and deadweight tonnage, and whether they have container, dry bulk or liquid bulk facilities, are described in Appendix A.1.

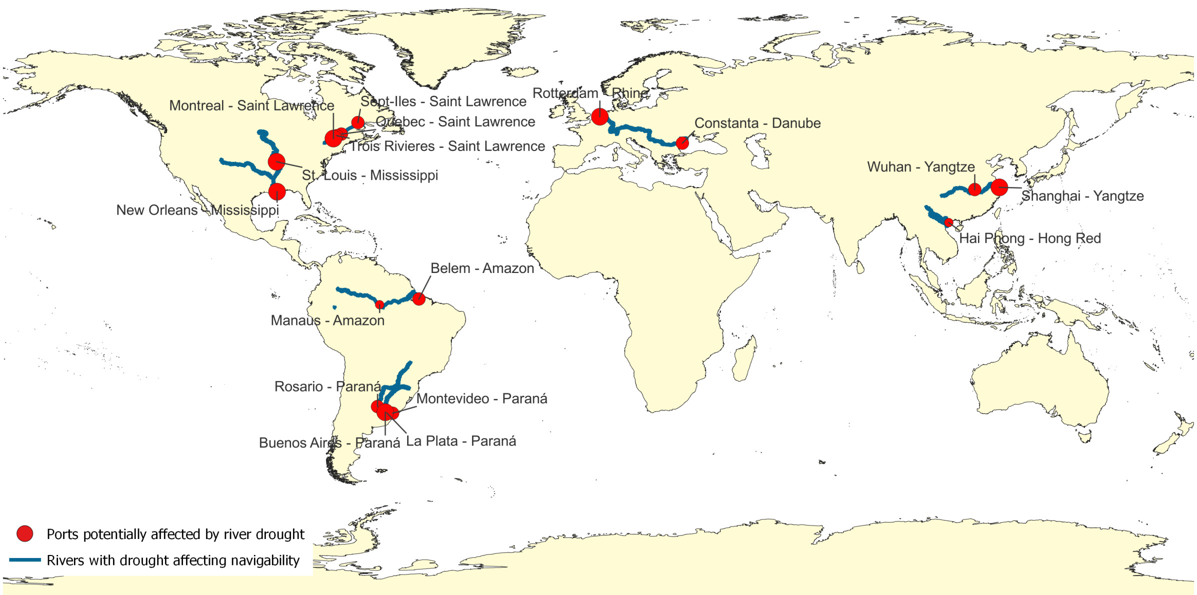


Figure 2.1: Global map of ports potentially affected by river drought

2.2. River Rhine corridor and available data

2.2.1. Rhine corridor and discharge levels

The length of the Rhine river measures 1,230 kilometres, originating in the Swiss Alps and proceeding through the borders between Austria and Switzerland, and then France and Germany, before continuing on through Germany and the Netherlands and finally discharging into the North Sea. The flow system is divided into 5 branches: Alp Rhine, High Rhine, Upper Rhine, Middle Rhine and Nederrijn, as depicted in Figure 2.2. Although the Rhine is originally a rain-snow river, created by snow that falls in the Alps in winter and melts in summer resulting in river discharge, it is shifting to a more rain-fed river due to climate change and higher temperatures, leading to less stored snow in the Alps and an increase in precipitation in winter (Jonkeren et al., 2008). From the Alps, water flows downstream where eventually the Nederrijn crosses the border of the Netherlands at Lobith and divides into the Nederrijn and the Waal. Lobith, located on the eastern side of Nijmegen and indicated by a red dot in Figure 2.2, is a critical point for the amount of water in the Netherlands. It determines the water depth for shipping and the availability of water for agriculture, nature and drinking water for a large area of the Netherlands (Rijkswaterstaat, 2023c). Moreover, this is the first location along the Rhine where Rijkswaterstaat (RWS) measures water levels and discharges when water enters from Germany (Rijkswaterstaat, 2023b).

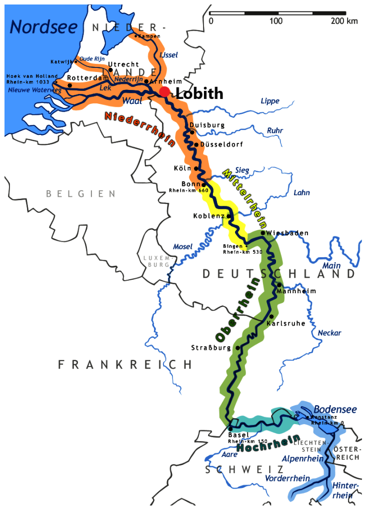
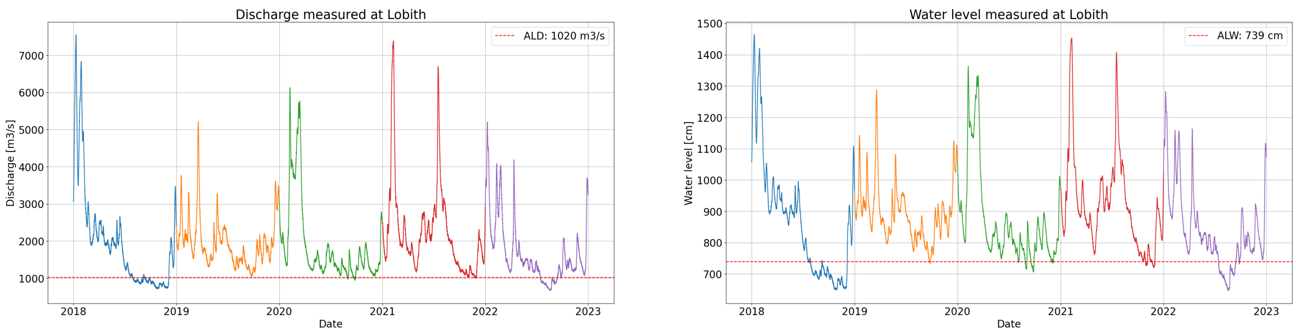


Figure 2.2: Rhine flow system branches (Mutton & Sinnhuber, 2023)

According to Rijkswaterstaat (2023c), the Agreed Low Waterlevel (ALW) for the Rhine at Lobith is 739 cm and the Agreed Low Discharge (ALD) in the Rhine is 1,020 m^3/s (Rijkswaterstaat, 2019). Thresholds for normal discharges are set between 1,000 and 4,450 m^3/s (Rijkswaterstaat, 2023c). Figure 2.3 shows the discharge and water levels at Lobith for the period 2018 to 2023. Each year is indicated with a different colour and the ALD and ALW are marked with a horizontal red line.



(a) (b)

Figure 2.3: Discharge and water level measured at Lobith for period 01-01-2018 until 01-01-2023 (Rijkswaterstaat, 2023b)

These figures show that the longest periods of low water were in 2018 and 2022, confirming the extreme drought in these years. Moreover, the lowest reached discharge of 726 m^3/s in 2018 has shifted to an even lower discharge of 680 m^3/s in 2022. Further details about the specific periods of drought can be found in Table A.2 of Appendix A.2. Additionally, Table C.1 presents the number of days per year with a specific discharge, which is divided into discharge bins of 200 m^3/s. For the future, it is expected that discharges will be even lower than 680 m^3/s as research conducted by Matiu et al. (2021) shows that less water will flow into the Rhine since the amount of snow in the Alps is reducing due to climate change. Wienk (2021) also showed that during the future climate scenarios, based on the KNMI expectations, the days with discharge at Lobith below 700, 850 and 1,020 m^3/s will increase.

2.2.2. Waterway system

The Rhine plays an important role in the waterway system of the Netherlands. Figure 2.4 indicates the passages of inland container vessels and shows that the Waal is the main route for shipping cargo from Germany to the Port of Rotterdam. In 2020, Germany and the Netherlands accounted for 70% of the EU inland waterway transport and are therefore the largest contributors to inland waterway transport (Zelichowska, 2021). The volume of cargo transported at the German measuring point Emmerich, 10 km southeast of Lobith which is indicated by the rightmost blue dot along the Rhine in Figure 2.4, was 168.6 million tonnes in 2021. Mineral oil products are the main shipping product on the Rhine, with 16.2% of the total Rhine transport goods shipped in 2021, followed by sand, stones, gravel (15.3%), coal (13.0%), iron ore (12.7%), chemicals (11.6%), agribulk[1] (10.1%), containers (8.9%) and metals (5.2%) respectively. Of which the share of iron ore, coal and metals grew tremendously from 2020 to 2021 (CCNR, 2022).

The Port of Rotterdam is the largest European seaport, handling twice as much cargo as the second-largest freight, the Port of Antwerp (Eurostat, 2020). In 2021, the Port of Rotterdam (un)loaded 158.2 million tonnes of IWT cargo. In addition to this port, the port of Duisburg in Germany has the second-largest share in inland waterway transport along the Rhine with 44.9 million tonnes in 2021, followed by Cologne, Mannheim, Strasbourg, Ludwigshafen, Neuss, Karlsruhe, Nijmegen, Basel, Kehl, Mulhouse, Krefeld, Mainz, Andernach, Wesseling and Wesel respectively, as depicted in Figure 2.5 (CCNR, 2022).

Figure 2.4: Main waterways in the Netherlands (Varen doe je samen!, 2018)

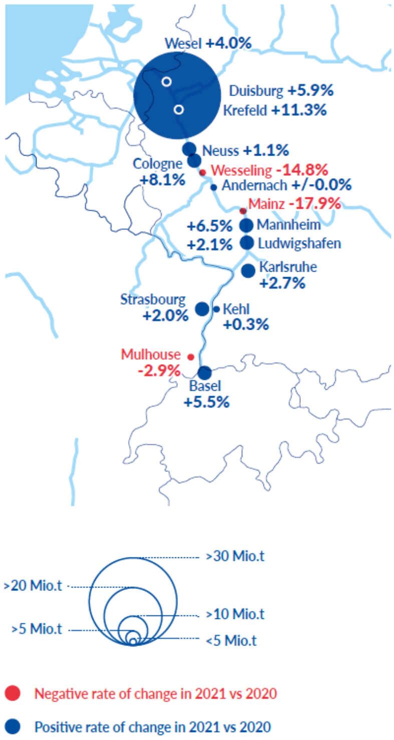


Figure 2.5: Total yearly waterside traffic along the Rhine (in million tonnes) (CCNR, 2022)

Effect of drought on inland shipping

The navigability of the Rhine is heavily dependent on water levels, which can fluctuate significantly depending on seasonal changes and weather conditions. During the droughts of 2018 and 2022, vessels had to reduce their load or shift to other modalities. Although vessels were still able to sail, more vessels were used to ship the same amount of load (CCNR, 2022; Oltermann, 2022; Vinke et al., 2022). The International Commission for the Protection of the Rhine (ICBR) moreover mentions that regular sailing routes on the Middle Rhine had to be closed temporarily due to low water levels in 2018 (ICBR, 2020). Van Hussen et al. (2019) also studied the low water levels in 2018 and according to their study,

[1]All agricultural bulk commodities, such as grain, oilseeds and animal feed raw materials

the low water levels led to 30% higher freight rates and the demand for trains and trucks increased correspondingly, leading to higher prices. Despite the use of other modalities, more vessels resulted in congestion on the inland waterway and longer waiting times at locks. Other sources also confirmed the impact of drought in 2018 (DSV, 2022; OOCL, 2018; Travelweek Group, 2022).

The amount of cargo a vessel can carry depends on the water level and the available draught. This available draught, as shown in Figure 2.6, can be determined with the following formula:

available draught = minimum navigational channel depth +
(actual water level - equivalent water level) - under keel clearance

If the water level is equal to the equivalent water level, indicating that the water level is very low, the available draught of the vessel should be equal to the minimum navigational channel depth minus the under-keel clearance (CCNR, 2021).

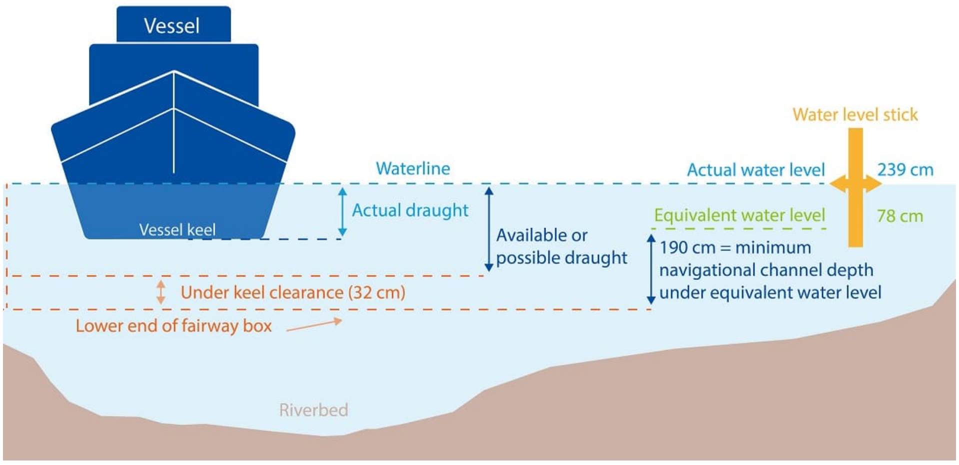


Figure 2.6: Explanation water level, equivalent water level, navigational channel depth and under keel clearance at Kaub (CCNR, 2021)

Located 45 km upstream of Koblenz, Kaub has been deemed the most critical location along the Rhine in relation to water levels. The figure presented above demonstrates that Kaub has an equivalent water level of 78 cm. In instances where water levels fall below 150 cm in Kaub, transport enterprises, such as DSV and Contagro, implement surcharges (CONTARGO, 2022; DSV, 2022). Surcharges are similarly applied at critical locations including Duisburg, Emmerich, and Cologne. It is worth noting, that the equivalent water level varies across these sites. For instance, Duisburg features an equivalent water level of 233 cm. In 2018, 128 days exhibited water levels below this threshold (CCNR, 2022). Consequently, the transport and logistics firm OOCL started to add surcharges for water levels that fell below 300 cm (OOCL, 2018).

2.2.3. Fleet composition

In 2021, the Netherlands had the largest inland fleet in Europe with a total of 3,470 cargo vessels, 739 liquid cargo vessels and 841 push and tug boats, which represents almost half of the Rhine fleet's total of 10,256 vessels (CCNR, 2022). The West-European fleet is divided by the Conférence Européenne des Ministres des Transports (CEMT) into six classes. These classes consist of three types of cargo-carrying commercial vessels: motor cargo vessels, pushed convoys and coupled units. Rijkswaterstaat has revised the CEMT classes since vessels have been lengthened and created their own classification system based on the CEMT classes in 2010 (Table A.3). The vessels are subdivided into different types of motor vessels (indicated with M), pushed convoys (barges indicated by B) and coupled convoys (convoys indicated by C). Motor vessels come in different sizes of vessels, while a pushed convoy consists of a combination of a push boat and a push barge. Various formations can be made, such as 4-pushed convoys or 6-pushed convoys. For those 6-pushed convoys, a distinction can be made between a long or a wide formation. Furthermore, coupled convoys are motor vessels combined with another vessel or a push barge attached in front or alongside (Rijkswaterstaat & Koedijk, 2020). For the transportation of dry bulk, which is 80% done by inland waterway transport, either push barges, coupled convoys or motor vessels can be used. In contrast, container transportation, for which 33% is carried out through inland waterway transport, predominantly relies on motor vessels and coupled convoys. Notably, the transportation of containers is primarily conducted using liner vessels, which follow a fixed route between standard points of origin and destination. Liquid bulk transport, on the other hand, exclusively employs motor vessels that function as tankers (Bureau Voorlichting Binnenvaart, 2023).

Effect of drought on the fleet composition
The effects of drought can cause changes in the fleet composition of Rhine vessels travelling to and from Germany. The vessels passing Lobith and continuing on to Duisburg or further upstream to Basel must adjust their cargo due to draught restrictions during low water levels (CCNR, 2022).

A study conducted by Van Dorsser et al. (2020) investigated the effect of low water on the deadweight capacity of inland waterway vessels. The study identified the minimum available draught for the different CEMT classes per tanker, dry bulk or container vessel and the amount of cargo that can be carried under such circumstances. If the water level at Kaub can fall below 1.50 m vessels with CEMT class higher than class V are unable to operate.

The Rhine Police Regulations impose restrictions on the lengths and widths of pushed convoys and coupled barges, based on the water level at various locations along the navigation route on the Rhine. For the section between Bad Salzig, 25 km upstream of Koblenz, and Gorichem, 40 km upstream of the Port of Rotterdam, length and width restrictions are respectively set to 269.6 m and 22.9 m for upstream sailing vessels, and 193 m and 34.35 m for downstream sailing vessels. In addition, the rule limits the number of barges to six, and a maximum draught of 1.50 m is allowed for four push barges during downstream sailing. The water level at Duisburg must be between 2.75 m and 7.15 m, and at Lobith between 8.50 m and 13.50 m unless authorities have authorised sailing at other water levels (Politie voor de Rijnvaart, 1994). This water level limit of 8.50 m at Lobith is equal to a discharge of approximately 1,000 m^3/s.

Dry bulk transportation, offers the best opportunity to adapt to low river discharges, as various types of vessels can be employed for this purpose. In contrast, containers are predominantly transported via liner vessels that operate on fixed routes, excluding the possibility of adjusting the fleet composition. Likewise, the number of available tankers constrains the flexibility of liquid bulk transport (Bureau Voorlichting Binnenvaart, 2023). In 2018, dry bulk transportation had the highest freight rates compared to container and liquid bulk (CCNR, 2021). In a study by Wienk (2021), a comparison of the cost per kilometre for inland waterway transport of liquid and dry bulk was conducted for future drought scenarios. The findings suggested that it would be more feasible for liquid bulk to shift to rail transport as soon as the discharge at Lobith remains below 700, 850, or 1,020 m^3/s for 35, 50, or 65 days, respectively. However, for dry bulk, vessel transportation remained the most viable option, even as discharge periods extended.

2.2.4. Available data for analysing inland waterway transport

In order to research vessel movements in a river, data is required. Information- and tracking system for inland shipping (Dutch: Informatie- en Volgsysteem voor de Scheepvaart), commonly referred to as IVS, is designed for all vessels utilising the Dutch waterways (Rijkswaterstaat, 2023a). This data encompasses vessel trip information, where each trip is characterised by a number of attributes, including the voyage date, an RWS ship type, an RWS ship class code (sk code), the load status of the vessel, the country and city of origin, the country and city of destination, the number of vessels involved in the voyage, and the quantity of cargo transported. The sk code is the vessel classes classified by RWS and is subdivided into motor vessels, pushed convoys or pushed barges, indicated by ‘M’, ‘C’ or ‘B’, as described in Section 2.2. These sk codes are listed in Table A.3 under the name ‘RWS class’. Although data is gathered at locations in the Netherlands, trip information with destination or origin outside the borders of the Netherlands (i.e. Germany) is also available. This makes it possible to analyse vessels along entire river corridors.

Previous studies showed that the use of IVS data can provide insight into inland waterway transport (Ligtenberg, 2022; Vinke et al., 2022). Ligtenberg (2022) determined the fleet of the Waal with IVS data to establish lock capacity at the Waal. Moreover, Vinke et al. (2022) utilised IVS data to show that the drought of 2018 affected the fleet between Rotterdam and Duisburg and caused more vessels to arrive in the Port of Rotterdam. However, this research did not yet investigate the potential congestion on the Rhine by looking at the total load shipped per day and no research has been conducted on the impact of drought on terminal processes within the Port of Rotterdam by analysing the number of vessels and load carried on the Rhine beforehand. Consequently, it is of interest to examine the total amount of cargo transported per day to obtain a thorough understanding of the situation. The total load per day depends on both the mean vessel load and the number of vessels operating per day on the Rhine.

2.3. Port terminal functionality and available data

2.3.1. Logistical chain and processes of a port

A port serves as a crucial hub in the logistical chain for the transportation of goods. Various terminals within the port serve distinct functions, enabling the handling of different types of products, for instance, dry bulk, container and liquid bulk terminals can be distinguished. For dry bulk terminals, the location of the port plays a primary role in the function of the dry bulk chain. A terminal that ships dry bulk is most often either an export or an import terminal. The export terminal is then mostly located at a remote port site close to a mine for which seagoing vessels are loaded to transport it overseas. It should be noted that if the mining source is located more inland, trains or barges are required to initially transport it to the export terminal. Import terminals are, however, often located closer to the end consumer where the product is loaded into trains, trucks or barges to transport to the hinterland. While the majority of dry bulk terminals serve as either import or export terminals, some are classified as transshipment terminals. These terminals receive cargo from overseas, unload the seagoing vessels, and store the goods in the storage yard. Subsequently, the products are reloaded onto barges or trains for transportation to the hinterland (PIANC WG 184 et al., 2019; Van Koningsveld et al., 2021). As this study centres on this specific type of terminal, it is assumed that the logistical chain of ports is established as a transshipment terminal. The logistical chains of container sea terminals with hinterland connections closely resemble those of dry bulk transshipment terminals. These terminals facilitate the transshipment and storage of containers, involving unloading from seagoing vessels, transportation to the storage yard, and subsequent loading onto trucks, trains, or inland waterway vessels for transport to the hinterland. Liquid bulk terminals are responsible for the handling of products such as oil, gas, and chemicals, typically transported from offshore extraction points to refineries via seagoing vessels. After storage in tanks at the refineries, these products are transported to the hinterland using pipelines, barges, trains, or trucks, with additional tank cleaning requirements for chemical shipments.

The loading and unloading process of each cargo type also differs due to the different sizes and volumes of these products. Containers are designed to ensure that all products are transported in uniformly sized containers, facilitating swift loading and unloading. The transportation of liquid bulk has the same advantage, which typically involves the use of pipes to pump gas, oil, or chemicals into a tanker. However, the transportation of dry bulk lacks this benefit, owing to the transport of loose particles, such as coal and iron ore. As a consequence, loading and unloading is done with different equipment. The unloading of large seagoing vessels can be done with self-unloading or with shore-based equipment using grabs, pneumatic systems, vertical conveyors, bucket elevators and slurry systems. A hold is emptied for approximately 70% after which the hold is further unloaded with portable equipment. During this process, the commodity is transferred onto a conveyor belt, which transports it to the appropriate storage location. Long stockpiles of material in the open air are segregated by conveyor belts and rails for stackers or reclaimers, enabling the material to be arranged into various piles. Depending on the nature of the product, the material may also be stored in enclosed silos. Notably, coal has a greater volume than iron ore, necessitating more storage space. Due to the different processes for loading and unloading, intermediate storage is often required. After it has been stored and modalities have arrived, the loading processes can start. The products are loaded onto the conveyor belt, which deposits them directly into vessel or train holds. This method for loading is therefore significantly quicker than unloading dry bulk (Ligteringen, 2017).

2.3.2. Port disruptions and critical parameters

The cargo handling capacity of a terminal depends on several factors, including the size of the terminal and the available equipment. For instance, a larger terminal with more berths is capable of handling a greater number of vessels, while a terminal with a larger storage area can accommodate more cargo. Additionally, the capacity of cranes plays a crucial role in determining the duration of the loading and unloading process, commonly referred to as service time. In a dry bulk terminal, the capacity of the unloading equipment is often decisive for the throughput capacity of the terminal, as unloading involves handling larger vessels and the time of unloading takes more time than loading. Since storage and cargo handling are the main processes in a terminal, the size of the storage area and the length of the quay are the main components determining the terminal's capacities (Ligteringen, 2017).

A terminal is designed such that a port can optimally perform and that the capacity for cargo handling and storage is sufficient to handle the throughput. However, a port may not optimally perform as a result of disruptions in the logistical chain causing downtime. This downtime can be a consequence of weather circumstances, making it unable for vessels to enter, due to congestion in the access channel, not enough cranes, insufficient storage capacities or congested hinterland connection. All of these cases can lead to a requirement for more capacity by optimisation or expansion (Van Koningsveld et al., 2021). As the scope of this study is limited to the cargo handling and storage processes, the potential disruptions to these operations and the critical parameters to assess their capacity will be elaborated upon.

Cargo handling
The need for cargo handling capacity arises when there are a large number of vessels awaiting handling. In port development, the waiting time is related to berth occupancy, which represents the proportion of the berth occupied by vessels. When the berth occupancy is high (close to 100%), numerous vessels must wait before they can be serviced, which impairs the terminal's efficiency (PIANC WG 184 et al., 2019; Van Koningsveld et al., 2021). Berths may become more occupied due to increased vessel arrivals or as a consequence of longer service times. For instance, when crane capacity is insufficient and cargo handling takes longer than usual, combined with a high demand for vessel handling, the berth becomes more occupied, leading to an increased number of vessels waiting for service. Hence, the critical parameter for cargo handling is the measure of **berth occupancy**, which depends on both service time and the number of vessel arrivals.

In the design of a terminal, the required berth occupancy varies among different terminal types. Container terminals, for example, are subject to strict conditions imposed by shipping companies, which demand minimum waiting times, resulting in a low required berth occupancy of approximately 35% (Ligteringen, 2017). On the other hand, liquid bulk terminals generally require a higher berth occupancy of between 50-65%, and for dry bulk, this may be even higher than liquid bulk due to the absence of strict conditions (Van Zwieteren, 2020).

According to Van Zwieteren (2020), it has been determined that the adjusted length occupancy metric is the most suitable for assessing berth occupancy at dry bulk and container terminals, considering the variability in the number of berths based on the length of vessels. The adjusted length occupancy represents the percentage of occupancy calculated by comparing the number of vessel lengths present to the available quay length, with an additional margin of 15 meters accounted for when multiple vessels arrive.

Storage
Insufficient storage capacity occurs when there is not enough space available to accommodate incoming cargo, resulting in a full stockpile. This can happen when more cargo is coming in than going out, leading to a capacity disruption. To prevent such disruptions, it is advisable to maintain a storage capacity range of 40-80% full, ensuring flexibility between incoming and outgoing stock fluctuations (PIANC WG 184 et al., 2019). Thus, the critical parameter for the storage capacity is the **stockpile**, which depends on the disparity between the amount of cargo entering and leaving the terminal.

2.3.3. Available data for analysing port processes

Automatic Identification System (AIS) data is a widely used source to analyse vessel movements and encompasses messages pertaining to all vessels detected within a specific polygon. AIS transponders are developed by the International Maritime Organization, an organisation responsible for the safety and security of shipping. An AIS transponder provides position, identification and information about the vessel to other vessels and coastal authorities. In accordance with international regulations, as of 2004, all passenger ships, international ships larger than 300 gross tonnages, and cargo ships larger than 500 gross tonnages are required to have AIS transponders on board (International Maritime Organization, 2019). When the data is properly filtered, it can be used to analyse port processes.

A number of studies have been conducted on terminal performances using AIS data (Feng et al., 2020; Triska & Frazzon, 2022; Van Zwieteren, 2020; Zhong et al., 2020). Feng et al. (2020) used AIS data to look at the time efficiency for different areas and different type of vessels in two ports in China. Zhong et al. (2020), created an AIS driven method to calculate the handling quantity of each tanker and how this affects key performance indicators of an oil terminal, for instance, the oil spill risk during handling. The study of Triska and Frazzon (2022) consist of a simulation-based approach for dimensioning the storage of port terminals to prevent terminal congestion that occurs due to lack of storage. AIS was also used to assess the impact on the port during strikes in Gothenburg, where it was found that fewer ships arrived and as a result, a decline in container volume handled occurred (Svanberg et al., 2021). Van Zwieteren (2020) created a tool to study the terminal performances of different terminals with AIS data and used queuing theory. The tool developed by Van Zwieteren (2020) is open to public use. However, this tool only considers vessels that arrived and were registered in Seaweb[2] and did not distinguish between unloading and loading berth locations. Therefore, an AIS filtering method that is able to analyse berth occupancy at different locations, including barge loading locations, is lacking and has to be developed. Due to its limitations, AIS data can only provide an approximate indication of a vessel's position and duration of activity, rendering it incapable of accurately determining the precise quantity of cargo carried by vessels.

2.4. Summary

The literature study has revealed that 17 ports worldwide have the potential to be affected by river drought. In the case of the Port of Rotterdam, which can also be influenced by river drought due to its connection to the Rhine, the background information provided in Section 2.2 gives insights into the system and fleet of the Rhine corridor, also in relation to low river discharge levels. IVS data has the potential to provide insights into inland shipping on the Rhine and the total load transported per day could offer an understanding of potential congestion or disruptions on the river. The total load is dependent on the average load per vessel and the number of vessels, these parameters can therefore be used to study the impact of low river discharge on IWT.

The processes within the port that can be affected by river drought include cargo handling and storage. Berth occupancy serves as a critical parameter for cargo handling and can be determined using adjusted length occupancy for dry bulk. This parameter is influenced by the number of vessel arrivals and the service time. Stockpile is a critical parameter for storage and can be measured by tracking the difference between inbound and outbound cargo in the terminal. AIS data, a global vessel movement data source, is commonly used for analysing port processes based on vessel movements in the port. However, there is currently no method to filter AIS data in order to determine processes that depend on both seagoing and inland vessels and should therefore be developed. It should be noted that AIS data cannot accurately identify the precise quantity of cargo carried by vessels.

[2]Seaweb Maritime Portal database comprises information from a comprehensive range of seaports and terminals globally, as further explained in Section 3.4.1

3

Materials and methods

This chapter outlines the second step in the research approach, mentioned in Section 1.2, by describing the materials and methods employed to assess the impact of low river discharge on seaport terminals. As research is conducted on one terminal, the case study is described in Section 3.1. The materials utilised encompass relevant vessel movement data, as found in the previous chapter, along with additional terminal cargo data, represented as input variables and indicated by the grey boxes in Figure 3.1. These available data sources and their limitations are described in Section 3.2. The figure shows the four processes analysed, indicated by 1 to 4, as previously described in Chapter 1. Vessel movement data, specifically IVS and AIS data, require filtering before parameters can be determined to apply to the various processes. The data processing of IVS and AIS data is described in Section 3.3 and 3.4, respectively. Section 3.5 describes the application of the data using the critical study parameters to evaluate the four processes. This section addresses the following sub-question as listed in Section 1.3: *How can available data be processed and analysed to determine the effect of river drought on shipping at the river and port terminals?*

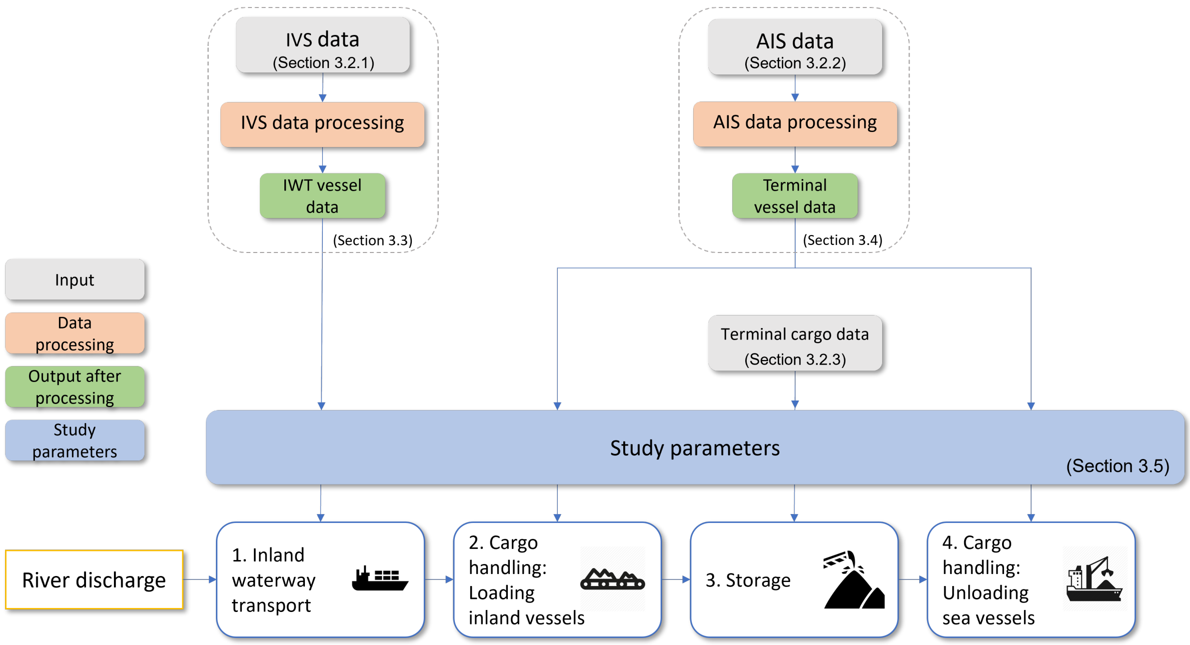


Figure 3.1: Schematic overview of procedure and section linkages for study analysis

3.1. Case study: Port of Rotterdam - EMO dry bulk terminal

A case study is conducted on the EMO dry bulk terminal within the Port of Rotterdam. This port is the largest freight port in Europe, primarily transporting liquid bulk, followed by containers and dry bulk.

The Port of Rotterdam covers a total area of 12,464 ha, stretching from the Maasvlakte, the leftmost extension of the port into the North Sea, to the Waalhaven, the rightmost part of the port, and a few small terminals in Dordrecht, as shown in Figure 3.2, which also presents the different terminal types.

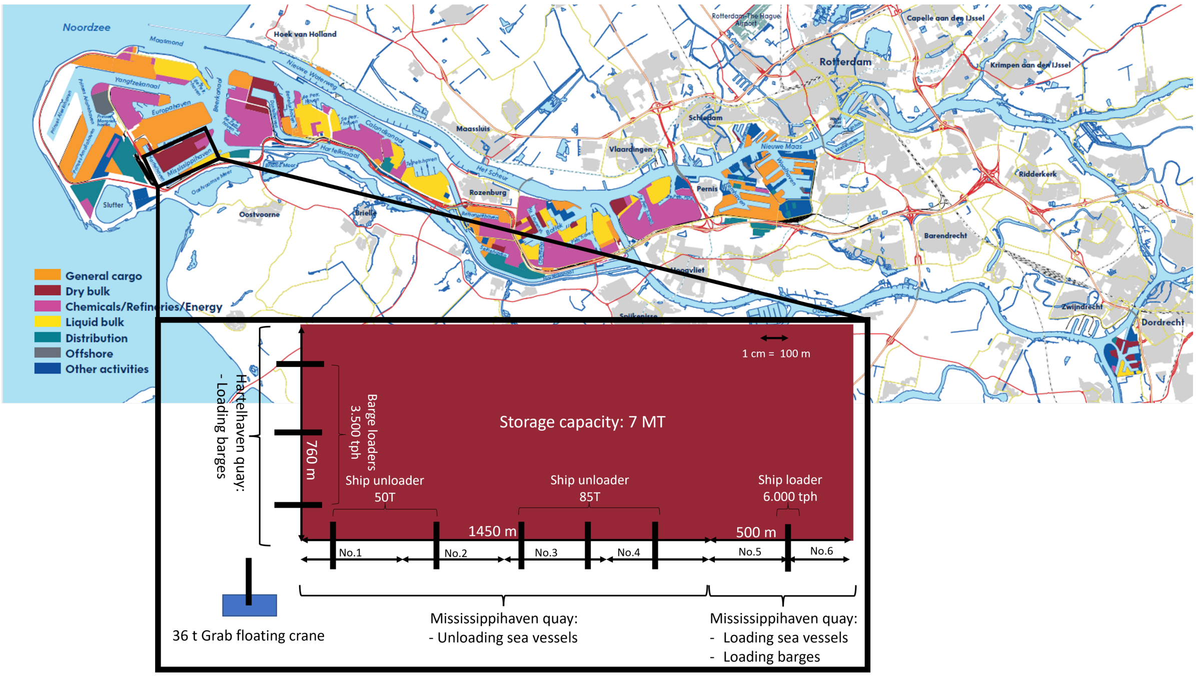


Figure 3.2: Map of Port of Rotterdam terminals with detailed EMO terminal layout (Port of Rotterdam, 2021)

The EMO terminal, located in the Maasvlakte of the Port of Rotterdam as shown in Figure 3.2, has been chosen as a case study due to its distinction as the largest dry bulk terminal in Europe and its role as a transshipment terminal, accommodating both seagoing vessels and vessels destined for the hinterland. With a terminal capacity of 42 million tonnes of iron ore and coal per year, it handles roughly 75% of all dry bulk cargoes processed in the Port of Rotterdam. Furthermore, the storage capacity of the terminal is 7 million tonnes of dry bulk. As a transshipment terminal, EMO specialises in the handling of iron ore, coking coal and steam coal, which are imported from overseas, stored in the storage area, and subsequently transshipped to barges, trains and seagoing vessels for further distribution to other countries or dispatched to nearby power plants for immediate consumption. After being stored at EMO, the majority of the coal and iron ore is transported to Germany. In 2022, inland waterway vessels accounted for 52% of the coal transportation, followed by 32% by train and 13% to power plants, with only 3% being shipped back overseas. In terms of iron ore transportation, the majority (70%) is transported by train, followed by 25% by inland waterway vessels and only 5% to overseas destinations (EMO, 2023).

As a consequence of differences in loading and unloading rates, a distinction between loading and unloading is necessary at the EMO terminal. The terminal is comprised of two quay walls: one for barges loading on the west side in the Hartelhaven (shown in Figure 3.2), and another for seagoing vessel unloading as well as barge and seagoing vessel loading on the south side in the Mississippihaven (shown in Figure 3.2). The depth at the Hartelhaven location is limited to 6 m due to the absence of seagoing vessels, while at the Mississippihaven, which serves both barges and seagoing vessels, the maximum depth is 23 m. The Hartelhaven terminal is equipped with three berths, each with a single conveyor belt. Loading operations involve the use of one belt per barge or one belt per two barges lying alongside, and the loading capacity is up to 3,500 tonnes per hour (EMO, 2015). The Mississippihaven has 6 berths, the most left berths, numbered 1-3 in Figure 3.2, have an available depth of 21.65 m and berth number 4 has a depth of 23 m. Seagoing vessels are unloaded at these 4 berths using one or multiple cranes simultaneously. There are a total of 5 cranes available at the 4 berths in the Mississippihaven. The two leftmost cranes have a grab capacity of 50 tonnes, while the three on the right have a grab capacity of 85 tonnes. The cranes with a capacity of 85 tonnes are capable of unloading an average of 1,800 tonnes per hour. Two additional berths on the right side of berth number 4 are used for loading smaller seagoing vessels and barges, with an available depth of 15.65 m at berth 5 and 6.65 m at berth 6. Additionally, only one loading belt with a capacity of 6,000 tonnes per hour is available at these two berths. Furthermore, the terminal also consists of a floating unloading grab crane with a capacity of 36 tonnes (PIANC WG 184 et al., 2019; S&P, 2022). The lengths of the different berths provided by PIANC WG 184 et al. (2019) and S&P (2022) have been reconsidered by utilising Google (2023). The length of the Hartelhaven illustrated in Figure 3.2 excludes the waiting area at the north side, moreover, berths 1 to 4 of the Mississippihaven have a length of 1,450 m, which is 100 m wider according to Google (2023) compared to PIANC WG 184 et al. (2019) and S&P (2022).

3.2. Data availability and limitations

This research makes use of the input of three different data sets: IVS data, AIS data and terminal cargo data, as indicated with the grey boxes in Figure 3.1.

3.2.1. IVS data

The IVS data utilised in this study consists of vessel registration data collected at the counting station of Lobith, as previously described in Section 2.2, from 2012 to 2022. While the IVS data is relatively extensive, a major limitation is that it is anonymised, thereby preventing the determination of the specific vessel, except for the vessel type, to which the data relates. Consequently, it cannot be matched with the later described AIS data. Additionally, some trips lack an sk code, which represents a minor drawback. Since the focus of the study is solely on dry bulk vessels and the data includes vessels with various origins and destinations, further processing is conducted as outlined in Section 3.3.

3.2.2. AIS data

AIS data is sourced from two distinct providers: Royal HaskoningDHV (RHDHV) and Rijkswaterstaat (RWS). While this data can offer valuable insights into vessel movements, it also has certain limitations, as explained below.

RHDHV AIS Platform

The AIS data that is collected from the AIS platform, developed by RHDHV, is obtained from the publicly available AIS data via the AIShub, which expands the coverage to approximately 700 stations globally. Figure 3.3 illustrates the global AIS coverage (AISHub, 2022) up to December 2022. The initiative for the creation of the platform was established in December 2018, with the installation of the first antenna in Scheveningen. Consequently, data can only be acquired from April 2019 onwards, thereby limiting the usage of data prior to this date (Royal HaskoningDHV, 2018).

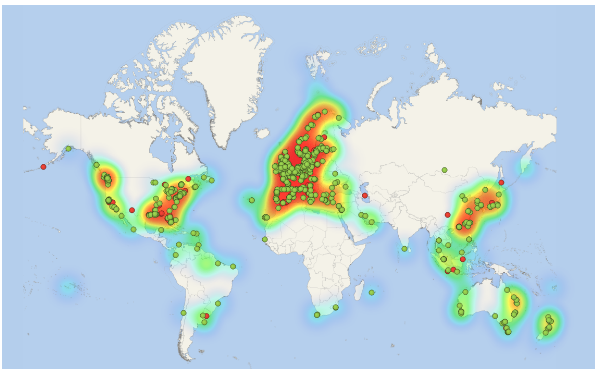


Figure 3.3: AIS Coverage Map (AISHub, 2022)

The AIS platform collects both static and dynamic information pertaining to a vessel. The static and dynamic information encompasses the following elements:

Static information

- Maritime Mobile Service Identities (mmsi) number: a unique nine-digit identifier
- Vessel call sign: a unique identifier containing both numbers and letters
- Vessel name
- International Maritime Organization (IMO) number
- Vessel length
- Vessel width
- Vessel types

Dynamic information

- Vessel position: coordinates indicating the position of the issued message
- Timestamp: time and date of the issued AIS message
- Course over ground: direction of the vessel during issued message
- Speed over ground: speed during issued message
- Heading: rounding numbers of course of ground
- Draught: vessel draught

Furthermore, the platform allows for the implementation of filters for different vessel types, and the selection of minimum and maximum parameters for the vessel's overall length, breadth, deadweight tonnage, draught and speed (AISHub, 2022; International Maritime Organization, 2015).

To analyse port processes using vessel movements within AIS data, it is necessary to create a specific polygon and employ thorough filtering to extract only vessels that are serviced at a terminal. The steps involved in this process are detailed in Section 3.4.

AIS limitations
During the analysis of the data, it was encountered that there are some limitations. Upon obtaining data from April 2019 until the end of 2022 from the RHDHV platform, it was discovered that certain dates were missing from the data set. These are listed in Table 3.1. This is caused by an unstable connection of the AIS platform, during which it was unable to receive events. Once the system was restarted, data was received again. All missing dates occur on weekends and were identified on Mondays when the system was restarted.

Table 3.1: Missing AIS data dates across the RHDHV AIS platform

Year	Periods
2022	23/07-25/07 & 27/08-29/08 & 15/09-19/09 & 12/11-13/11
2021	24/07-25/07 & 17/11
2020	none
2019	01/05-02/05 & 11/12

The use of AIS data in research can be complicated by several limitations. As AIS is an open-source system, the data depends on what information is voluntarily transmitted by ship operators. This can result in incomplete or private information being withheld. Additionally, the transponder may have been moved to another ship, leading to inaccuracies in identification and information. The coverage of AIS data collection depends on the distribution and reach of antennas, which may not be evenly distributed and can result in varying levels of data availability in different geographic locations. Alternatively, many vessels do not transmit specific information, such as speed, gross tonnage, net weight tonnage, TEU capacity, length overall, breadth depth and vessel type. In order to get insight into the total missing data per parameter, Table B.1 in Appendix B.1 presents the percentage of missing data for several aspects, based on the 2022 data set, after filtering out irrelevant vessel types.

RWS AIS data
Additional to the RHDHV AIS data, AIS data is also obtained from RWS. Prior to usage, all privacy-sensitive information such as vessel name, mmsi number, and IMO number in the RWS AIS data is

anonymised. Consequently, it is challenging to compare data from RHDHV to RWS, as it is not feasible to detect the same vessels in both datasets. Furthermore, another dissimilarity between RHDHV and RWS AIS data is the extent of the data coverage. While RWS data is limited to the Netherlands, larger polygons can be created within the country as compared to RHDHV. This enables the visualisation and identification of a vessel's entire trajectory, including its origin and destination. Additionally, the RWS dataset does not contain any missing data points. However, this data set is solely utilised to overcome the missing data limitations of the RHDHV AIS platform.

3.2.3. Terminal cargo data

Terminal cargo data is used to establish the amount of cargo handled within the port, as AIS data is lacking the ability to determine the precise quantity of cargo carried by vessels. Data regarding the amount of cargo handled by the EMO terminal per month in the year 2022 is provided as a result of a conversation with Peter de Klerk, technical service manager of the EMO terminal (EMO, 2023). The data is used to analyse the impact of low Rhine river discharge levels on the stockpile of the EMO terminal, as further described in Section 3.5.3, and consists of six distinct graphs. One of these graphs, depicted using bar plots, represents all cargo that enters the terminal per month by the unloading of seagoing vessels in the year 2022. The other five graphs illustrate the amount of cargo leaving the terminal via various modalities and destined for different locations: cargo that is loaded into inland waterway vessels, cargo loaded into trains, cargo that goes to the power plant, cargo that is transshipped from seagoing vessel to barges, and cargo that is loaded into seagoing vessels. These graphs are also illustrated as bar plots but moreover accompanied by the tonnage per product transported per month.

3.3. IVS data processing: From raw data to IWT vessel data

IVS data is translated into a database consisting of relevant IWT vessel data, more specifically vessel load and the number of vessels, that can be related to the occurring Rhine discharge levels. The IVS filtering process is presented in Figure 3.4. The data is subsequently filtered, along with RWS discharge data, to eliminate irrelevant information, as explained in Section 3.3.1. Finally, a route is selected using the filtered IVS data, and the filtered discharge data is incorporated to generate vessel data for this specific route, as outlined in Section 3.3.2.

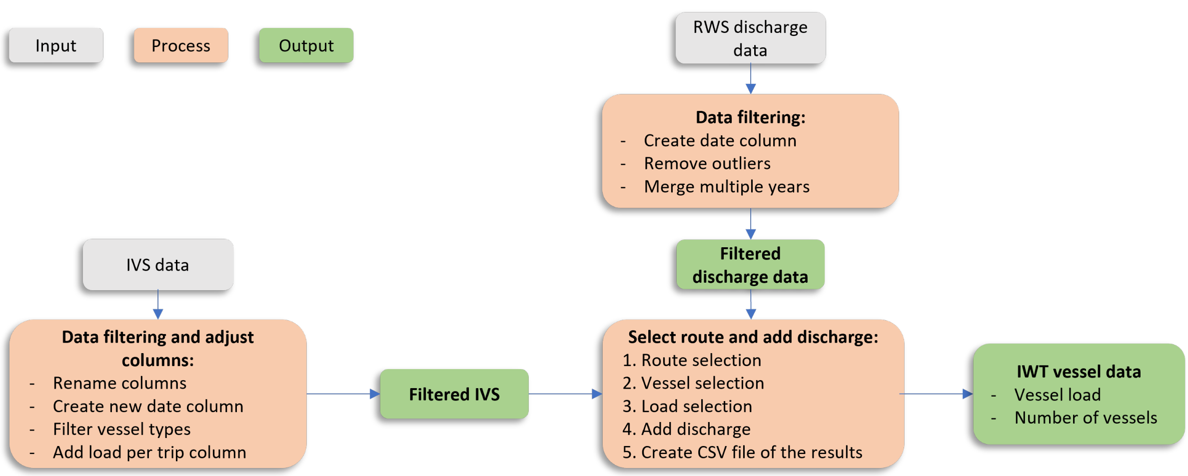


Figure 3.4: Flowchart of IVS data proccessing

3.3.1. Data filtering and adjusting columns

The flowchart in Figure 3.4 depicts that filtering of raw data is performed for the two previously mentioned data sets. These filtering steps, as also depicted in the figure above, are described for these two data sets separately.

IVS data to filtered IVS

After loading IVS data into Python, column names are renamed to utilise it more easily. Subsequently, a new date column had to be generated due to the fact that Python interchanged the day and month columns. Recreational vessels and vessels without cargo are removed from the data set, as these do not moor at a terminal. The column that indicates the amount of load carried contains the total load for the number of vessels making a trip. If a trip is made by 2 vessels, the amount of cargo is also twice as high as for trips made by one vessel. Therefore, an additional column is created with the amount of load per trip, which is equal to the load column divided by the number of vessels making the trip. As a result of these steps, a filtered IVS DataFrame is created. A DataFrame is a definition for a data set created by the Python package 'Pandas'[1], it contains data in a table with rows and columns.

RWS discharge data to filtered discharge data
The hourly discharge levels are extracted from the measuring point Lobith obtained from Rijkswaterstaat (2023b) for each year. This data, collected as CSV files, are processed using Python. A date column is created by parsing time and date information and, outliers, such as unrealistic discharge numbers, are removed. In the case of multiple years being analysed, the yearly data is merged into a single DataFrame spanning multiple years. Refer to Figure 2.3a in Section A.2 for an example of the discharge levels from 2018 to 2023. As a result, a filtered DataFrame with hourly discharge levels at Lobith over a 10-year period is created.

3.3.2. Select route and add discharge

Using the filtered IVS data from the previous step, this stage selects a route and adds discharge, resulting in trip-specific IVS data that can be used for analysis. The process to come up with trip-specific data is depicted in Figure 3.4 as the bottom right process square named: 'Select route and add discharge'. Each step is separately described below.

1. Route selection
It is assumed that a large share of the inland waterway vessels arrives at the EMO terminal to load their cargo for transportation to the hinterland. To align with this assumption as closely as possible, solely vessels are selected with Rotterdam as the origin and Germany as the destination. It should be noted that the IVS data is not specific to a terminal and therefore can not be compared to the AIS data.

2. Vessel selection
To comply with this research's scope, only dry bulk vessels are selected. Therefore, vessel types that are identified as tankers or solely container carriers are excluded from the analysis.

3. Load selection
Since it is assumed that barges in a terminal are being loaded to transport their cargo to the hinterland, only trips are selected that carry load with them.

4. Add discharge
The filtered discharge data is used as input. A new DataFrame is created that contains the mean discharge level per day, resulting in the data set having only one discharge value per day. This DataFrame is then merged with the trips DataFrame, creating a new column named *discharge*. This column represents the mean discharge level for the start date of each trip.

5. Create CSV file of the results
Finally, a CSV file is created with all dry bulk vessels, counted at Lobith, sailing from Rotterdam to Germany over a time span of 10 year period. Making it possible to analyse the vessel load and number of vessels during different years with various discharges. The application of the data to these parameters is further described in Section 3.5.1.

3.4. AIS data processing: From raw data to terminal vessel data

Raw AIS data is translated into a database containing information about vessels served by the terminal, specifically the number of vessels and the duration of the vessels, such that these can be related to the occurring Rhine discharge levels. This translation process is divided into several steps, as illustrated in

[1] A package for Python programming that can be used for data analysis

the flowchart depicted in Figure 3.5. The inputs for this process encompass five distinct data sources, wherein the foremost one is the monthly AIS terminal data (left grey box in Figure 3.5). The Seaweb data, filtered discharge data, AIS sea data, and AIS Rhine data are utilised as subsequent inputs in the process. Section 3.4.1 describes the retrieval and process of filtering of the aforementioned subsequently inputted data sources, accompanied by a description of the retrieval of monthly AIS terminal data. The overall process consists of three main stages as indicated by the three lower orange boxes in the figure below: filtering the AIS data and creating trips (Section 3.4.2), defining all vessels that are lying idle in the terminal based on these trips (Section 3.4.3) and further vessel filtering and adding features (Section 3.4.4), resulting in a database of vessels being served which is suitable for analysis. This last step is required since there may still be vessels in the data, after defining which vessels lie idle, that are not being served. Moreover, the steps that are taken in the methodology are occasionally accompanied by explanations for the later applied case study, the EMO terminal, which is described in Section 3.1. Data for the year 2022 is utilised in these examples for illustrative purposes. Additional information and examples of this section can be found in Appendix B.

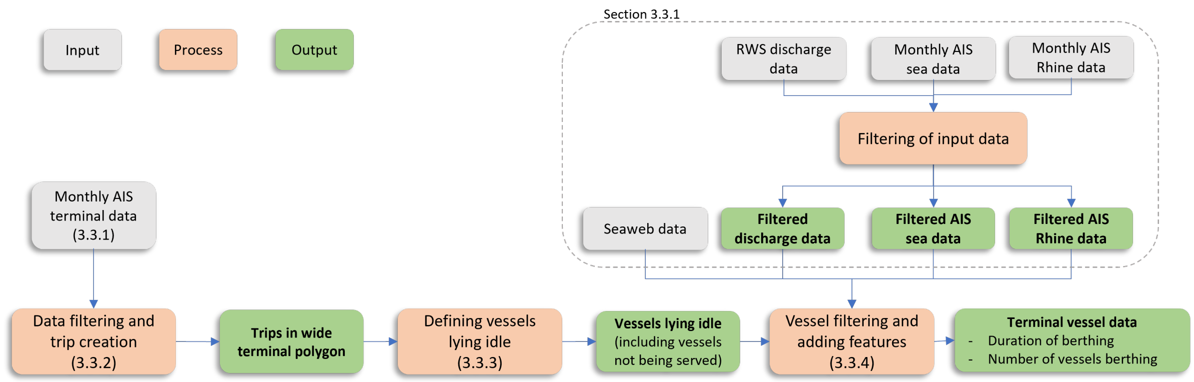


Figure 3.5: Comprehensive flowchart of AIS data processing with indicated sections for each processing part

3.4.1. Retrieving and filtering of input data

The input data sources in the grey boxes of the flowchart above are explained alongside the filtering process of the RWS discharge data, monthly AIS sea data, and Rhine data. Discharge data retrieved from RWS undergo individual filtering, while AIS data extracted from a polygon created in the Rhine and in sea undergo a similar procedure, as illustrated in Figure 3.6. Additionally, the retrieval of monthly AIS terminal data is described.

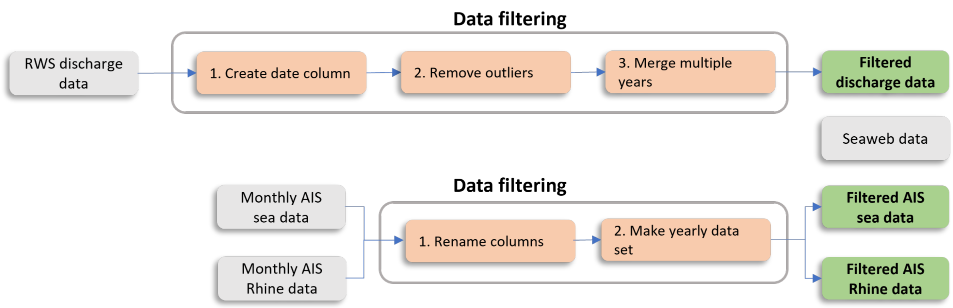


Figure 3.6: Flowchart of remaining data sets filtering

Rijkswaterstaat discharge data

The retrieval and filtering process of the RWS discharge data is almost similar to the steps described for the IVS data in Section 3.3.1. However, a minor distinction is the length of the dataset, for IVS data the years 2012 to 2023 are obtained from Rijkswaterstaat (2023b), while AIS data only requires discharge data from April 2019 to 2023.

AIS Rhine and sea data

The AIS data from both Rhine and sea regions is used to determine the origin of vessels in the terminal. Polygons are created for both data sets and are presented in Appendix B.2.2. The Rhine polygon is selected at Lobith, where Rhine vessels cross the border with Germany and discharge is measured. Similarly, a sea polygon is established near the entrance of the Port of Rotterdam to capture the vessels that are leaving and entering the sea at that location. The data is extracted for a one-month period in a CSV file and used as input, as shown by Figure 3.6. The columns are renamed and monthly data is merged in Python to create a yearly DataFrame. This procedure yields filtered AIS data, which can subsequently be utilised as input in later stage.

Seaweb data

The Seaweb Maritime Portal database comprises information from a comprehensive range of seaports and terminals globally, including the movements of vessels, such as arrivals and departures at port terminals (S&P, 2022). In this study, both Seaweb and the sea polygon are utilised to determine the identification of seagoing vessels arriving at the studied terminal. These data sets are later compared to determine the most optimal one for identifying seagoing vessels. No further filtering is necessary for Seaweb.

Retrieving monthly AIS Terminal data

To retrieve monthly AIS Terminal data, a polygon is created in the RHDHV AIS platform for the EMO terminal, as shown in Figure 3.7. An area encompassing more than just the terminal's berths is established to be able to display a larger part of a vessel trip. Data for a terminal polygon with the columns: *mmsi number, latitude, longitude, coursOverGround, speedOverGround, vessel type, sub-category, main category, dead weight tonnage, breadth, lengthOverall, receivedAt, name and flag name* is extracted from the AIS platform for a one-month period. Using a longer timespan is not possible due to processing limitations. This retrieved data is used as input prior to filtering and trip creation, as described in the following paragraph.

Figure 3.7: Polygon to retrieve data in EMO terminal (Royal HaskoningDHV, 2018)

3.4.2. Data filtering and trip creation

Figure 3.8 provides a comprehensive explanation and detailed insights into the stage referred to as 'Data filtering and trip creation', which is represented by the leftmost orange box in Figure 3.5. In this stage, the monthly AIS terminal data undergoes a filtering process, and subsequently, vessel trips are generated to extract trips specifically within the defined polygon, as illustrated in Figure 3.7.

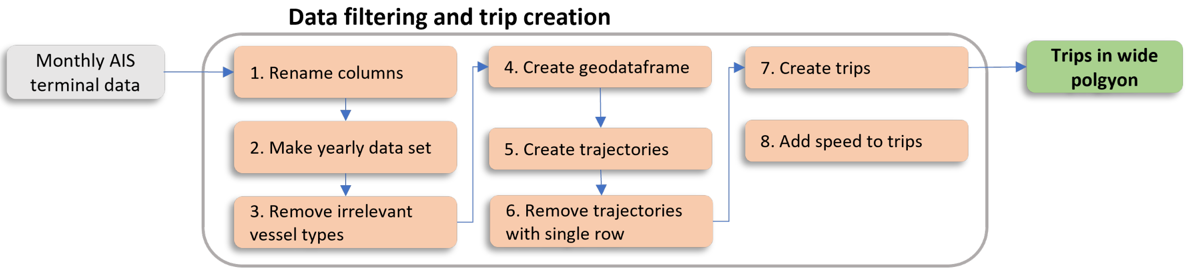


Figure 3.8: Flowchart of AIS data filtering and trip creation

Python is used to process the CSV file which is created from the monthly extracted AIS terminal data, as described in the previous subsection. The process begins with renaming columns, such as renaming *receivedAt* by *date* or *lengthOverall* by *LOA*. Moreover, separate monthly DataFrames are merged into a yearly DataFrame. Subsequently, vessel types that are not relevant to the study are removed. Since further analysis is carried out on a dry bulk terminal, only dry bulk vessels are selected. The selected dry bulk vessel types are presented in Table 3.2. If vessels do not return a vessel type in the data, the category is indicated by 'NaN'. As described before, a high percentage of vessels do not return a vessel category, therefore these are also included. It should be noted that there exist numerous vessels classified as 'NaN' which do not necessarily belong to the dry bulk category.

Table 3.2: Vessel type classification for dry bulk terminal as indicated by AIS data

MainCategory	SubCategory	VesselType
Bulk Carriers	Bulk dry	Bulk carrier
		Bulk ore carrier
	Other Bulk Dry	Bulk cement carrier
	Other Dry Cargo	barge
Dry Cargo/Passenger	General Cargo	General cargo
		General cargo with container capacity
Miscellaneous	Other Activities cont	Vessel Type (unspecified)
NaN	NaN	NaN

Upon elimination of vessel types, a geodataframe is generated, which utilises the longitude and latitude of a message to establish geometry points. Since each vessel transmits AIS messages that already produce a path, the Python package ‘Movingpandas’ is utilised to define individual vessel trajectories. This package facilitates the determination of a vessel’s sailing route based on the geodataframe. During trajectory creation, an error may occur if a single-row trajectory is generated due to the occurrence of only one message per unique mmsi number. To avoid this error, it is necessary to verify the presence of such single-row trajectories. If such trajectories exist, these are discarded, and the process of creating trajectories is restarted. Alternatively, the existing trajectory data set is utilised for a trip generation. A trip is established when the time interval between trajectories is at least 12 hours, allowing for trip detection even when an AIS transponder is turned off for a period shorter than 12 hours. Appendix B.2.1 presents an example of trip creation from trajectories.

The AIS data, however, is subject to certain limitations, such as missing speed values. To resolve this issue, ‘Movingpandas’ is utilised to add speed values to all data points based on the geodataframe. After these steps have been completed, a yearly set of trips is generated for the specific polygon. It should be noted that not all vessels arrive at the berths of the EMO terminal. Hence, additional steps are taken.

Additionally, the same polygon as with the AIS platform is created for the RWS AIS data. Data is retrieved for the days which are missing in the months of July, August and September 2022, including one day prior and later to the days stated in Table 3.1. Subsequently, filtering is similarly done and trips are created as stated above.

3.4.3. Defining vessels lying idle

The created trips in the previous stage are used as input to determine which vessels are lying idle in the terminal, which is the process indicated by the second orange box in Figure 3.5. The steps leading to a DataFrame of vessels lying idle in the terminal are depicted in detail in Figure 3.9. Each individual step, indicated by an orange box, is outlined and described separately.

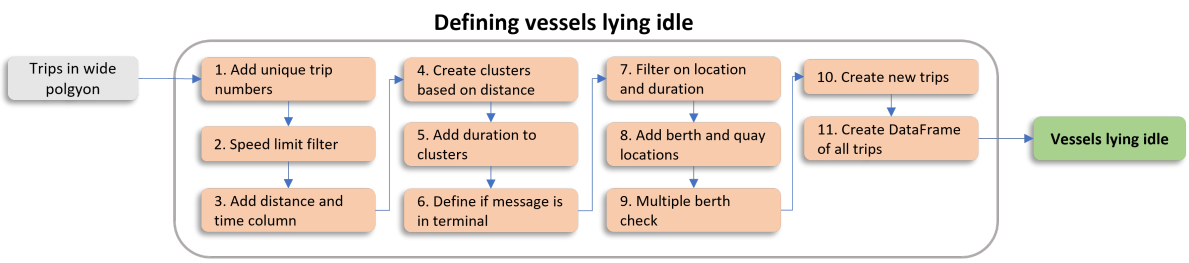
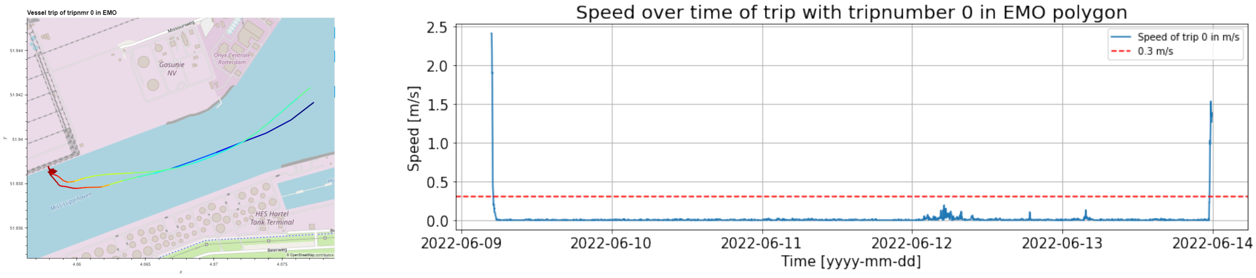


Figure 3.9: Flowchart of AIS data defining which vessels are lying idle

1. Add unique trip numbers

Each trip that is generated constitutes a distinct DataFrame that can be visualised by applying its corresponding unique trip number. To achieve this in Python the following code is utilised: *trip.trajectories[‘unique trip number’].df*. This unique trip number is not initially included in the DataFrame. In order to distinguish between the different trips when merging, this distinguishing trip number is added as an additional column to each respective trip.

2. Speed limit filter
Since speed is added by 'Movingpandas' based on geodataframe in the previous filtering stage, each message consists of a speed. To ensure that a vessel is lying idle, a speed filter is applied. A limit of 0.3 m/s is assumed to determine a vessel lying still. The speed over time for the trip depicted in Figure 3.10a is illustrated in Figure 3.10b. The red line indicates the speed of 0.3 m/s. The graph shows that the speed for a vessel lying at one location does not exceed 0.3 m/s. It can also be found that on the 12th of June some small movements are made which could, for instance, be caused by strong gusts of wind or changing position for unloading.



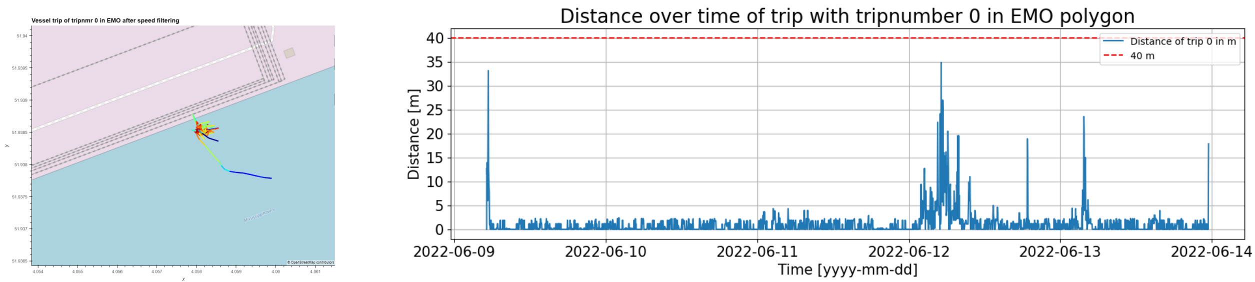
(a) Example trip in wide polygon (b) Speed over time for the trip depicted in Figure 3.10a

Figure 3.10: Trip speed displayed by route and over time

The filter process leads to the removal of all messages with a speed value lower than 0.3 m/s in every individual trip. Consequently, some trips become entirely empty if they originally had only speeds exceeding 0.3 m/s. For trips with also speeds lower than 0.3 m/s, the filtering partially eliminates speed values.

3. Add distance and time columns
Prior to adding distance and time values, it is checked whether a trip DataFrame is empty or not. Empty DataFrames are excluded from further processing. If a DataFrame contains data, a column representing the distance between two successive messages is appended based on the respective latitude and longitude. Similarly, the time interval between two successive messages is computed based on the date between two messages in seconds.

4. Create clusters
Based on the distance column created in the previous step, clusters are created. Clusters are defined as a row of messages for which the distance between those messages is less than 40 m. The trip depicted in Figure 3.11a is altered from the trip illustrated in Figure 3.10a due to speed filtering. The distance over time for the altered trip is shown in Figure 3.11b.



(a) Trip of Figure 3.10a after speed filtering (b) Distance between two successive messages for the trip depicted in Figure 3.11a

Figure 3.11: Trip distance displayed by route and over time

Although it is known from Figure 3.11a that the vessel stays in one location, Figure 3.11b illustrates that the distance between two successive points is larger during the time when speed was also little higher. As distances may increase while the vessel remains in one location, a threshold of 40 m is imposed based on analysing multiple trips. In most cases where vessels sail to different locations during a trip, the distances exceed 40 m and a new cluster is created. An example is provided in Appendix B.3.2.

A cluster is generated by including an additional column containing cluster numbers for each message in all trips. A new cluster number is assigned when three conditions are met: the message is the first message of a trip; the distance between consecutive messages exceeds 40 m; or the considering message has a distance smaller than 40 m, but the preceding message has a distance larger than 40 m, necessitating a new cluster number for the first message following a message with a distance greater than 40 m. Further details regarding the created DataFrame are presented in Appendix B.3.2.

5. Add duration to clusters
The duration of a cluster is defined as the total time per message summed for a unique cluster number. However, for cluster numbers that only consists of one message, which are the ones with distances larger than 40 m, the duration is set to 0 hour. This is done to ensure that cluster numbers with large distances, are distinguished and later can be neglected. The duration is added as a new column, called *duration*, to each message of a cluster.

6. Define if message is in terminal
Since the polygon shown in Figure 3.7 covers a larger area, including berthing locations beyond just the quay wall of the terminal, a smaller polygon is created specifically for the berthing locations within the terminal. This is achieved using the shapely geometry package in Python. The resulting smaller polygon is indicated by the yellow marks in Figure 3.12. For each message, it is checked whether the latitude and longitude are in that polygon. If the latitude and longitude are in the polygon, the newly created column *In_terminal* returns the value ‘True’, else the row returns ‘False’.

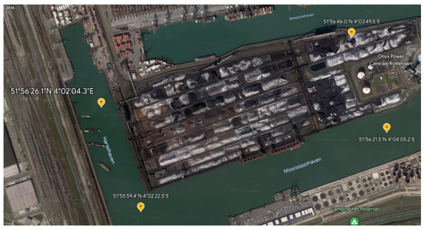
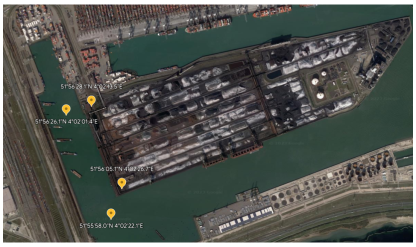


Figure 3.12: Polygon utilised to determine the boundary of the EMO terminal

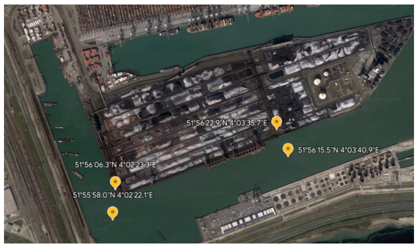
7. Filter on location and duration
To extract vessels solely at the EMO terminal, messages with a value ‘False’ in *In_terminal* column are excluded. Additionally, a filter is imposed on the duration of a cluster, which is set to 1 hour. A detailed explanation for this chosen limit is provided in Appendix B.3.3. The application of this filter further shortens the route of several trips, however, the trip utilised in the preceding steps remains unaltered, since it encompasses a single cluster in EMO with a duration exceeding 1 hour.

8. Add berth and quay locations
Prior to adding berth and quay locations, it is checked whether a trip is empty. For trips that contain data, specific berth locations are added. To specify the locations of the berths, it is necessary to consider their distinct functions as described in Section 3.1. To add these locations to each trip, two new columns are created: *berth* and *quay*. The former identifies the specific berth location, while the latter identifies the entire quay wall.

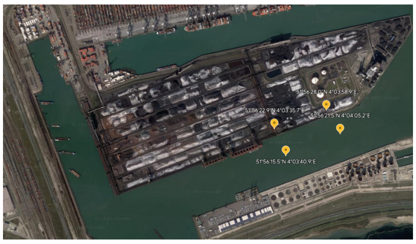
The *berth* column distinguishes between three different locations: the entire Hartelhaven quay consisting of 3 loading berths, the 4 Mississippihaven sea unloading berths, and the 2 Mississippihaven loading berths. The *berth* values are labeled as ‘hartel’ for the Hartelhaven berths, ‘missi_sea’ for the sea unloading berths, and ‘missi_barge’ for the loading berths. Similarly, the *quay* column indicates the location as either ‘hartel’ for the Hartelhaven quay or ‘missi_tot’ for the Mississippihaven quay. These locations are defined using the yellow marking points in Figure 3.13.



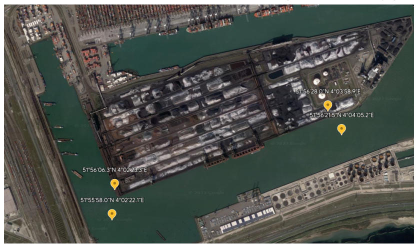
(a) Hartelhaven quay polygon



(b) Mississippihaven sea unloading berths polygon



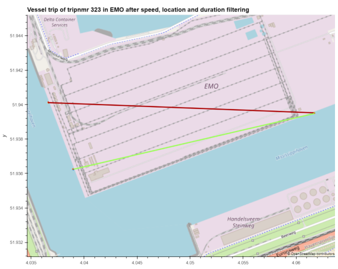
(c) Mississippihaven loading berths polygon



(d) Mississippihaven quay polygon

Figure 3.13: Polygons utilised to specify quay walls and berths

9. Multiple berth check
In contrast to the trip depicted in the preceding steps, it was found that certain trips have clusters at multiple berths. Figure 3.14a shows a trip that consists of clusters arriving at both the Hartelhaven and the Missippihaven quay. As these berths serve different purposes, these clusters are differentiated by adding an extra column named *multiple_berth*. This column returns a value 'True' if the message is not in the first or last row of the trip and the value in the *berth* column, described in the previous step, differs from the value in the previous message. In all other instances, the messages in this column are assigned the value 'False'. Figure 3.14b demonstrates an example of the DataFrame.



(a) Trip after filtering on speed, location and duration

	date	speed	distance	time	clustnr	berth	quay	multiple_berth
13	2022-01-08 09:22:58	0.003640	1.539334	422.0	1750.0	hartel	hartel	False
14	2022-01-08 09:31:02	0.001976	0.958443	484.0	1750.0	hartel	hartel	False
15	2022-01-08 09:33:56	0.015565	2.710785	174.0	1750.0	hartel	hartel	False
16	2022-01-08 10:51:00	0.027045	11.202952	413.0	1759.0	missi_barge	missi_tot	True
17	2022-01-08 10:58:59	0.002361	1.131628	479.0	1759.0	missi_barge	missi_tot	False
18	2022-01-08 11:06:56	0.003482	1.664433	477.0	1759.0	missi_barge	missi_tot	False
19	2022-01-08 11:20:57	0.001571	1.325454	841.0	1759.0	missi_barge	missi_tot	False

(b) Example of DataFrame

Figure 3.14: Trip and DataFrame of trip with multiple berth locations

10. Create new trips
Based on the previous step, new trips are created for those trips that consists of clusters that arrive at multiple berths and thus have a value 'True' for the first value of the their cluster in the *multiple_berth* column. New trips are generated by appending an extra column with new trip numbers, named *trip_nr _clust*. As a result, a new trip numbers appears based on two conditions: it is a new trip; or the value in the *multiple_berth* column is 'True'. Alternatively, clusters that have as first value 'False' in the *multiple_berth* column are merged to one trip, an example of such a cluster is provided in Appendix B.3.5.

11. Create DataFrames of all trips
As a result of the previous steps, a new DataFrame is generated for all trips that are not empty. The DataFrame contains the following columns: *mmsi, start_date, start_time, end_time, trip_dur, trip_nr, trip_nr _clust, longitude, latitude, vesseltype, maincat, berth, quay, LOA, width and DWT*. With the exception of *end_time, trip_dur, longitude* and *latitude* columns, each value in the columns is retrieved from the first message of a unique newly created trip number. The *end_time* is the final date value of a unique cluster, and the *trip_dur* is calculated as the difference between the *end_time* and *start_time*

of a specific cluster. For the *longitude* and *latitude*, the mean values for all longitudes and latitudes in a cluster are used, as these approximately remain in one location for a cluster. An example of the resulting DataFrame is provided in Appendix B.3.6.

3.4.4. Vessel filtering and adding features

The generated DataFrame in Subsection 3.4.3 serves as input for this stage, where it is used to identify the vessels that are actually being served at the terminal. To accomplish this, trips are filtered and features are added to exclude the trips that are assumed to not be served. The steps to achieve this outcome are depicted in Figure 3.15 and are described separately below. Appendix B.4 provides additional information on several steps taken.

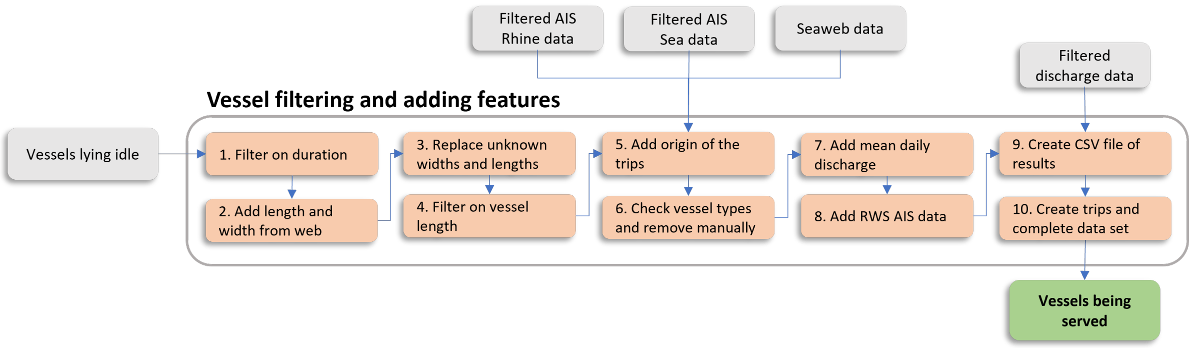


Figure 3.15: Flowchart of AIS DataFrame filtering and adding features

1. Filter on duration

The creation of new trip numbers based on clusters leads to the establishment of new durations. Therefore, trips with durations shorter than 1 hour are filtered out.

2. Add length and width from the web

It has been observed from the data a significant number of trips do not have vessel length and width information. Therefore, a script developed by Sørensen (2022) available on Github is employed. The script retrieves vessel data from myshiptracking.com based on the vessels mssi number and adds the corresponding length and width information to the dataset. When a mmsi number, length or width is not available on the website, all messages in the trip are assigned a value of -1 for their vessel length or width.

3. Replace unknown vessel widths and lengths

The vessel lengths that have a value shorter than 10 m and a width shorter than 2 m, as a result of the previous step, are replaced by the original length and width given by the retrieved AIS data. This length and width limit is chosen, as it is illogical that a vessel has dimensions below these limits, moreover this ensures that the -1 values are replaced. Consequently, the value is either 'NaN' if the AIS data also lacks the length and width information or if the value is replaced by the original value given by the extracted AIS data. Finally, information regarding the vessel length and width is as complete as possible.

4. Filter on vessel length

Data is filtered based on vessel length, as a considerable number of trips have small vessel lengths. Further investigation reveals that these lengths match those of tugboats, which are used to assist larger vessels in mooring. Additionally, the literature suggests that the smallest Rhine vessels have a length greater than approximately 38 m. Consequently, all vessels with a length smaller than 38 m are filtered out and assumed as tug boats.

5. Add origin of the trips

To define the origin of the trips, the filtered AIS Rhine and sea data and the Seaweb data are used as input, as described in Subsection 3.4.2. The mmsi numbers of the vessels in the terminal and the mmsi numbers in either the AIS Rhine data, AIS sea data and the Seaweb data are compared. All mmsi numbers in the terminal DataFrame that match with the ones in these data sets are labelled as 'Rhine vessel', 'Sea vessel', 'Seaweb vessel' respectively. This is achieved by creating an extra column for each data set, named respectively *rhine*, *sea_poly* and *seaweb*, and assigning a value 'True' when it appears in that data set. It is thus assumed that when a mmsi number appears once in the Rhine or sea data sets, the vessel always makes trips in those directions.

6. Check vessel types and remove manually
To determine whether the vessels in the data are actually served, an analysis is conducted on the vessel types. This involves a step-by-step analysis of the individual mmsi numbers for vessels with varying origins. The mmsi numbers are then cross-referenced with marinetraffic.com, a provider of ship tracking information (Marine Traffic, 2023). As a result of this process, all trips that are within the sea polygon but not found in Seaweb are removed, as analysis shows that these vessels are primarily tankers. For vessels within either the sea polygon or sea web, only vessels remain that are situated within both the sea polygon and Seaweb or solely within the sea polygon. Consequently, the column labelled *seaweb* is eliminated and the *sea_poly* column is renamed *sea*. Additionally, other tankers are manually identified and removed from the data set. Appendix B.4 provides an example of the steps taken for data from the year 2022 in EMO.

7. Add mean daily discharge
The filtered discharge data is used as input. A new DataFrame is created that contains the mean discharge level per day, resulting in the data set having only one discharge value per day. This DataFrame is then merged with the trips DataFrame, creating a new column named *discharge*. This column represents the mean discharge level for the start date of each trip.

As for the IVS data, the mean discharge at Lobith is merged into the AIS data. The discharge of a specific day is merged with the day on which the trip takes place. As a result, each trip has the mean discharge of that day in an extra column.

8. Add RWS AIS data
The preceding steps are repeatedly conducted for the RWS AIS data. For this filtered data, trips with a duration shorter than 1 hour are filtered out. It was found that not all messages had a length given and because of anonymisation, this length could not be added manually. When analysing the trips, it was found that few vessels that arrived at Mississippihaven unloading berths had either a length above 200 m or a length below 60 m. However, since this is a location where most seagoing vessels arrive, vessels with lengths smaller than 60 m are removed. Subsequently, the origin per vessel with the use of data retrieved from a polygon at sea and at Lobith is added and the discharge at Lobith is added in an additional column. Additionally, these days are added to the AIS data retrieved from the RHDHV platform for the year 2022.

9. Create CSV file of results
As a result, a CSV file with vessels served at the terminal for a single year is generated, which is subsequently utilised for further analysis. This approach is repeated for all years with available data on the AIS platform, spanning from April 2019 to January 2023. To conduct a comprehensive analysis of all available years, the results of all years are merged into one DataFrame.

10. Create trips and complete data set
A value of 1 is added to a new column named *trips* in order to count the number of vessels per day. It is found that not all days have vessels arriving in the terminal, so in order to make the data set complete, these days are added to the dataset. These extra days are given a value of 0 in the *trips* column. Subsequently, the days for which no RWS data was available and on which the platform was unstable and hence data is missing are left out of the data set, since it is not sure that there were no arrivals on these days. These days are listed in Table 3.1, except for the days in July, August and September in 2022, for which RWS AIS data is added.

Based on the comprehensive dataset containing the duration and the number of vessels berthing in relation to the Rhine discharge, it becomes possible to quantify the impact of low Rhine discharge levels on the cargo handling process of the EMO terminal. This analysis is facilitated by examining the study parameters, which will be elaborated upon in Section 3.5.2.

3.5. Data application on processes

After filtering the IVS and AIS data, the data can now be utilised to assess the effects of low river discharges on the four processes within the logistical chain. An overview of the analysed parameters to quantify the impact of low Rhine river discharge on these processes is presented in Figure 3.16. The processed IVS data, which leads to the generation of IWT vessel data, is employed to evaluate the influence of discharge on IWT, as detailed in Section 3.5.1. Additionally, the processed AIS data, resulting in terminal vessel data, is utilised to investigate the impact on cargo handling processes for both inland and seagoing vessels. Furthermore, the terminal cargo data, as described in Section 3.2.3, is employed to analyse storage operations. Based on the three data sources, the determination of the required parameters for analysing the impact of river drought on the processes is described.

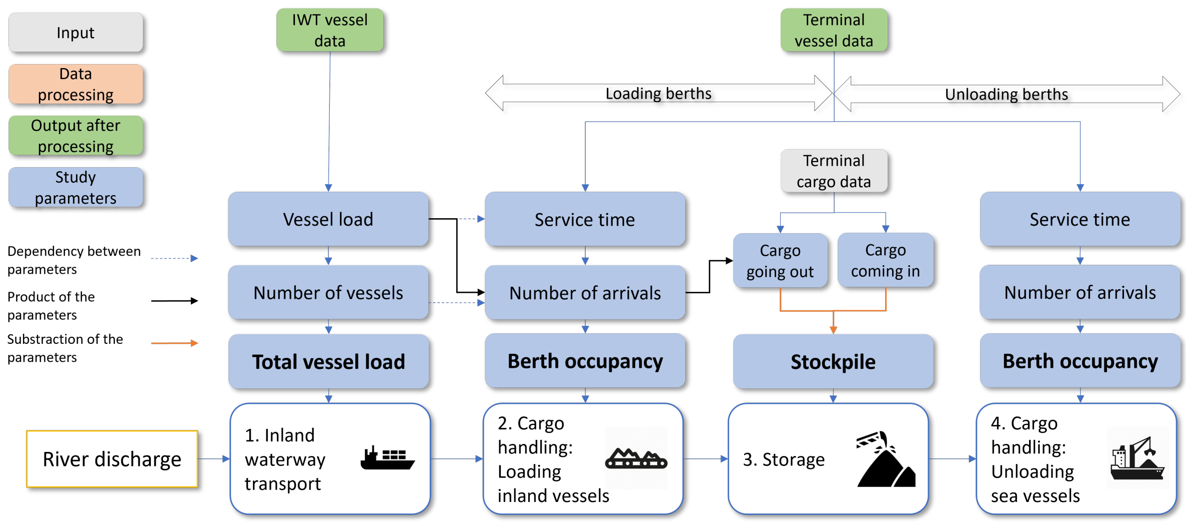


Figure 3.16: Overview of the required steps and parameters to conduct the research

3.5.1. Application of IWT vessel data

Since the vessel load is probably subject to adjustments in response to low river discharges, it is the primary parameter for analysis, indicated as the upper left study parameter in Figure 3.16. Additionally, fluctuations in the number of vessels are secondarily examined due to their response to the changing vessel load. Finally, the total load per day is determined as it is a combination of the changing vessel load and the number of vessels as a result of low discharges. If the total cargo carried per day declines due to reduced discharge, it implies that the demand carried by inland waterway vessels may not be met and disruptions may occur. This parameter is therewith the crucial factor in assessing the ability of the transport system to withstand low discharge conditions. Each parameter is analysed in relation to the discharge levels at Lobith for both the two driest years, 2018 and 2022, and the 10-year time span. Both the different vessel types, as the entire fleet are analysed per parameter, since Politie voor de Rijnvaart (1994) and Vinke et al. (2022) showed that some vessel types are more restricted when discharge gets lower than others. The vessel types are analysed based on their sk codes, as described in Section 2.2. Solely 14 out of 30 vessel types that have made more than 20 trips in the year 2022 are taken into consideration. From these vessel types, only 7 types show a clear relation with the discharge and are therefore further analysed.

3.5.2. Application of terminal vessel data

The terminal processes are separated into two groups: the processes that relate to vessels being loaded and the processes for vessels being unloaded, as indicated by the two large arrows in Figure 3.16. This separation is made since vessels that are loaded probably sail along the Rhine and are outgoing, while most vessels that are unloaded probably come from overseas and are incoming. As described in Section 3.1, the berths at EMO have different functions and therefore the preceding created columns *berth* and *quay* are used to make this separation. Figure 3.17 shows that the outgoing vessels arrive at both Hartelhaven and two loading berths in the Mississippihaven, while the incoming vessels arrive at the Mississippihaven unloading berths.

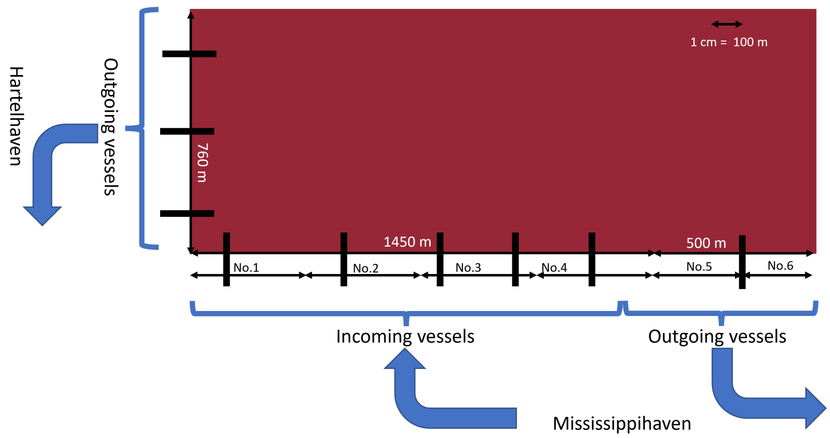


Figure 3.17: Plan view of locations of incoming and outgoing vessels at the EMO terminal

For outgoing vessels, of which some are destined into the direction of the Rhine, the vessel types, compared to the sk code in the IVS data, are added. This is done by adding a column named *vessel_type* and using the vessel classifications of Rijkswaterstaat and Koedijk (2020). This is only done for vessels that are detected to sail into the direction of the Rhine since the classifications of Rijkswaterstaat and Koedijk (2020) are made for Rhine vessels only.

In order to examine the effect of low discharges on the cargo handling processes, service time, the number of arrivals and the berth occupancy, in relation to low river discharges at Lobith for the year 2022 and a 3.5-year period. Consequently, the time a vessel is at berth is determined as the service time and is used as an indicator of its cargo load. For outgoing vessels travelling along the Rhine, it is assumed to be dependent on the hinterland transport's vessel load. Additionally, the number of arrivals at the loading berths is dependent on the number of vessels sailing along the Rhine, as indicated by the blue dashed lines. The crucial factor for determining the cargo handling capacity is berth occupancy, which is based on both the service time and the number of arrivals.

As vessels may not necessarily be precisely located at the designated berth it is unfeasible for dry bulk to make distinctions between different berths (Van Zwieteren, 2020). Therefore, the length of the quay and the vessels are utilised to determine the adjusted length occupancy. This is done by creating a new DataFrame existing from the first time a vessel arrives until the time the last vessels leave the terminal in hourly time steps. Additionally, the length of a vessel is added to this DataFrame when it occurs during the hourly timespan. Since some of the vessels within the RWS data do not have a vessel length, the mean vessel length for the vessels arriving at the specific quays is added to the vessels without a length. If more than one vessel is arriving at the quay during that timespan a length of 15 m is summed up by the total length of both vessels, since this is the space that is required between two vessels. Then the Dataframe is regrouped to daily values of which the maximum per day is considered. Subsequently, the occupancy is computed by dividing the vessel length of that day by the total length of the quay, so for the two loading quays the length is 760 m for Hartelhaven and 500 m for the Mississippihaven loading berths and for the unloading berths at the Mississippihaven the length is 1,450 m. Finally, a list is created of all the maximum berth occupancies per day and discharge of that day.

3.5.3. Application of terminal cargo data

As outlined in Section 2.3, the storage capacity of a terminal is determined by the surplus of cargo resulting from a greater volume of incoming than outgoing cargo. Thus, the impact of low river discharge on both incoming and outgoing cargo volumes is assessed. Prior to utilising terminal cargo data provided by the EMO terminal, the outgoing cargo volume is calculated based on the mean vessel load, determined using IVS data, multiplied by the number of arrivals at the loading berths of the terminal, as indicated by the black arrows in Figure 3.16. It is assumed that all vessels arriving at the loading berths sail in the direction of the Rhine. Additionally, this result is compared to the monthly terminal cargo data. As the data provided by the EMO terminal also includes the amount of load leaving the EMO terminal by different modalities, a distinction is made between different modalities. Subsequently, the surplus is determined for each month by subtracting the cargo going out from the cargo going in, as indicated by the orange arrows. Finally, summing up each monthly surplus is used to assess whether the stockpile exceeds the maximum storage capacity of 7 million tonnes. This is carried out for initial stockpile quantities of 40%, 60% and 80% of the maximum storage capacity.

3.6. Summary

The impact of low river discharge levels on the seaport terminal is quantified through a case study of the EMO terminal within the Port of Rotterdam, which is connected to the Rhine. The research begins by computing the influence of Rhine river discharge levels on the cargo load of various dry bulk vessels and the number of vessels, following determining the impact on the entire dry bulk fleet sailing from Rotterdam to Germany. This analysis utilises IVS data from a time span of 2012 to 2022. Subsequently, the cargo handling process at the EMO terminal is examined, focusing separately on the loading of vessels bound for the hinterland and the unloading of vessels arriving from the sea. AIS data from April 2019 to 2023 is utilised for this analysis. However, as the data contains frequent messages sent by vessels, comprehensive filtering is necessary to consider only the vessels that are being serviced. The following assumptions are made during AIS data processing:

- A new trip is created when a new vessel occurs or the time two between messages is at least 12 hours, assuming that the transponder has not been turned off
- A vessel is assumed to lie idle when the speed is smaller than 0.3 m/s
- A vessel is assumed not to move when the distance between two messages is smaller than 40 m
- The minimum service time is assumed to be 1 hour
- Vessel filtering: All vessels with lengths smaller than 38 m are assumed to be tug boats and every vessel that is in Seaweb but is not detected by the sea polygon is assumed to be a tanker
- A vessel is originating from the Rhine or sea when the mmsi number is detected once in the Rhine or sea polygon
- Trip creation based on the position of clusters: (1) A trip with multiple clusters at one quay is assumed to be one served vessel; therefore, all clusters are merged into one trip. (2) A trip with multiple clusters at different quays is assumed to have been served for multiple purposes (first loading then unloading or vice versa) and therefore separated into multiple trips

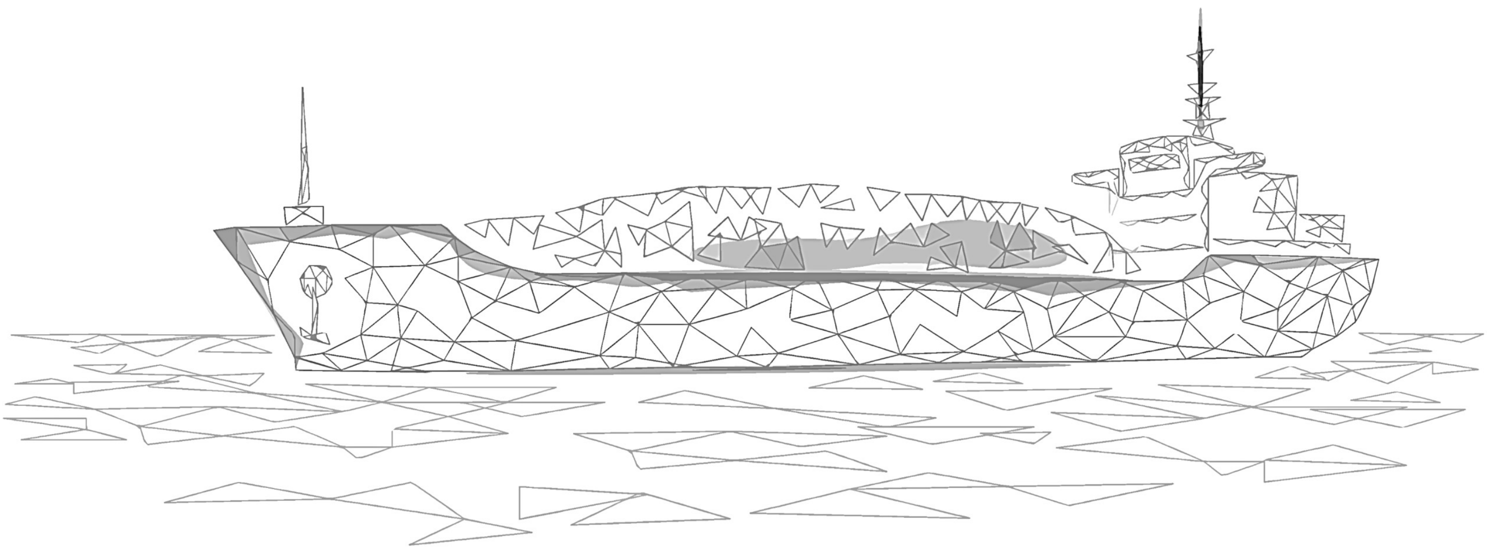
After filtering, the vessels that are served, are analysed by examining the impact of low Rhine discharges on the number of arrivals, service time (based on the duration vessels spend at the berth), and berth occupancy at the loading and unloading locations within the terminal.

Subsequently, the study investigates the effect of low river discharge on the storage capacity of the EMO terminal. To estimate the amount of cargo leaving the terminal, the mean vessel load obtained from the IVS data is multiplied by the number of vessels arriving at the loading berths identified using the AIS data in the year 2022. This estimate is validated using monthly terminal cargo data. Additionally, the impact on the stockpile in 2022 is determined by subtracting the incoming cargo from the outgoing cargo using the terminal cargo data.

The following three result chapters will discuss the impact of low river discharges on inland waterway transport, the cargo handling process and the storage of the EMO terminal, and therewith answering sub-questions 2, 3 and 4 as listed in Section 1.3, respectively.

II

Results



4

Results: Impact of low Rhine discharge levels on inland waterway transport

This chapter examines the impact of low river discharge levels on the navigability of the Rhine river by utilising IWT vessel data of dry bulk vessels, as outlined in Chapter 3. By analysing the data, it evaluates the impact of low river discharges on the vessel load, the number of vessels and total vessel load in Section 4.1, 4.2 and 4.3, respectively. Furthermore, it addresses the third step of the approach, as described in Section 1.5, aiming to establish a correlation between river discharge and inland waterway transport, by addressing the following sub-question: *How do low Rhine river discharge levels impact the amount of load carried and the number of vessels for the fleet navigating the Rhine?*

4.1. Impact of low river discharges on vessel load

4.1.1. Seasonality

As the drought causes river water levels and discharges to drop, vessels are required to reduce their load. The years with discharges higher than 1,020 m^3/s at Lobith do not show considerable change in the mean vessel load. Therefore, it is assumed that vessels do not have to adapt their load when discharge is above 1,020 m^3/s and the effect of seasonality is not further considered, Appendix C.1 elaborates on this. In order to gain insight into the relationship between discharge levels and vessel load, the analysis involves an examination of the vessel load for different types of vessels and for the entire fleet, in relation to discharge levels at Lobith.

4.1.2. Vessel load of various vessel types

The relationship between discharge and the amount of vessel load carried by various vessel types is depicted in Figure 4.1. The figure is generated by plotting the average vessel load per trip for distinct vessel types, employing the sk code, with each type represented by a differently coloured dot, against the discharge recorded at Lobith on the corresponding day of the trip. The sk codes associated with each vessel type, as specified in the legend, were previously expounded upon in Section 2.2, while the characteristics of these vessel types are enumerated in Table A.3. Notably, the discharges under consideration are derived from a 10-year data set and the frequency of their occurrence was not uniform. For instance, a discharge below 800 m^3/s was recorded only on a few days during 2 out of the 10 years. Appendix C.2 further elaborates on the discharge distribution. The figure illustrates that most vessel types have to reduce their load when discharge falls below approximately 2,000 m^3/s, but the strongest correlation between the load and discharges is found for 6- and 4-push barges (BII_6l, BII_4). The blue dots relating to 6-push barges also seem to have a minimum discharge for which no load is carried anymore, while the other vessel types are still able to sail with the reduced load during the lowest discharge. Additionally, various vessel types seem to have multiple maxima, such as C4 vessels, indicated by the green dots, that operate at a maximum of 10,000 and 7,500 tonnes. Appendix C.3 shows a graph for each vessel type plotted separately.

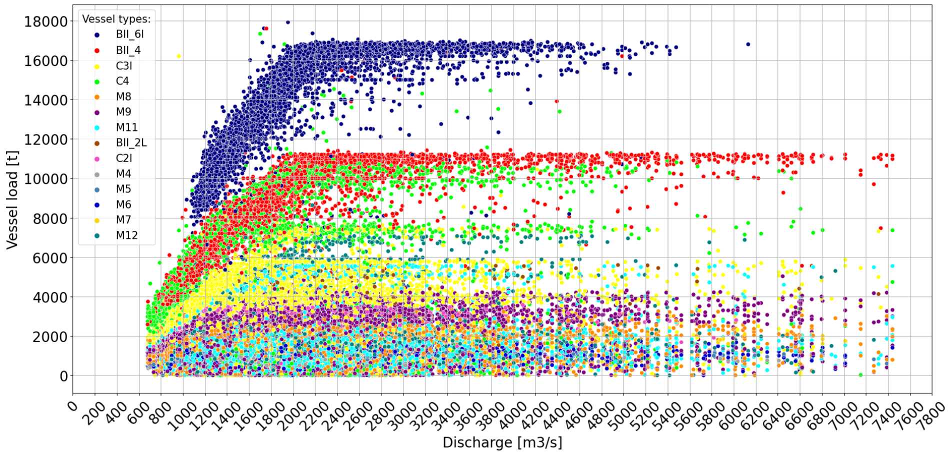


Figure 4.1: Vessel load per discharge of various Rhine vessels sailing from Rotterdam to Germany from 2012 to 2023

A linear regression is applied to the discharge and vessel load data for 6- and 4-push barges to determine the discharge tipping point. The largest coefficient of determination (R2) is selected to determine the tipping point. The R2 for the 6-push barge is 0.77 with a cut-off discharge of 2,200 m^3/s, suggesting that 6-push barges experience a reduction in vessel load when the discharge falls below this threshold. The figure also shows that when discharge falls below 2,000 m^3/s, 6-push barges are not able to sail at their maximum load capacity of around 17,000 tonnes. Moreover, this vessel type typically stops carrying vessel load when the discharge drops below 1,000 m^3/s.

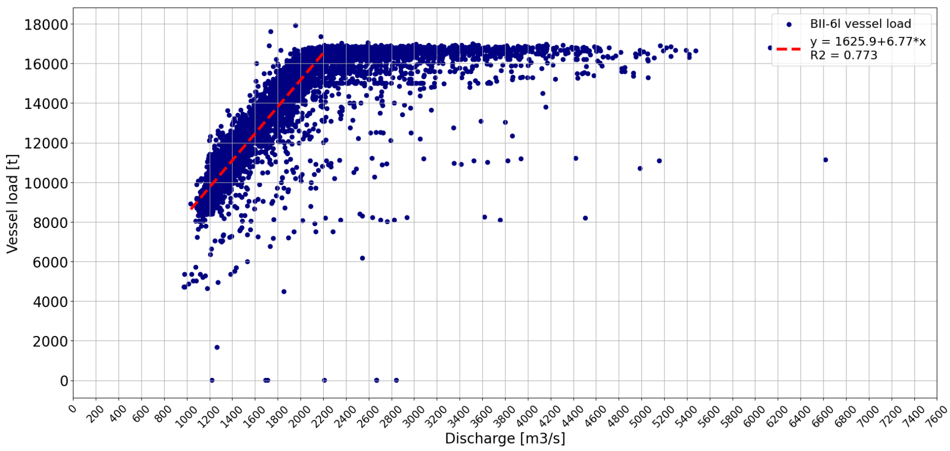


Figure 4.2: Vessel load per discharge for 6-push barges sailing from Rotterdam to Germany from 2012 to 2023

A similar analysis is carried out for 4-push barges, and a discharge value of 2,110 m^3/s is found to have an R2 value of 0.76, as depicted in Figure 4.3. At this threshold, 4-push barges start to reduce their load, but only from a discharge value lower than 1,900 m^3/s, vessels can not sail at their full carrying capacity of approximately 11,300 tonnes. The barge mostly stops operation when the discharge is below 800 m^3/s.

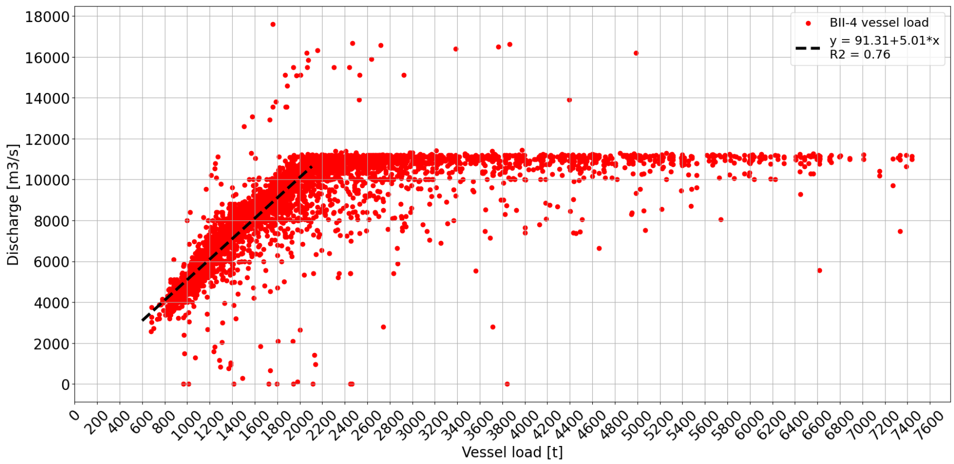


Figure 4.3: Vessel load per discharge for 4-push barges sailing from Rotterdam to Germany from 2012 to 2023

For analysis of mean daily vessel load over time, Figures 4.4 and 4.5 show the two driest years, 2018 and 2022, plotted for different vessel types along with discharge data at Lobith. As indicated in Section 3.5, the plotted vessel types are those that appear to undergo adjustments during periods of low river discharge. The other vessels of the fleet that remain unaffected are presented in Appendix C.4. The upper two figures show 6- and 4-push barges, while the lower two show motor vessels and coupled convoys. Each coloured line represents a different vessel type, identified with 'M' for the motor vessel and 'C' for the coupled convoy, followed by a number indicating the vessel's size. The grey dashed line represents Lobith's discharge level, and the background colours indicate low discharge periods in bins of 200 m^3/s, starting at 600 m^3/s.

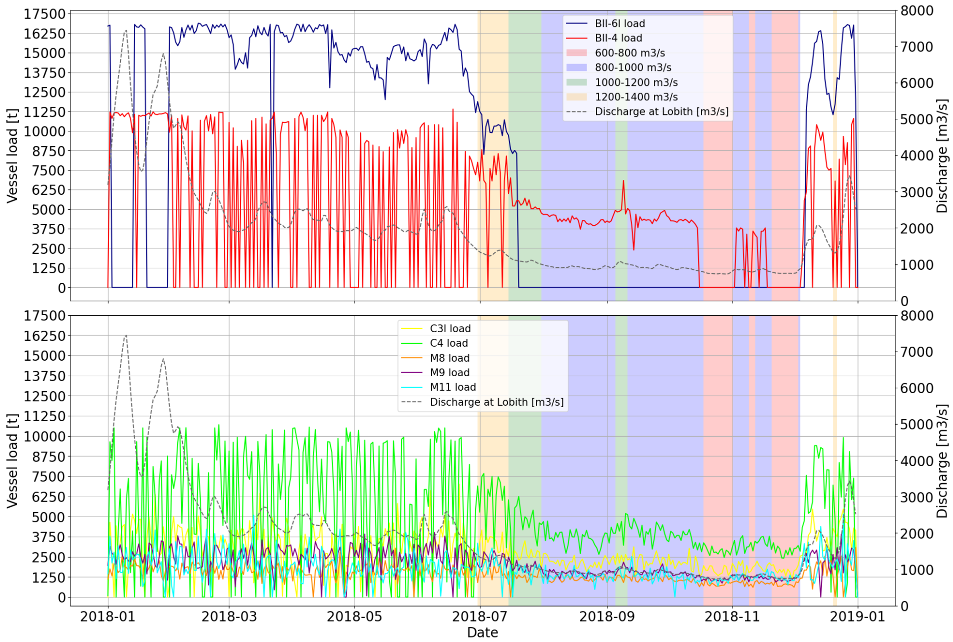


Figure 4.4: Mean daily vessel load of various Rhine vessel types sailing from Rotterdam to Germany in 2018

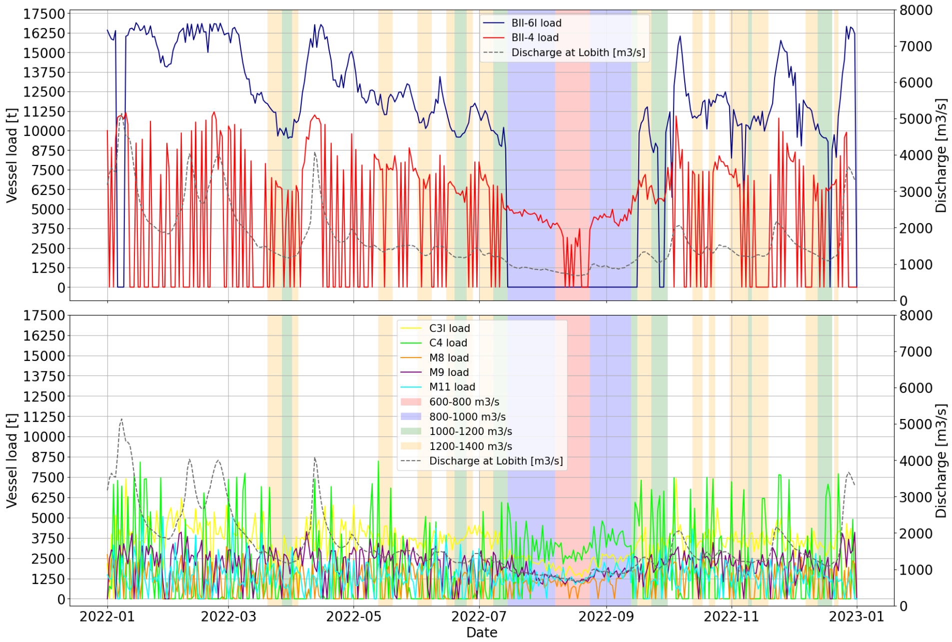


Figure 4.5: Mean daily vessel load of various Rhine vessel types sailing from Rotterdam to Germany in 2022

The figures for both 2018 and 2022 confirm that 6-push barges, indicated by the blue line, cease operation when the discharge is below 1,000 m^3/s in 2022 and already a little earlier than in 2018. Moreover, the mean vessel load of 6-push barges gradually decrease as soon as the discharge is below a discharge of approximately 2,200 m^3/s. This confirms the correlation in Figure 4.2. Another interesting note is that 6-push barges also cease operation when discharge is approximately 4,000 m^3/s.

In the case of 4-push barges, the figures reveal that these vessels did not constantly sail every day, while when they did, a maximum load capacity of approximately 11,300 tonnes is found during discharges above 1,900 m^3/s. Once the discharge level falls below this threshold, 4-push barges begin to decrease their load capacity, as also illustrated in Figure 4.3. Notably, when discharge levels drop below 1,000 m^3/s (or exceed 4,000 m^3/s) and 6-push barges are no longer in operation, 4-push barges begin to operate continuously until the discharge level drops below 800 m^3/s, at which point they appear to cease operations in 2018, although some vessels are still capable of sailing in 2022. By substituting the discharge levels of 1,000 and 800 m^3/s into the linear regression formula for the 4-push barge shown in Figure 4.3, the mean vessel loads are found to be approximately 5,100 and 4,100 tonnes, respectively. These values correspond to the starting points of the blue and red backgrounds on the graph, which indicate discharge levels of 1,000 and 800 m^3/s, respectively.

The lower two graphs in Figures 4.4 and 4.5 illustrate the behaviour of motor vessels and coupled convoys. The green lines, representing C4 vessels, show that this vessel type operates mostly at a maximum of 10,000 tonnes in 2018, but they also experience days without sailing. When the discharge drops below 1,400 m^3/s in July 2018, vessels start to constantly sail, while the average load is reduced to around 3,000 tonnes during the lowest discharge, which represents a 70% reduction. In contrast, in 2022, the C4 fleet only sails at a maximum of 7,500 tonnes and starts to fully operate only when discharge is below 1,000 m^3/s half of July. During the lowest discharge period, the average vessel load reduces to 3,000 tonnes, which is a 60% reduction. C3l vessels exhibit a similar pattern during 2018 and 2022, with the average load before and after low discharge at around 4,000 tonnes, which is reduced by 50% to 2,000 tonnes during the lowest discharges. On the other hand, M8 vessels show a reduction from approximately 2,000 tonnes to 1,000 tonnes when they start to sail constantly during the lowest discharges in 2018. However, in 2022, these vessels still do not sail constantly when discharges are low and M8 vessels also have more days before low discharge without operation. Both M9 and M11 vessels exhibit an approximate decline in vessel load of 50% when the discharge is at its lowest, with the vessels only able to carry 1,250 tonnes compared to around 2,500 tonnes during normal discharges.

4.1.3. Mean vessel load of the entire fleet

The summation of the average amount of cargo carried by all vessels in the fleet provides insight into the average vessel load of the entire Rhine fleet. The blue line in Figure 4.6 represents the mean daily vessel load of the entire fleet in 2018. The Savitzky-Golay filter, represented by the red line, has been applied to smoothly follow the pattern exhibited by the blue line. Moreover, the discharge at Lobith is added with the grey dashed line, as well as the periods of low discharges indicated by the colours in the background.

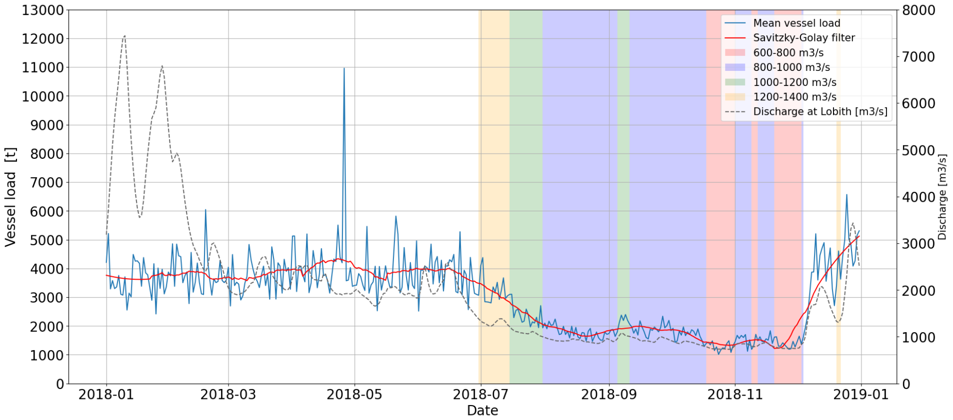


Figure 4.6: Mean daily vessel load of the entire Rhine fleet sailing from Rotterdam to Germany in 2018

On average, in July 2018, when the discharge level is above 1,400 m^3/s, the vessel load is around 3,750 tonnes. However, there is a clear reduction in the average load a little before the discharge level drops below 1,400 m^3/s. This decline further aggravates until the discharge level ranges between 800 and 1,000 m^3/s, and thereafter, it experienced a slight drop, to 1,500 tonnes, probably due to the discontinuation of cargo transportation by 4-push barges. If the blue line is followed, it can be observed that, as soon as the period with a discharge level below 800 m^3/s ends, vessels started carrying more cargo again and at the end of December even more cargo compared to the period before low discharge levels.

The mean vessel load of the entire Rhine fleet in 2022 is illustrated in Figure 4.7.

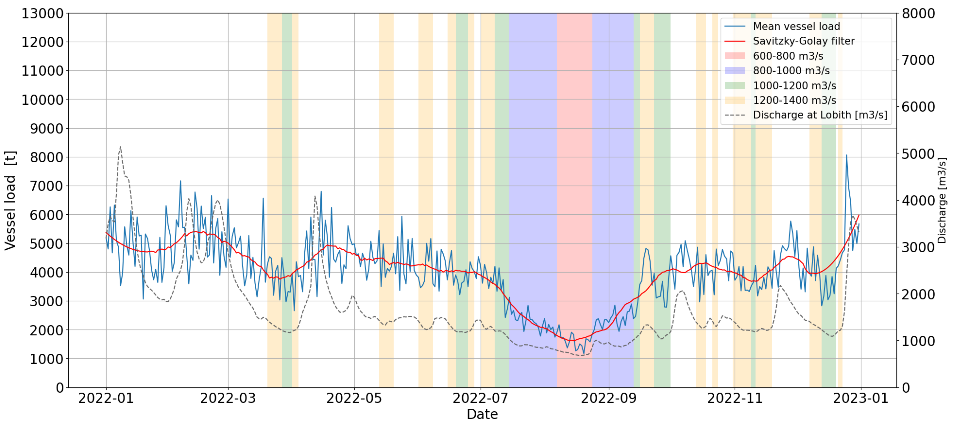


Figure 4.7: Mean daily vessel load of the entire Rhine fleet sailing from Rotterdam to Germany in 2022

In March 2022, which is a few months before the period with low discharges, the mean vessel load starts to decline already, from around 5,000 to 4,000 tonnes, as the discharge falls below 1,400 m^3/s. This might be due to a reduction in load for 6 and 4-push barges, which is apparent in Figure 4.5. Subsequently, the average amount of cargo increases again. However, once the discharge falls below 1,400 m^3/s for the first time again in May, the amount of cargo continued to decline on average. The decline in cargo load becomes more pronounced as the discharge drops below 1,000 m^3/s, and it reaches its minimum of around 1,800 tonnes when the discharge falls below 800 m^3/s. As the discharge gradually increases, the load also gradually increases. Until around October, the discharge remained slightly above 1,400 m^3/s, but the amount of cargo transported remains at around 4,000 tonnes, while it is consistently at 5,000 tonnes in January.

A comparison of the two years reveals that, despite the occurrence of more periods with lower discharges in 2022, vessels carried a greater amount of cargo on average during this year compared to 2018.

The results depicted in Figure 4.8 display the mean vessel load of the entire fleet over a 10-year time span, which has been summarised into discharge bins of 200 m^3/s. It should be noted that the x-axis ought to be read at the midpoint of each bin, thereby signifying that the smallest discharge bin ranges from 600-800 m^3/s.

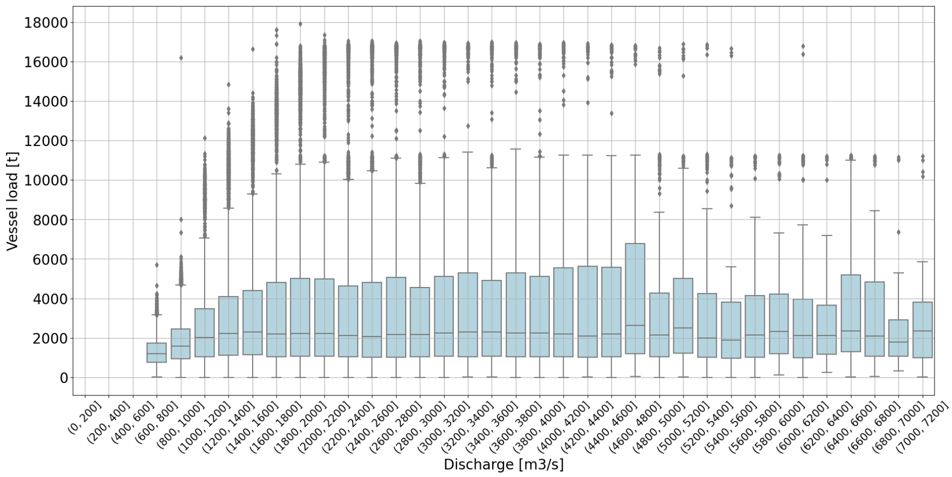


Figure 4.8: Boxplots showing variation of the daily average vessel load per discharge bin for the entire Rhine fleet sailing from Rotterdam to Germany from 2012 to 2023

The figure shows that the maximum vessel load decreases from a discharge below 2,000 m^3/s downwards. This reduction in maximum can then be declared by Figure 4.1, which shows that 6- and 4-push barges stop sailing at maximum load capacity as soon as the discharge is below 2,000 and 1,900 m^3/s. When the discharge is between 1,000 m^3/s and 1,200 m^3/s, 50% of the vessels on these days carry a vessel load with less than 2,000 tonnes, while this is for a discharge above 1,400 m^3/s 2,200 tonnes. Moreover, this further reduces to 1,500 tonnes and 1,000 tonnes as soon as discharge drops below 1,000 m^3/s and 800 m^3/s, respectively.

4.2. Impact of low river discharges on number of vessels

The effect of low river discharge levels at Lobith on vessel types is initially assessed, given that the fleet composition is known to vary during such conditions. Following this, an analysis of the overall fleet is conducted.

4.2.1. Number of vessels of various vessel types

Figures 4.9 and 4.10 show the total number of vessels per day for 2018 and 2022, respectively. Similar to Figures 4.4 and 4.5, the upper figure comprises data from 4 and 6-push barges, whereas the lower figures consist of both motor vessels and coupled convoys. For each type, the total number of vessels per day is determined.

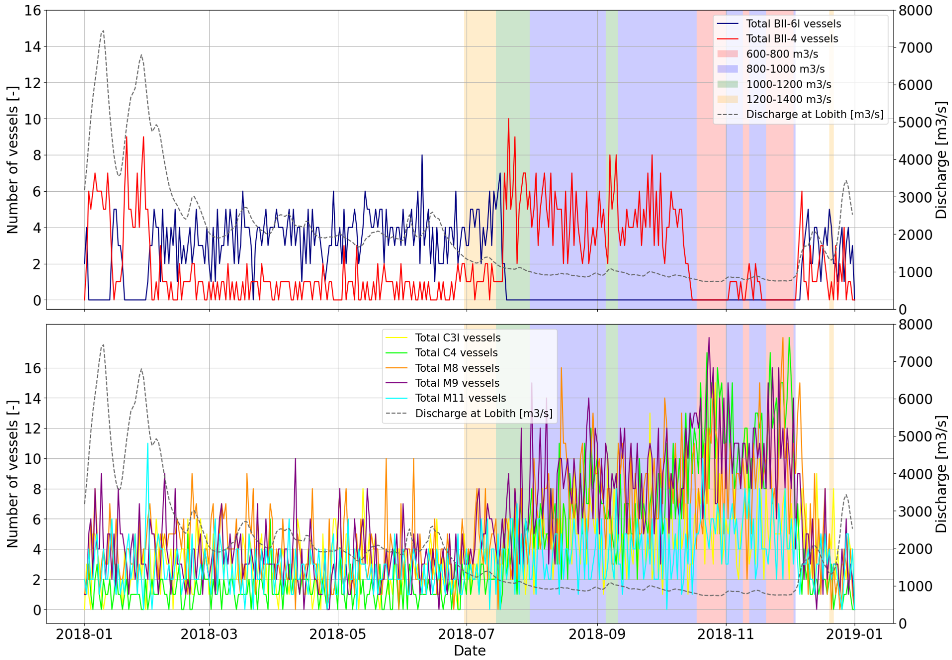


Figure 4.9: Total daily number of various Rhine vessel types sailing from Rotterdam to Germany in 2018

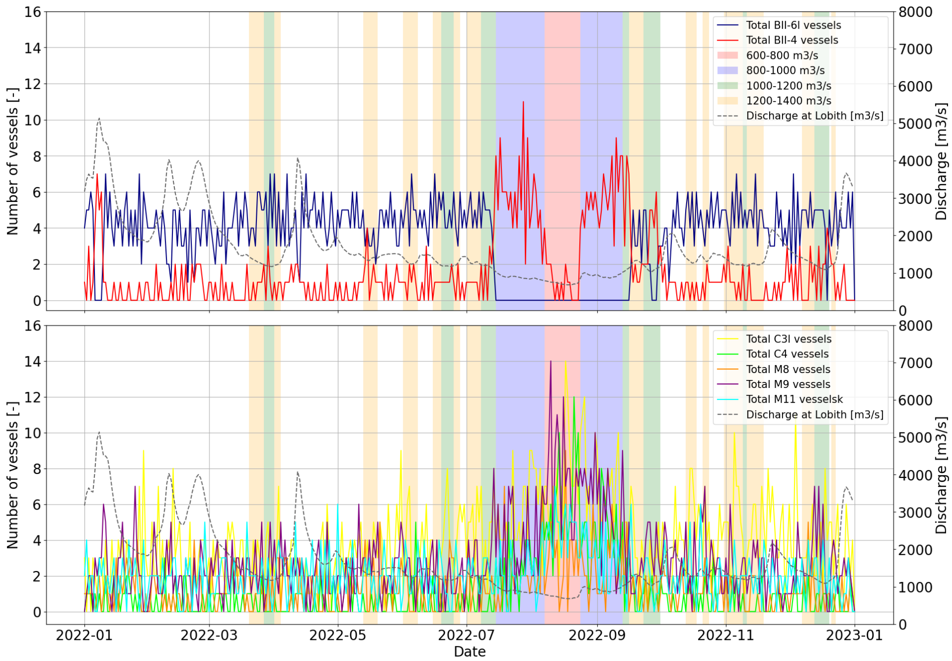


Figure 4.10: Total daily number of various Rhine vessel types sailing from Rotterdam to Germany in 2022

The upper two figures in both 2018 and 2022 demonstrate that the fleet size of 6-push barges, indicated by the blue line, constantly sailed with on average 2 to 6 vessels per day but ceases operation, as also earlier found, when discharge is below around 1,200 m^3/s in 2018 and at 1,000 m^3/s in 2022. As a result, the fleet size of 4-push barges starts to increase as the discharge level drops below 1,200 m^3/s, by five times more vessels in 2018 and even six times more vessels in 2022. Moreover, when the discharge falls below 800 m^3/s, the number of vessels operating by 4-push barges almost comes to a halt, with only one or two vessels sailing on some days in 2022. It is again found that when river discharge is extremely high (> 4,000 m^3/s), 6-push barges also cease operation and 4-push barges start to increase their fleet size. When discharge reduces again, the number of 6-push barges increases and 4-push barges decreases. The effect of high discharge, however, is not in the scope of this research and hence is not further taken into account.

The lower two figures in 2018 and 2022 illustrate that the number of vessels of vessel types, other than the push barges, begin to increase as soon as the discharge level drops below 1,400 m^3/s and then decreases again when the discharge level is above 800 m^3/s. A further increase in these vessels is noticeable when the 4-push barges also cease operation, suggesting that these vessels tried to compensate for the loss of push barges. Remarkably, the total increase for both years differs significantly. In 2018, when discharge is between 800 and 1,000 m^3/s for an extended period, the number of vessels gradually increases until the discharge drops below 800 m^3/s. Subsequently, the number of vessels remains stable and decreases again when the discharge increases above 800 m^3/s. The largest share in this progression is from C4, M8 and M9 vessels. During the lowest discharge period, 12 times as many C4 vessels sail compared to the months before July, and for M8 and M9, this is approximately 4 times more vessels. In 2022, this increase is smaller, and the period of low discharges is also shorter. The largest increase can be observed for M9 and C3l vessels, and not for C4 and M8 vessels. The number of vessels for these two vessel types is approximately 3 times more compared to the period before July.

4.2.2. Number of vessels of the entire fleet

When adding up the number of vessels per day for various vessel types, the total number of vessels for the entire Rhine fleet is visible. Figures 4.11 and 4.12 show these numbers for 2018 and 2022, respectively, for which is observable that the total fleet strongly increases during low discharge levels.

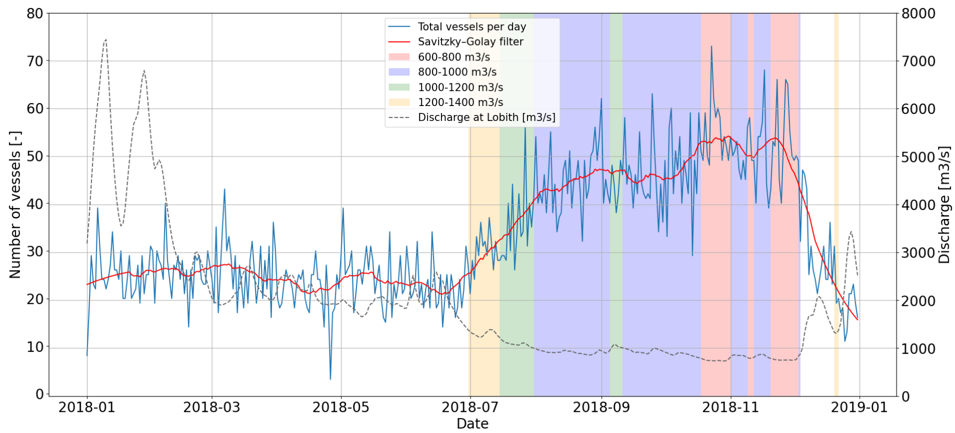


Figure 4.11: Total daily number of vessels of the entire Rhine fleet sailing from Rotterdam to Germany in 2018

In 2018, the mean number of vessels before July is approximately 25 vessels per day, while before July 2022, this is only 15 vessels per day. Moreover, it shows that the total increase in 2018 is more significant than in 2022. During a discharge between 600 and 800 m^3/s, the total number of vessels is approximately 55 per day in 2022, while in 2022 this is only 35 vessels per day. The figures depict a discernible pattern, indicating that the number of vessels increases as the discharge falls below 1,200 m^3/s and a slight increase in the number of vessels could already be observed just before a discharge of 1,400 m^3/s in 2018. Moreover, the figures indicate that when the lowest discharge, below 800 m^3/s, has been exceeded again, the number of vessels also started to decrease.

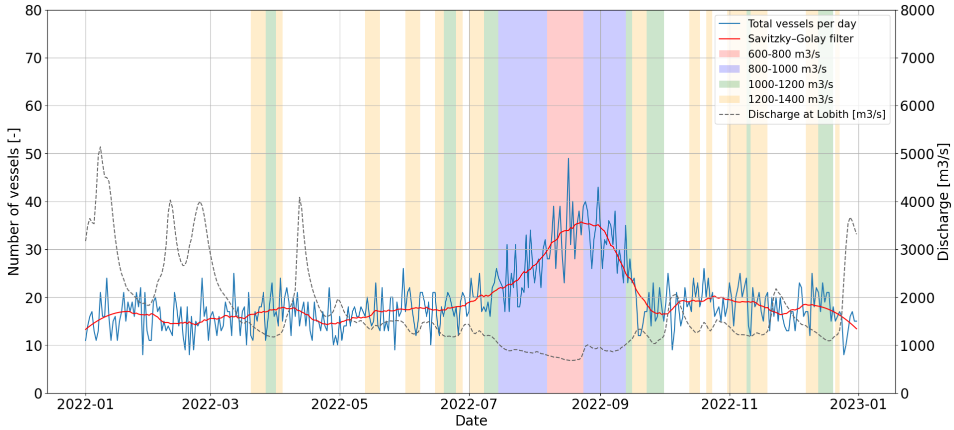


Figure 4.12: Total daily number of vessels of the entire Rhine fleet sailing from Rotterdam to Germany in 2022

Figure 4.13 shows the total number of vessels per day per discharge ranging in bins of 200 m^3/s. The average number of vessels is around 20 and mostly fluctuates between 15 and 25 vessels per day. Moreover, it can be found that the 25th, 50th and 75th percentiles of the boxplot increase when discharge drops below 1,400 m^3/s. The maximum number of vessels is increasing rapidly when comparing the lowest three discharge bins. Although discharge between 600 and 800 m^3/s does only occur for less than 50 days over a period of 10 years, the maximum number of vessels per day is significantly higher, with 72 vessels per day, than when discharge is above 800 m^3/s. The figure also shows that the spreading of the boxplots increases considerably when discharge is below 1200 m^3/s. This variability can be attributed to the fact that the number of vessels during the drought year of 2018 is almost 1.5 times higher compared to 2022. Conversely, during high discharges exceeding 1,200 m^3/s, the number of vessels is more consistent.

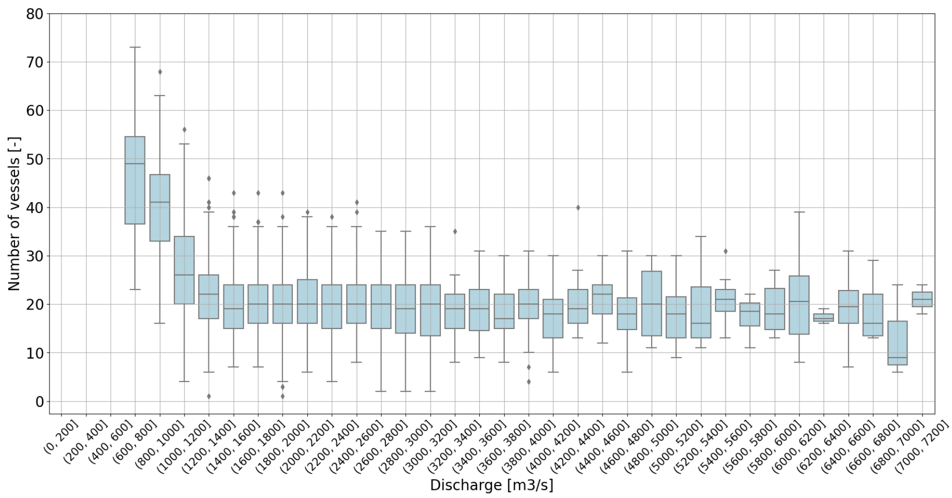


Figure 4.13: Boxplots showing variation of the total daily number of vessels per discharge bin for the entire Rhine fleet sailing from Rotterdam to Germany from 2012 to 2023

4.3. Impact of low river discharges on total load

In addition to examining the mean vessel load and the number of vessels, it is crucial to consider the total daily load carried, to evaluate the impact of low river discharges on potential inland waterway transport disruptions. Although vessels may carry less cargo on average during low discharge periods, an increase in the number of vessels may compensate for this reduction, resulting in a similar total cargo volume as during high discharge periods. However, if the total cargo carried per day declines as a result of a reduced discharge, it implies that the demand carried by inland waterway vessels may not be met. Therefore, this study investigates the relationship between low river discharges and different vessel types, along with the total load for the entire fleet.

4.3.1. Total vessel load of various vessel types

Figures 4.14 and 4.15 depict the total load transported per day by various vessel types in the years 2018 and 2022, respectively.

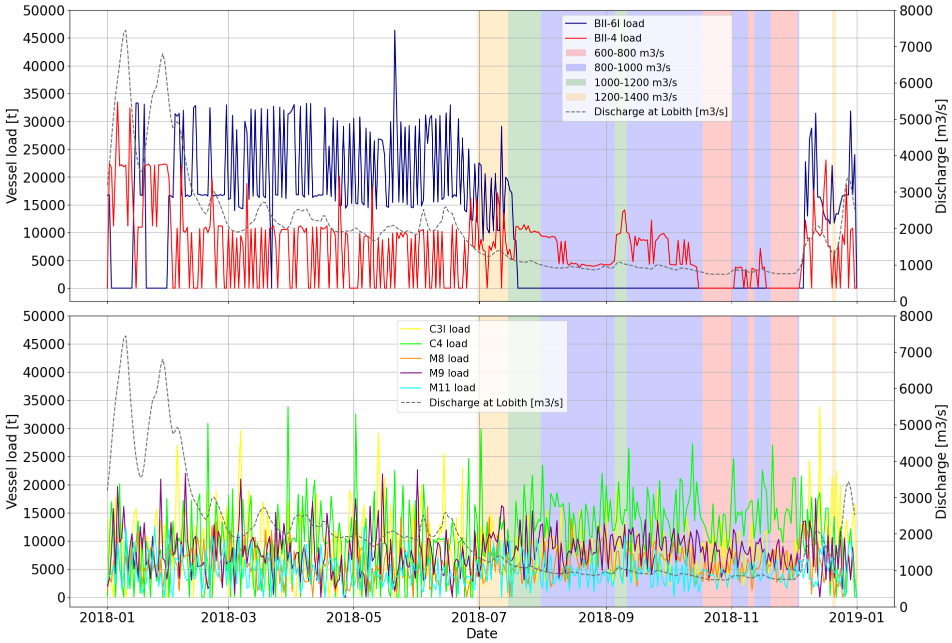


Figure 4.14: Total daily vessel load of various Rhine vessels sailing from Rotterdam to Germany in 2018

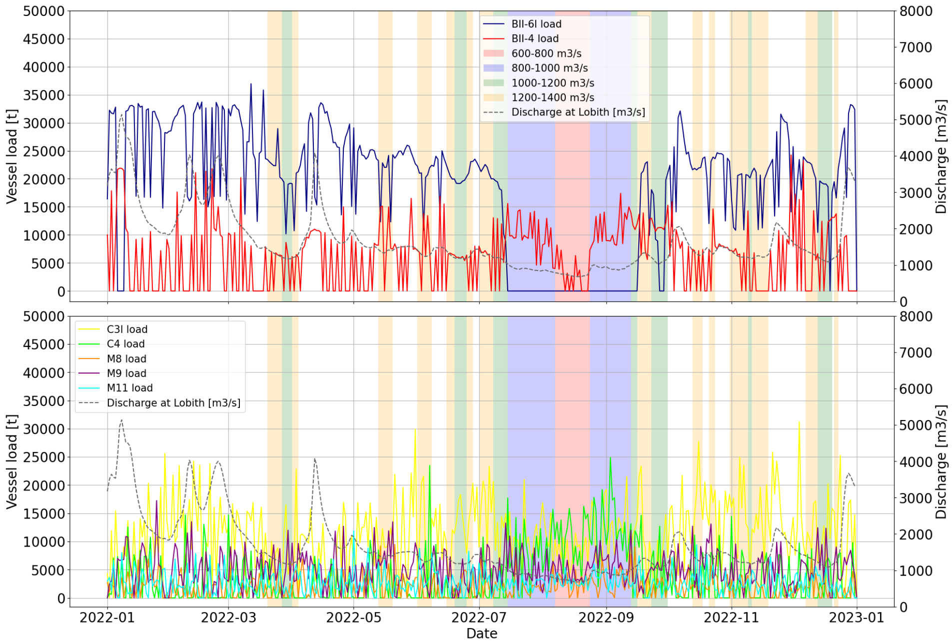


Figure 4.15: Total daily vessel load of various Rhine vessels sailing from Rotterdam to Germany in 2022

In both years, 6-push barges account for the most transportation of all dry bulk vessel loads shipped from Rotterdam to Germany, fluctuating based on the number of vessels sailing. As it is found that the 6-push barges do not increase their fleet size, the total load carried per day starts to reduce as soon as the discharge is again below 2,000 m^3/s when vessels can not sail at maximum capacity anymore. For the 4-push barge, no significant change is found at that threshold of 1,900 m^3/s, however, the total load carried by 4-push barges gradually increases when 6-push barges cease but are not able to carry as much as the 6-push barges.

Once the 6-push barges cease their operation, the total load per day carried by C4 vessels increase, especially in 2022, which is caused by the increase in fleet size while these vessels are also constrained by the amount of cargo they can carry. Despite the increase in the number of vessels shown in Figure 4.11, the overall increase in total load is less evident for C3l and M9 vessels. The increase in the number of vessels ensures that the total load they transport per day remains approximately constant for all discharge levels.

Despite the vessels' constraints during drought, the increase in the number of vessels compensates for this, enabling the vessels to transport the same total load per day throughout the year. A few vessel types even increase their total load during drier periods, compensating for the barges' cessation of operation.

4.3.2. Total vessel load of the entire fleet

Based on the figures presented above, it is observable that during periods with extremely low discharge levels, barges are unable to transport load. Conversely, the total load carried by C4 vessels increases during such periods. However, other types of vessels maintain a consistent total load carried per day throughout these dry periods. To assess whether this compensation by C4 vessels suffices to ensure that the total load carried by the entire fleet remains unaffected, Figures 4.16 and 4.17 illustrate the total load per day for the entire fleet in both 2018 and 2022.

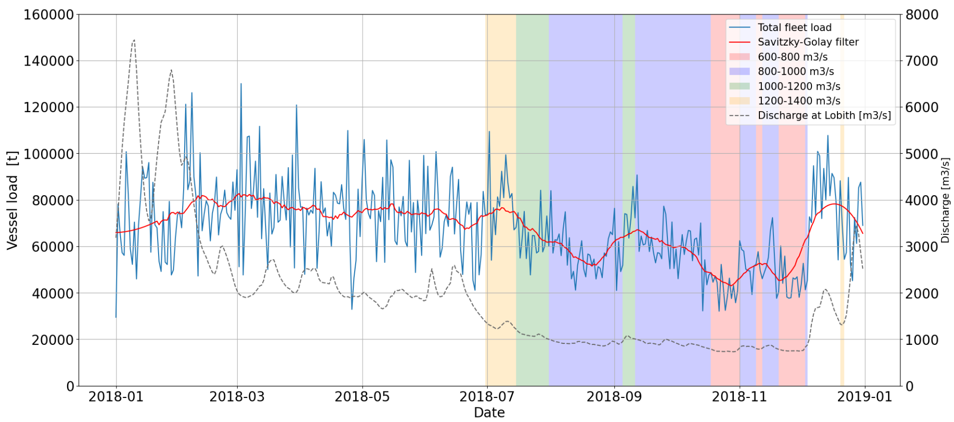


Figure 4.16: Total daily vessel load of the entire Rhine fleet sailing from Rotterdam to Germany in 2018

At higher discharge levels in 2018, the total load is approximately 75,000 tonnes per day. However, as the river discharge drops below 1,200 m^3/s, the total load carried by the fleet starts to decline. This downward trend continues until the river discharge stabilises at a certain level between 800 and 1,000 m^3/s. The total load increases again when the river discharge increases above 1,000 m^3/s for a few days, reaching a total vessel load of 70,000 tonnes per day. However, the total load starts to decline again as the river discharge drops. At the lowest total vessel load per day, which occurs when the river discharge is below 800 m^3/s, the total load carried by the fleet is approximately 40,000 tonnes per day. This represents a decrease of almost 50% compared to the days with higher river discharge.

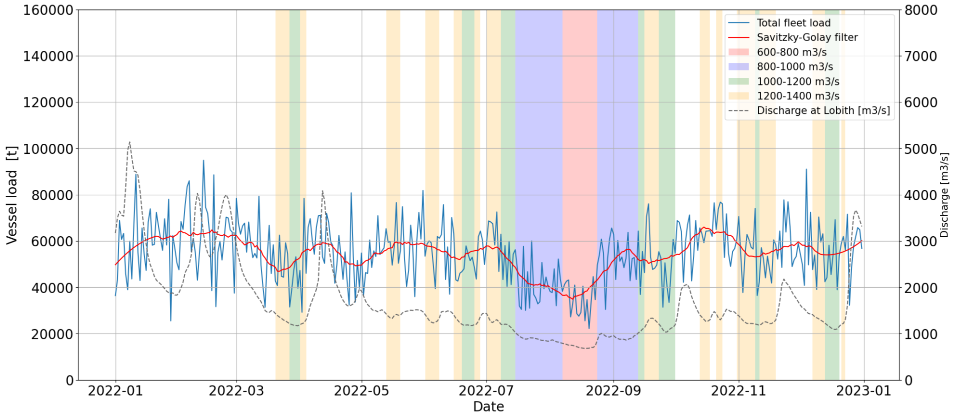


Figure 4.17: Total daily vessel load of the entire Rhine fleet sailing from Rotterdam to Germany in 2022

In 2022, the total load during non-dry periods amounts to 60,000 tonnes, slightly lower than the corresponding figure for 2018. However, as depicted in Figure 4.17, the load diminish as the discharge drops, reaching a minimum of 40,000 tonnes. Subsequently, it increases when the discharge exceeds 1,200 m^3/s and then stabilises around 60,000 tonnes.

From the preceding figures, it is known that the number of vessels increases, while the mean load decreases during lower discharge levels. Figure 4.18 shows the total load per day distributed over the same discharge bins. It shows that when discharge drops below 2,000 m^3/s, the maximum and 50th percentile of the total vessel load per day slowly decreases. In days with discharges above 2,000 m^3/s, the 50th percentile of the total vessel load is approximately 70,000 tonnes, while this further reduces to even 40,000 tonnes when discharge is between 600 and 800 m^3/s, which is a decline of 43%.

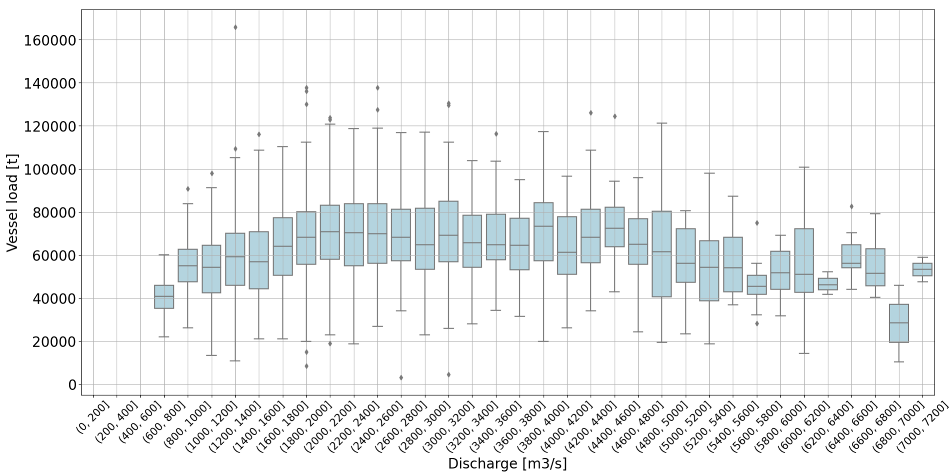


Figure 4.18: Boxplots showing variation of the total daily vessel load of the entire Rhine fleet per discharge bin sailing from Rotterdam to Germany in 2018

4.4. Summary

It is found that the low river discharge levels impact the mean vessel load for each vessel type differently. The analysis reveals that 6-push barges start to reduce cargo from 2,200 m^3/s, cannot ship at maximum capacity when discharge is lower than 2,000 m^3/s and stop carrying cargo from 1,000 m^3/s. 4-push barges start to reduce their load at a discharge of 2,210 m^3/s and are unable to sail at maximum capacity when discharge falls below 1,900 m^3/s. Motor vessels and coupled convoys are also constrained by low water, and their cargo-carrying capacity decreases accordingly. As a result, the mean vessel load for the entire Rhine fleet reduces, as shown in Figure 4.8. Additionally, the motor vessels and coupled convoys start to sail with an increased number of vessels, leading to an increase in fleet size (Figure

4.13). This is however not enough to compensate for the losses of the load of the push barges, the total load carried during discharges below approximately 1,200 m^3/s reduces. Based on these results it is expected that the loading process of inland waterway vessels will become shorter due to a reduced load capacity and that the number of arrivals will increase. It is moreover expected that during low river discharges, less cargo leaves the terminal compared to normal discharges. Hence the sufficiency of the cargo handling capacity and the storage capacity is evaluated in the following two chapters.

5
Results: Impact of low Rhine discharge levels on cargo handling processes

This chapter elaborates on the impact of low Rhine discharge levels on the cargo handling processes of the EMO terminal, implementing the fourth step of the approach, as described in Section 1.5. The processes for loading and unloading are examined separately. Initially, an evaluation of the loading process is conducted and discussed in Section 5.1 since these vessels are expected to primarily navigate towards the hinterland and consequently relate to the results of the preceding chapter. Subsequently, an evaluation of the unloading process is carried out in Section 5.2. AIS data filtered according to Section 3.4 is utilised to determine both the service time and the number of arrivals, and based on these two parameters, the berth occupancy for each berth can be obtained, which can be used to give an indication for the sufficiency of the cargo handling capacity. This chapter addresses the following sub-question: *How do low Rhine river discharges affect the cargo handling process for both loading of inland waterway vessels and unloading of seagoing vessels in EMO?*

5.1. Impact of Rhine low discharges on the loading processes

Although it is found in the previous chapter that various individual vessel types, such as push barges, play a major role in fleet composition changes, the determination of vessel types led to the overlap of multiple classifications. Therefore, it is not possible to determine these different types with AIS data. As a result, only the entire fleet as a whole can be analysed. Appendix D.1 further elaborates on the determination of vessel types.

The impact of Rhine low discharges on the service time, the number of arrivals and the berth occupancy are evaluated over a period of 3.7 years. The shorter time span considered in this analysis leads to a different discharge distribution compared to the preceding chapter. Hence, the discharge distribution for the 3.7-year timespan is presented in Appendix D.2.

5.1.1. Service time

The service time for 2022 is plotted in Figure 5.1. Service times longer than 20 hours are assumed to be outliers and hence disregarded, which is 3% of the vessels. Appendix D.3 provides the service time distribution. The figure below shows that service time in 2022 starts to decrease when discharge is falling below 1,400 m^3/s and is on average 3.5 hours on days when discharge is lowest. This is a reduction of approximately 40% compared to other days when discharge is higher. As soon as discharge increases again, the service time also increases. This is approximately in line with the mean load carried by vessels sailing from Rotterdam to Germany in Figure 4.7.

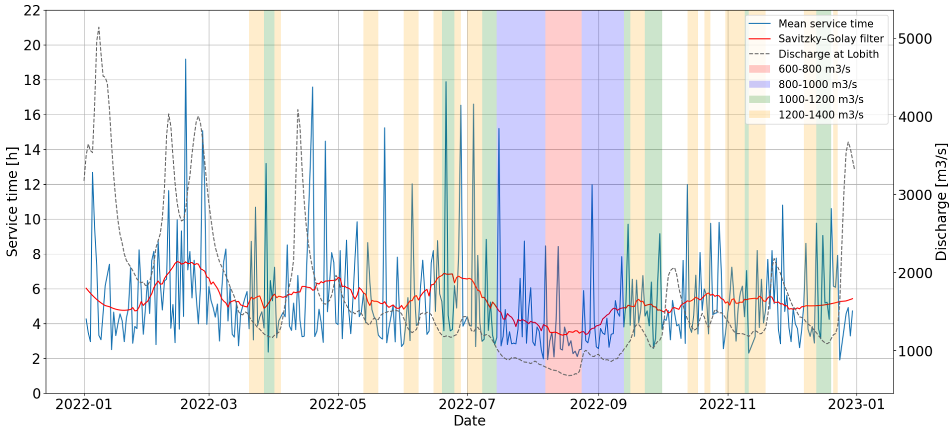


Figure 5.1: Mean daily service time at the EMO loading berths in 2022

The impact of the Rhine discharge is obviously only valuable for vessels that transport their cargo over the Rhine. It was found that of all vessels that arrive at the two loading berths, Hartelhaven and Mississippihaven loading berths, 89.4% of vessels sail over the Rhine. Due to the high proportion of Rhine's vessels, no further differentiation is made between vessels that originate from the Rhine and those that do not. Appendix D.4 demonstrates that no significant deviations have been observed.

Figure 5.2 shows various boxplots for the service times at both loading berths during different discharges at Lobith, subdivided into bins of 200 m^3/s. It should be noted that due to the short time span of 3.7 years, only the year 2022, as illustrated in the figure above, encounters a few days with discharge below 1,000 m^3/s.

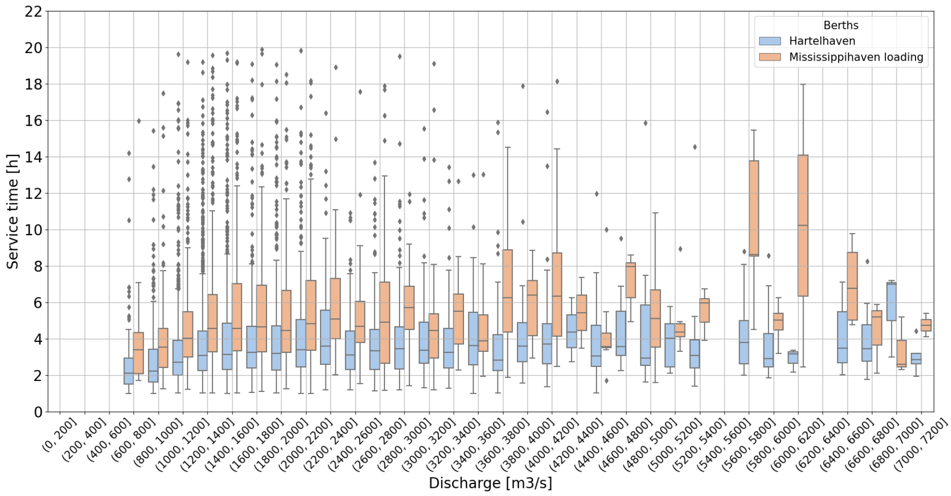


Figure 5.2: Boxplots showing variation of the mean daily service time per discharge bin at different EMO loading berths from April 2019 to 2023

In accordance with service time data from 2022, the boxplots indicate that the service time at both berths in the preceding 3.7 years also decreases when the discharge drops below 1,400 m^3/s. For discharges exceeding 1,400 m^3/s, the median service time ranges from 4.5 to 6 hours at the Mississippihaven loading berths, including some outliers in this range. At Hartelhaven, the median service time is around 3 hours, as indicated by the blue boxplots. The service time at the Mississippihaven is on average longer compared to the Hartelhaven, indicating that despite Mississippihaven having a conveyor belt crane with greater crane capacity, vessels arriving in Mississippihaven are probably larger. From a discharge below 1,400 m^3/s, a reduction in service time is observed, with a median service time of 3 hours at the Mississippihaven and 2 hours at the Hartelhaven when discharge falls below 800 m^3/s. This suggests a service time reduction of roughly 40% and 30% at the Mississippihaven and the Hartelhaven, respectively.

5.1.2. Number of arrivals

The figure depicted in Figure 5.3 illustrates the number of arrivals per day at the EMO loading berths, denoted by the blue line, which is further smoothed by the red line. Additionally, it shows the number of vessels sailing from Rotterdam to Germany per day, denoted by the green line, which is further smoothed by the purple line.

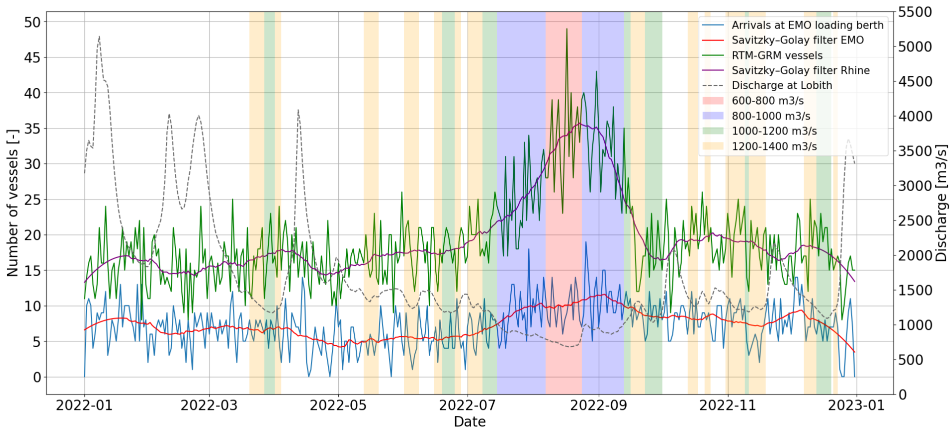


Figure 5.3: Number of arrivals at EMO loading berths and number of vessels sailing from Rotterdam-Germany per day in 2022

The figure shows that the gradient for both data is approximately equal. Obviously, the EMO vessels are only a portion of all vessels going from Rotterdam to Germany and are therefore approximately 3 times lower. In the months before July, approximately 15 vessels per day sailed from Rotterdam to Germany, while in EMO approximately 5 vessels per day arrived to load and sail in the direction of Germany through the Rhine. When discharge then gradually starts to decrease in July, the number of vessels for both data is increasing, until the beginning of September, for which approximately 35 vessels per day sail from Rotterdam to Germany and approximately 10 vessels arrived at EMO to sail to the hinterland. Both data show that the number of vessels decreases again when discharges start to increase and that the number of vessels per day is a little higher after October than in the first months of the year.

Figure 5.4 moreover illustrates boxplots of the service times for various discharge bins at both loading berths over a timespan of 3.7 years.

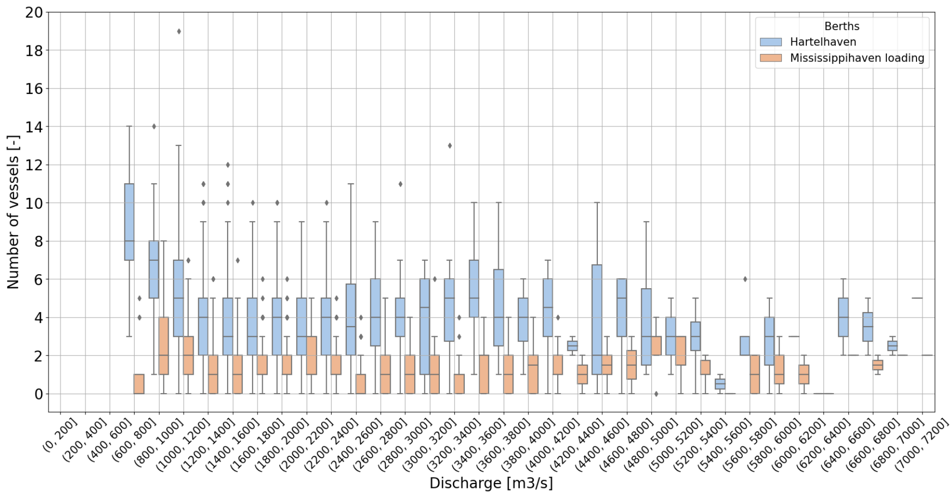


Figure 5.4: Boxplots showing variation of the total number of vessels arriving per day per discharge bin at different EMO loading berths from April 2019 to 2023

The figure above exhibits that on occasions where the discharge rate at Lobith surpasses 1,200 m^3/s, 2 to 5 vessels arrive at Hartelhaven per day, whereas Mississippihaven only accommodates 0 to 2 vessels. This discrepancy can be explained by the fact that Hartelhaven comprises three cranes, whereas Mississippihaven only has a solitary crane, making it less suitable for serving a larger number of vessels. Moreover, it has been determined that when discharge drops below 1,200 m^3/s, the number of arrivals at Hartelhaven tends to increase, resulting in 7 to 11 vessels arriving on days when discharge falls below 800 m^3/s. Furthermore, it is evident that on days when discharge is below 1,000 m^3/s, the minimum number of arrivals is 3 and 1 vessels per day for the lowest two discharge bins, respectively, indicating that no days occur without any arrivals. Similarly, the number of arrivals at Mississippihaven also increases when examining the 25th, 50th and 75th percentile. However, when discharge levels subsequently drop below 800 m^3/s, almost no vessels seem to arrive at the Mississippihaven. This may also account for the slight drop in the number of arrivals during the discharge bin of 600 to 800 m^3/s in 2022, as shown in Figure 5.3.

As a result of the service time and the number of arrivals, the total service time per day can be computed. It is found that the total service time per day increases when discharge reduces. This might be a result of more vessel arrivals with still some time included for pre- and post-operations. Appendix D.5 further elaborates on this.

5.1.3. Berth occupancy loading berths

The maximum berth occupancy per day for both loading berths, Hartelhaven and Mississippihaven, is determined separately. This separation is necessary due to a difference in quay lengths. The berth occupancy is computed based on the percentage of vessel length occupying the total quay length as described in Section 3.5.

Hartelhaven

Figure 5.5 illustrates the maximum berth occupancy per day of the Hartelhaven quay in 2022. The graph demonstrates an upward trend in berth occupancy as the discharge drops below 1,000 m^3/s in the month of July, reaching a maximum of approximately 65% occupancy when discharge is between 600 to 800 m^3/s. Additionally, a notable deviation is observed on the 26th of August, with berth occupancy reaching close to 120%. Moreover, in the aftermath of droughts, berth occupancy remains relatively high, ranging from 50% to 60%. This contrasts with the lower levels of occupancy recorded in the period leading up to months characterised by low discharge levels, where berth occupancy ranges from 40% to 50%.

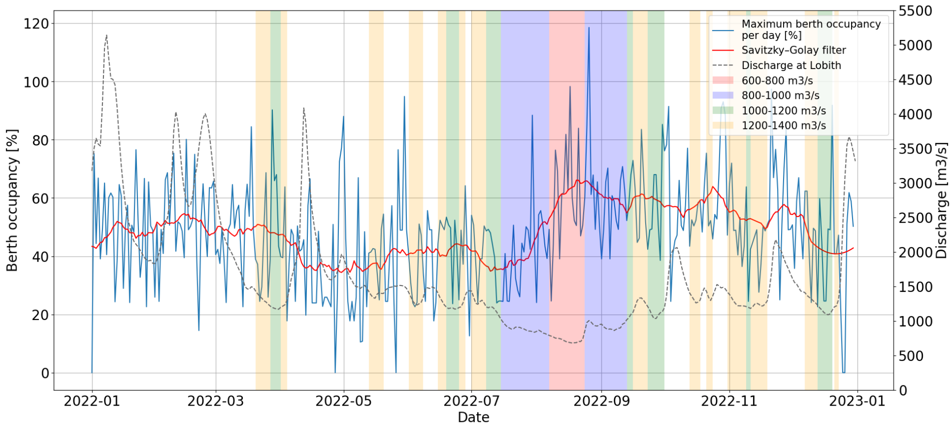


Figure 5.5: Maximum berth occupancy per day at Hartelhaven laoding berth in 2022

Figure 5.6 displays the boxplots representing the maximum daily berth occupancy levels across various discharge bins observed at the Hartelhaven quay over a period of three and a half years. Appendix D.6 shows that a change in vessel length during certain discharges is not influential on berth occupancy. The boxplots displayed in Figure 5.4 demonstrate a trend similar to that observed in the case of the Hartelhaven arrivals. Specifically, it is observed that when the discharge levels fall below 1,000 m^3/s, the berth occupancy is consistently non-zero, indicating that the berths remain occupied during these discharges. It also shows that the 25th, 50th and 75th percentile of the berth occupancy increases during these discharges. The 50th percentile of approximately 60% berth occupancy per day for the lowest discharge bin, which is consistent with the berth occupancies for dry bulk terminals as described in Section 2.3, may indicate that there is available capacity to handle additional vessels during low discharge periods. Furthermore, the boxplots include a few outliers with occupancies above 100%. Chapter 7 further discusses these outlying occupancies.

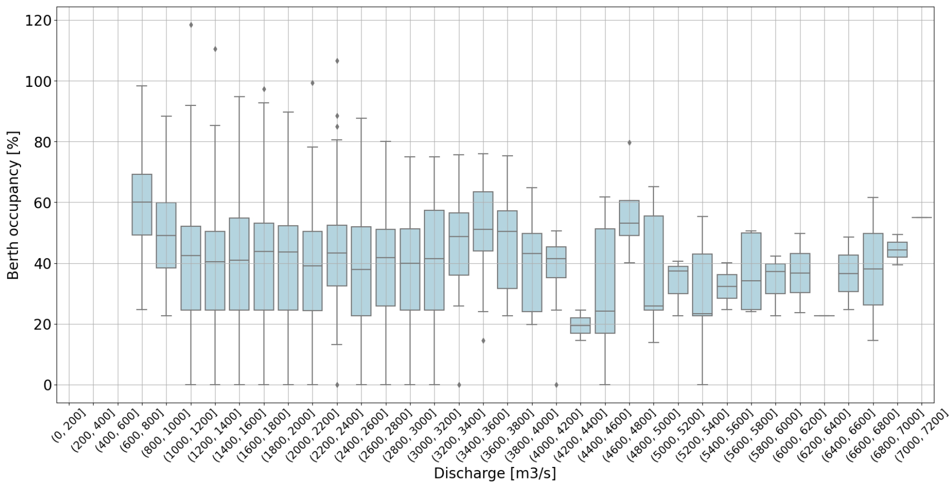


Figure 5.6: Boxplots showing variation of the maximum berth occupancy per day at Hartelhaven loading berth per discharge from April 2019 to 2023

Mississippihaven loading berth

Figure 5.7 depicts the maximum berth occupancy per day at the Mississippihaven loading berths for the year 2022. A noteworthy observation is the reduction in berth occupancy a few days subsequent to discharge falling below 800 m^3/s, with occupancies dropping even to 0%. This corroborates the finding presented in Figure 5.4, where it is observed that the number of arrivals at the Mississippihaven during discharge between 600 to 800 m^3/s is minimal. Additionally, there is a discernible increase in berth occupancy levels, with a maximum occupancy of approximately 60 to 65%, before and after the discharge levels fall below 800 m^3/s. However, as the discharge levels once again exceed 800 m^3/s in September, the berth occupancy levels begin to decline, reaching an occupancy rate of approximately 40% to 50%.

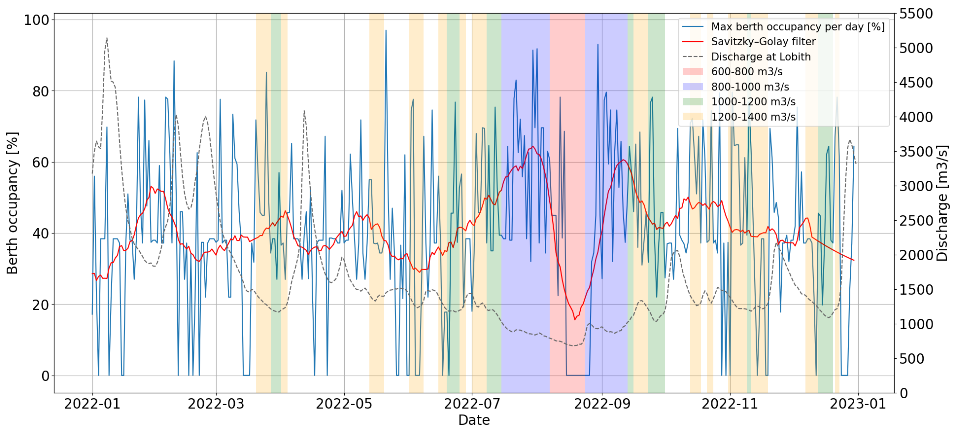


Figure 5.7: Maximum berth occupancy per day at Mississippihaven loading berth in 2022

In contrast to the clear increase in berth occupancy levels observed at the Hartelhaven during periods of low discharge, the same trend is not as readily apparent at the Mississippihaven, as illustrated in

Figure 5.8. Specifically, the boxplot for the discharge levels ranging from 600 to 800 m^3/s contains only few data points, which can be attributed to the minimal number of vessels arriving and berth occupancy during this period in 2022, as depicted in the graph above. Despite the relatively low berth occupancy levels during the aforementioned discharge range, it is noteworthy that the maximum daily berth occupancy rates are on average higher during the discharge range of 800 to 1,200 m^3/s as compared to the higher discharge ranges. Additionally, the fewer arrivals at the Mississippihaven contribute to more fluctuating boxplot trends when compared to those observed at the Hartelhaven. Moreover, a few outliers have been identified, which did not occur in 2022 and are further discussed in Chapter 7.

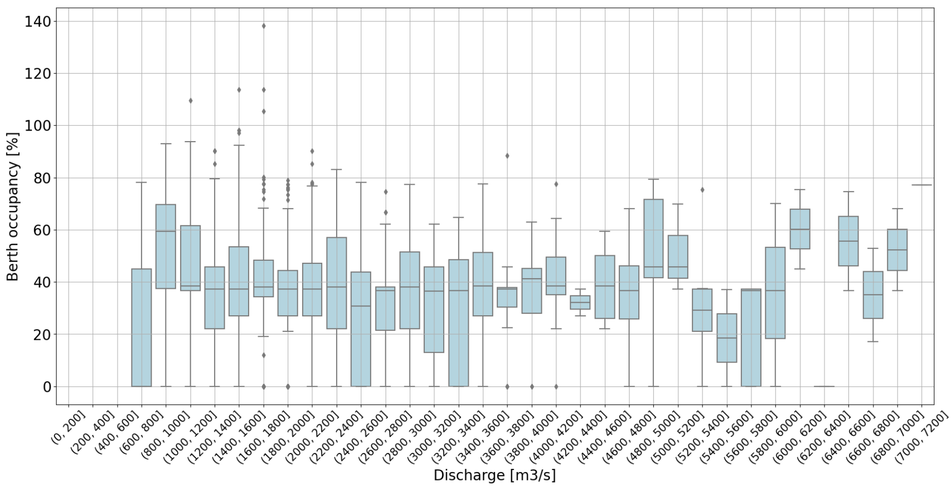


Figure 5.8: Boxplots showing variation of the maximum berth occupancy per day at Mississippihaven loading berth per discharge from April 2019 to 2023

As indicated in Appendix D.6, berth occupancies at both locations are not impacted by variations in vessel lengths. Across each discharge, the mean vessel length displays negligible fluctuations, thereby having minimal effect on berth occupancy. An examination of the vessel length data reveals that vessels arriving at Mississippihaven are longer compared to Hartelhaven. This is as expected since Hartelhaven consists of berths for primary barges and Mississippihaven also has berths for larger coaster and seagoing vessels.

5.2. Impact of Rhine low discharges on the unloading processes

This section discusses the impact of low Rhine discharges on the service time, number of arrivals and berth occupancy of the unloading berths. According to the AIS data, approximately 16% of the arrivals at the unloading berths originate from the Rhine region, while 51% originate from the sea, indicating that 33% of the arrivals originate from other destinations. However, this does not seem to be reasonable and will be further discussed in Chapter 7.

5.2.1. Service time

Figure 5.9 illustrates the mean daily service time for the unloading berths in 2022. Service times longer than 150 hours are excluded from this analysis, this results in an elimination of 1.5% of the vessels. Additional information regarding the distribution of service times can be found in Appendix D.3.2.

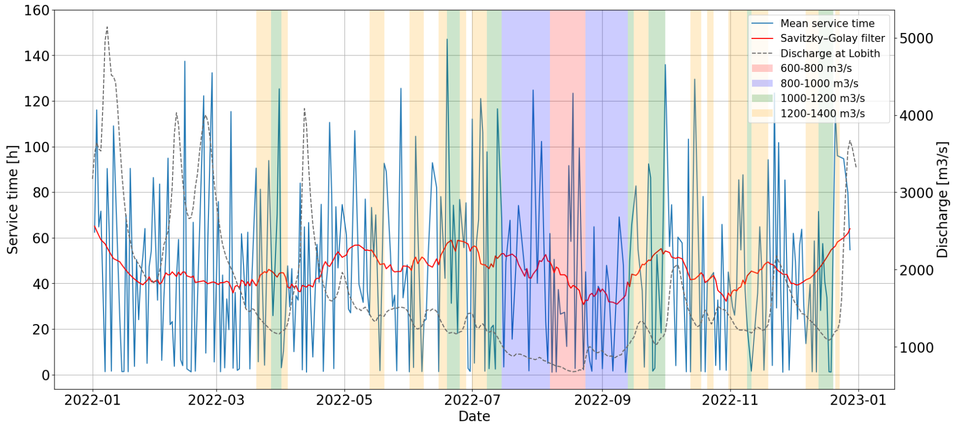


Figure 5.9: Mean daily service time at Mississippihaven unloading berths in 2022

The graph above depicts significant fluctuations in the service time of the unloading berths. On average, the service time amounts to approximately 40 hours per day, but it slightly decreases during periods of discharge below 800 m^3/s, while in September, the service time is approximately 35 hours. Similarly, a reduction is observed at the end of October, and therefore this may not be attributed to the river discharge.

5.2.2. Number of arrivals

Figure 5.10 visualises the daily number of vessel arrivals at the unloading berth of the Mississippihaven in 2022.

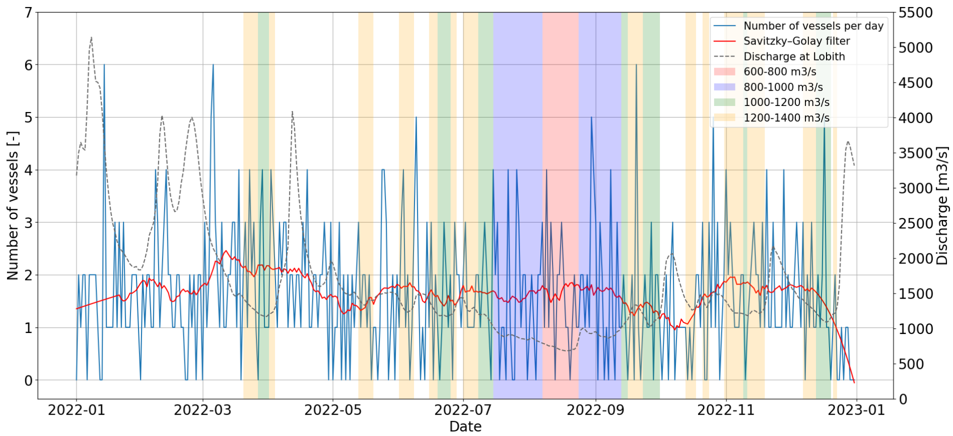


Figure 5.10: Total number of vessels arriving per day at EMO unloading berths in 2022

It is found that on average 1 to 2 vessels per day arrive at the Missisippihaven unloading berths. During days with lower Rhine discharge, no deviations can be observed. Furthermore, it is evident that the number of arrivals in December decreases, which is consistent with the seasonality graphs provided in Appendix C.1. This reduction in arrivals is likely attributable to the Christmas and New Year's Eve holidays.

5.2.3. Berth occupancy Mississippihaven unloading berths

Figure 5.11 displays the maximum daily berth occupancy of the Mississippihaven unloading berth in 2022.

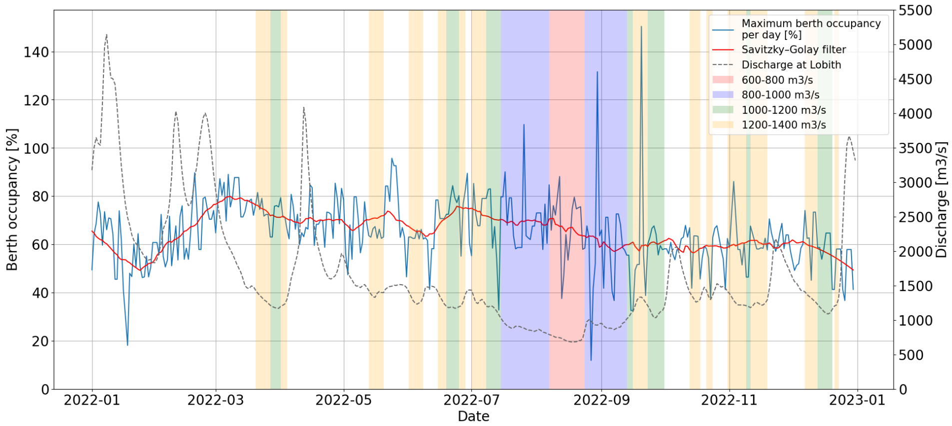


Figure 5.11: Maximum berth occupancy per day of the Mississippihaven unloading berths in 2022

The figure reveals that the berth is continuously occupied, with berth occupancy never reaching 0%. By comparing this result with the number of arrivals depicted in Figure 5.10, it was discovered that many days pass without any vessel arrivals. This observation may be linked to the service time of vessels that exceeds one day, causing the berth to remain occupied even when only a few vessels arrive. On average, the berth is occupied at a rate of 60-80%, with a reduction in February. Notably, no significant changes are observed during periods of lower discharge.

5.3. Summary

Figure 5.2 indicates that the service time for vessels arriving at the loading berths starts to decrease when the discharge at Lobith drops below 1,400 m^3/s. This finding suggests that vessels carry less cargo during low discharges. Additionally, it was observed in Figure 5.4 that more vessels arrive during discharges lower than 1,200 m^3/s, resulting in higher berth occupancy. At Hartelhaven, this increase is particularly evident (Figure 5.6), while at Mississippihaven, the arrivals and berth occupancy decrease again at a discharge lower than 800 m^3/s (Figure 5.8). The maximum berth occupancy at both locations is around 65%, compared to approximately 40% during normal discharges, indicating that there is still room for more vessels to arrive and that the handling capacity is sufficient during low river discharges.

In contrast, the number of arrivals of unloading vessels remains unaffected by low discharges, resulting in a stable berth occupancy between 60-80% in 2022, as illustrated in Figure 5.11. This finding suggests that the unloading capacity is not affected by low river discharges. Based on the observed trend of vessels sailing to the hinterland carrying reduced cargo while the incoming vessels maintain a constant load, it is crucial to conduct a study to assess whether the increasing number of inland waterway vessels can effectively transport the same volume of cargo to the hinterland, or whether this impacts the stockpile. Therefore, this is analysed in the next chapter.

6

Results: Impact of low Rhine discharge levels on the storage

This chapter implements the final step of the research approach, as outlined in Section 1.2. The cargo data for 2022, sourced from the EMO terminal as described in Chapter 3, is employed for analysis of the cargo flows. Section 6.1 is devoted to examining the impact of low river discharge on the volume of dry bulk cargo leaving the terminal. Additionally, Section 6.2 delves into the impact on the amount of cargo entering the terminal and its consequential effect on the overall surplus, which depends on the differences between the amount of cargo entering and leaving the terminal in tonnes. This section aims to answer the following sub-question: *How do low Rhine river discharges affect the storage capacity of EMO?*.

6.1. Impact of low Rhine discharge levels on outgoing cargo

Firstly, the outgoing cargo load by inland vessels is computed based on the mean vessel load and number of arrivals obtained in the preceding chapters. Secondly, it is compared with data provided by the terminal itself. Finally, after comparing the outgoing cargo load with the data provided by the terminal itself, it is also possible to determine the amount of load carried via modalities other than inland waterway vessels.

6.1.1. Determination of total load leaving the terminal

Figure 6.1 shows the amount of load leaving the EMO terminal per day in 2022 based on the number of arrivals at the loading berths as obtained from AIS data and depicted in Figure 5.3, multiplied by the mean vessel load that is computed with the use of the IVS data as depicted in Figure 4.7.

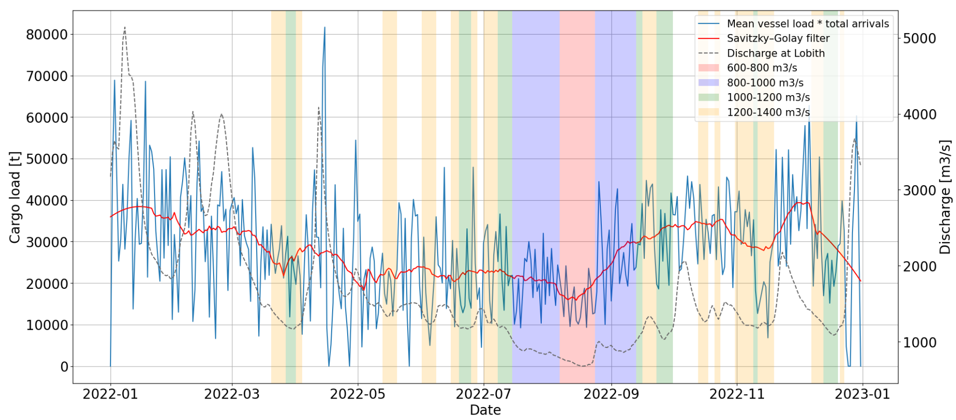


Figure 6.1: Amount of dry bulk cargo leaving the EMO terminal per day in tonnes based on the mean vessel load (IVS) multiplied by the total arrivals (AIS) at EMO in 2022

The figure above illustrates that approximately 30,000 tonnes of dry bulk cargo are transported per day from the terminal by inland waterway vessels, with a minimum of 20,000 tonnes during periods of low discharge at Lobith. Despite more vessel arrivals during the days with the lowest discharge at Lobith, as indicated in Figure 5.3, this increase in vessels is not sufficient to compensate for the reduction in mean vessel loads. As soon as the discharge is above 800 m^3/s, the daily load increases correspondingly. However, during a brief period in November, when discharge falls below 1,200 m^3/s, the total load once again decreases to 30,000 tonnes, while on the days before and after this period, transportation volume is roughly 35,000 tonnes daily.

An alternative approach to determining the total load is to multiply the crane capacity by the service time. Appendix E.1 provides an illustration of the discrepancies between the total load by using this method and the total load as shown above. Since the resulting figures are subject to significant variations due to several underlying assumptions and external factors that may affect the service time and crane capacity, these findings have not been investigated further.

6.1.2. Validation with EMO data

In order to validate the accuracy of the determined load quantities mentioned earlier, a comparison was conducted with the authentic data provided by the EMO terminal, which indicates the total amount of load leaving the terminal per month and is represented by the blue line in Figure 6.2. Consequently, the daily values depicted in the above figure are summed up to formulate monthly data, as indicated by the red line in the figure below. The middle plot in the figure displays the difference in total load per month between the computed total load and the total load according to EMO. The lower figure provides a representation of the discharge at Lobith, with an x-axis assigned to each month's 15th day, offering an indication of the discharge amount for each month in 2022.

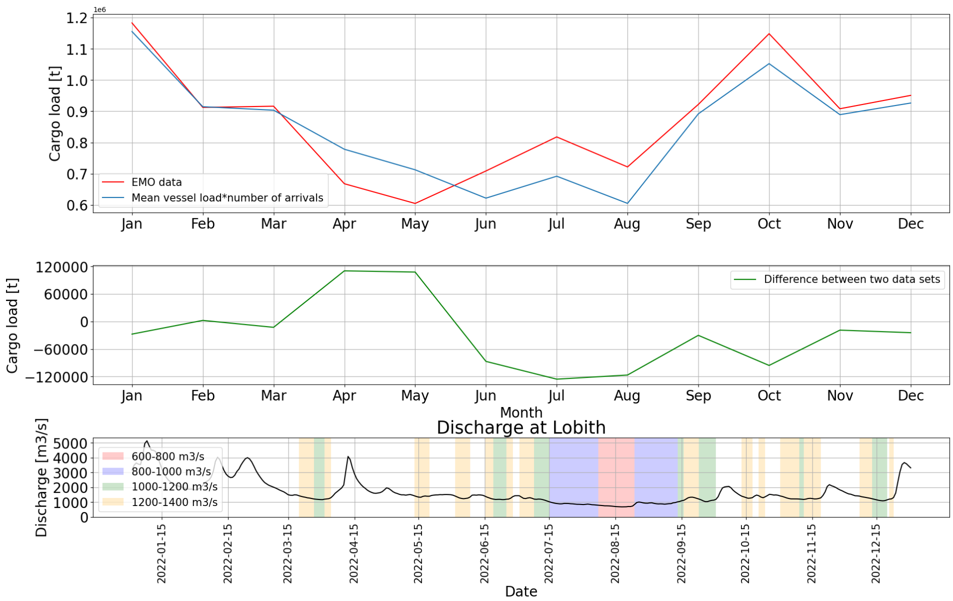


Figure 6.2: Amount of dry bulk cargo leaving the EMO terminal per month, as determined in Figure 6.1, compared to data provided by the EMO terminal in 2022 in the upper plot. Middle plot: the difference between the two datasets

The two datasets exhibit similarity in their patterns, with the first three months of 2022 having identical cargo loads. In both April and May, the actual transport of cargo outside the terminal by inland waterway vessels is approximately 0.12 million tonnes less than anticipated based on the IVS and AIS data. However, during months with decreasing discharge levels at Lobith, the EMO data reveals that 0.1 to 0.12 million tonnes more cargo are transported to the hinterland than expected according to the IVS and AIS data. This indicates that in the real-world scenario, more cargo is transported outside the terminal during periods of reduced discharge than what is reflected in the processed data. Furthermore, the transported load increases again in September and October, followed by a decrease in November and December, providing a good indication of the computed total load.

Conversely, it is feasible to compute the average vessel load using these outcomes by dividing the total load by the total arrivals and comparing it to the mean vessel load of the IVS. Furthermore, this analysis highlights the same pattern as discussed above and is demonstrated in Appendix E.2.

6.1.3. Cargo leaving terminal via different modalities

The figure below depicts the quantity of load departing from the EMO terminal on a monthly basis, considering all modes and directions, based on data provided by the EMO terminal. The red bar corresponds to the amount of cargo loaded onto inland waterway vessels for IWT, which is equivalent to the red line displayed in the preceding figure. Furthermore, the blue bar represents the quantity of load transported to the hinterland by rail, while the green bar denotes the load that is conveyed to the power plant. Additionally, the orange bar represents the amount of load that is directly transhipped from seagoing vessels into barges and the purple bar indicates the amount of cargo loaded onto large seagoing vessels, intended for transportation overseas.

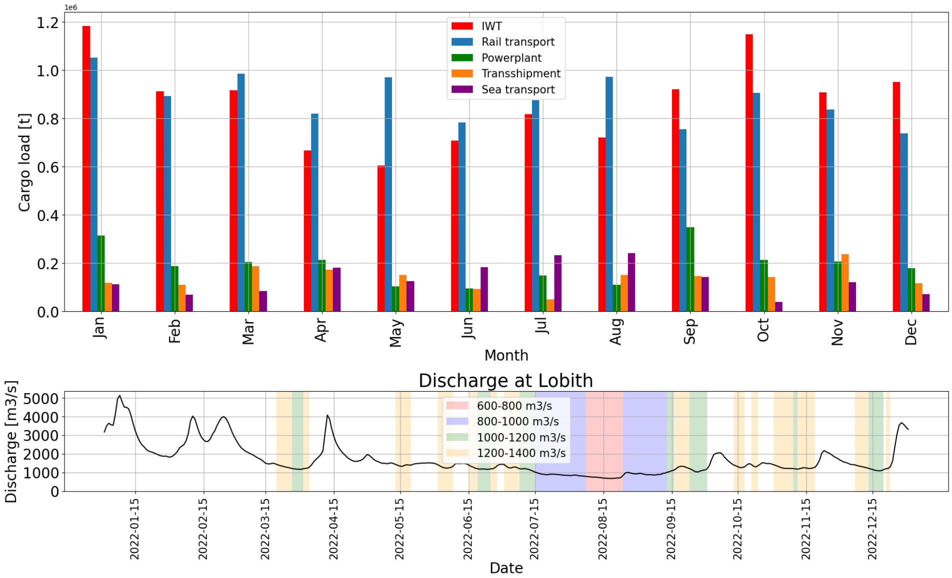


Figure 6.3: Amount of cargo leaving the EMO terminal per month via different modalities in 2022, according to data provided by EMO

During the months of July, August, and September, when discharge is low, more cargo is still transported via IWT compared to the months of April, May, and June. The proportion of load transported by rail is higher than that transported via IWT during the months of March to August. However, none of these months reflects a transportation level by rail as high as that of January, when 1.05 million tonnes were transported, indicating that the maximum rail capacity is not being reached during these months, including the months with low river discharge.

6.2. Impact of low Rhine discharge levels on the stockpile

To give an indication of the impact of low river discharges on the storage capacity of the EMO terminal, the surplus is initially determined. The surplus is the difference between the cargo volume that arrives at the terminal and the cargo volume that leaves the terminal. The amount of cargo leaving the terminal is the summation of all bars in Figure 6.3, represented with the blue line in the upper graph in Figure 6.4. Moreover, the incoming cargo load according to the data provided by the EMO terminal is indicated by the red line in the figure below. Since it was already found in the preceding chapter that this cargo flow is not affected by low river discharges, no further elaboration is done on this. The green line in the centre graph in Figure 6.4 represents the difference between the blue and red lines.

The green line demonstrates that the months with the largest difference in cargo, are April and May, with a difference of approximately 0.8 million tonnes. These are also the months when less cargo is transported via IWT, as indicated in the above figure. Consequently, the stockpile is increasing. Moreover, during the months with low river discharge, the stockpile also increases, but only by approximately 0.4 million tonnes. Since this is not as much in other months, it indicates that the low river discharges may not have a significant impact on the stockpile and that other factors may also be at play. These findings are further discussed in Chapter 7.

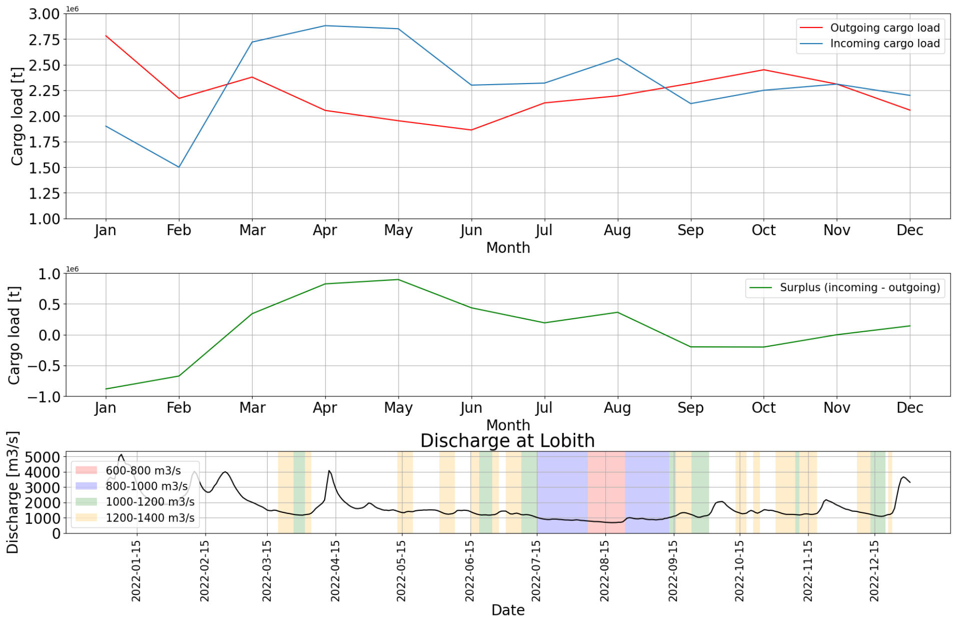


Figure 6.4: Upper plot: Total load in tonnes entering and leaving the EMO terminal per month in 2022. Middle plot: Surplus in tonnes (cargo entering - cargo leaving) of the terminal

Figure 6.5 shows the summation of the surplus, as found with the green line in the figure above, for each month, starting with different stockpile volumes. Since literature shows that a storage capacity can flexibly operate when it is occupied for 40-80% capacity, the values 40, 60 and 80% of the total maximum 7 million tonnes of storage capacity are used as starting values of the stockpile.

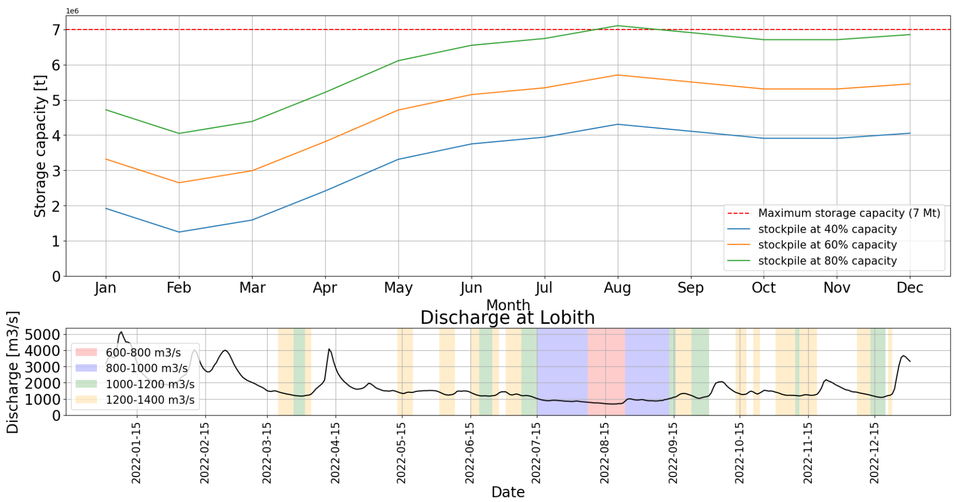


Figure 6.5: Influence of monthly surpluses on the stockpile of the EMO terminal with different starting stockpiles in 2022

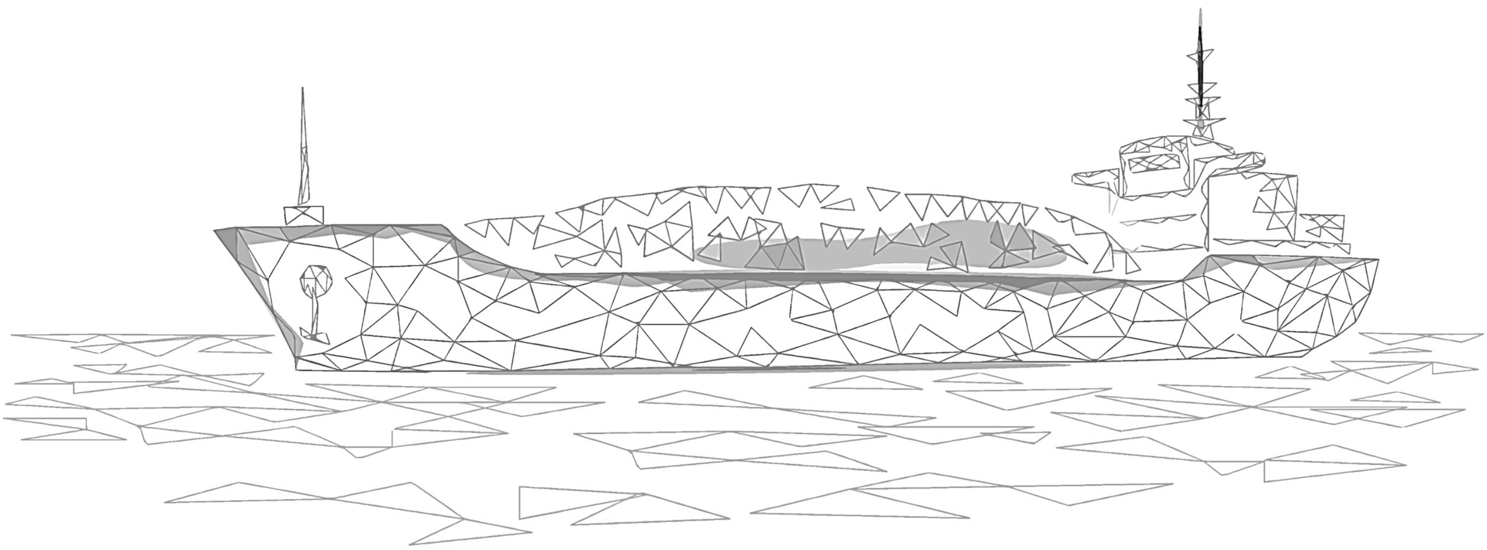
The figure shows that if the stockpile begins at 80% of its maximum capacity (5.6 million tonnes), it would have been surpassed in August. This outcome is mainly due to the substantial difference in cargo inflow and outflow in April and May and this would require the terminal to utilise sister terminals in these months located close to the EMO terminal. Following September, there is roughly an equal amount of cargo entering and leaving the terminal, resulting in no further stockpile increase. However, this 80% stockpile occupancy in January seems not reasonable and is further discussed in Chapter 7.

6.3. Summary

No significant variations are observed in the amount of load leaving the terminal during July and August, despite the lowest discharge levels observed during these months. The share of transport by train is higher in these months compared to IWT, as found in Figure 6.3, however, the amount of load that can be transported by train is not yet at its maximum. During these months a difference is noted between the amount of load entering and leaving the terminal, leading to an increase in the stockpile (Figure 6.4). This difference is moreover found to be highest in April and May, reaching approximately 0.8 million tonnes, whereas, in August, the surplus is only 0.42 million tonnes. Figure 6.5 shows that the maximum storage capacity is estimated to be reached in August if the terminal is 80% full in January, but this is not expected to be related to the low river discharges.

III

Discussion, Conclusions and Recommendations



7 Discussion

The present discussion chapter aims to provide a critical review of the material and method employed and the results obtained. Section 7.1 will focus on the methodology, highlighting potential uncertainties. Additionally, the outcomes of the results are discussed and discrepancies are explained for the inland waterway transport and the port processes, in Sections 7.2 and 7.3, respectively. Section 7.4 provides reflections on alternative scenarios.

7.1. Limitations of the materials and method

The quantification of the impact of low river discharge levels on seaport terminals was conducted using IVS data, AIS data, and cargo data provided by the EMO terminal. Each dataset was respectively employed to analyse the impact of Rhine discharge levels on the IWT of the Rhine, cargo handling capacity of the EMO terminal and storage capacity of the EMO terminal. It is important to acknowledge that the utilisation of these data sources may introduce uncertainties and limitations.

IVS data relies on the counting of vessels passing through Lobith, which may result in certain inaccuracies in the actual vessel count due to potentially missed observations. Additionally, vessels without an sk code, which is the situation for certain vessels as previously indicated in Section 3.2.1, were excluded from the analysis. This exclusion criterion may result in a lower number of vessels included in the analysis compared to the actual reality. Furthermore, the analysis of the impact of river drought on the IWT specifically focused on dry bulk vessels sailing from Rotterdam to Germany. It is worth noting that not all vessels arriving at the EMO terminal are destined for Germany and therefore, the inclusion of vessels sailing in different directions would have provided a more comprehensive understanding of hinterland transport bound from the EMO terminal. This omission may introduce further uncertainties when estimating the cargo throughput with the mean vessel load derived from IVS data and the number of vessels arriving at loading berths obtained from AIS data at the EMO terminal since IVS data only encompasses vessels sailing in the direction of Germany.

The use of AIS data is a feasible approach to identify ships that are served at the terminal for a certain period of time. However, the availability of a limited dataset and the need to make assumptions to extract the relevant vessel-related information create uncertainties in the analysis. Only a dataset spanning 3.7 years was available, including only one year (2022) characterised by extreme drought conditions. This limited dataset makes it challenging to identify meaningful trends, such as expectations for future scenarios. Additionally, the RHDHV platform utilised for retrieving AIS data had occasional data gaps when the connection was unstable, requiring the use of RWS data as a substitute. Since AIS data provides vessel messages on a minute-by-minute basis, precise filtering was necessary to determine which vessels arrived at the terminal, based on assumptions outlined in Section 3.6. One of the last filtering steps includes manual filtering to remove non-dry bulk vessels, but this process may have inadvertently overlooked some vessels, resulting in the inclusion of unserved vessels in the dataset. In the case of RWS data, manual filtering was not possible due to anonymisation, potentially leading to a higher number of vessels in the dataset that were not served on days when data was missing from the

RHDHV platform. Moreover, the determination of service time is based on the time a vessel spends at the berth, which may include periods when cranes are not in operation, leading to overestimated service times. Furthermore, step 10 in defining which vessels lie idle in Section 3.4.3 introduces new trips based on the vessel's location cluster. Since the reasons behind a vessel's presence at multiple locations or slight movements are not entirely certain, this step introduces further uncertainties and may inaccurately estimate service times by including activities unrelated to loading or unloading.

The analysis of the impact on the stockpile at the EMO terminal relied on monthly cargo data from 2022. While this data facilitated an understanding of the cargo flows during that specific year, its scope was limited to a single year, thereby posing challenges in identifying long-term trends. The utilisation of daily-based data would have offered a more refined differentiation between dry and non-dry days, allowing for more detailed analysis in this research.

It is important to note that the methodology presented in this study was applied solely to dry bulk vessels and a single terminal. Although the methodology could be extended to other terminals in Rotterdam, it is only applicable to a certain extent to terminals situated along other rivers worldwide due to the unavailability of IVS data for analysing hinterland transport. Therefore, the applicability of this methodology with AIS and terminal data alone is limited in such cases.

7.2. Discussion of the inland waterway transport

The study analysed vessel load, number of vessels, and total vessel load per day for various vessel types and the entire dry bulk fleet sailing from Rotterdam to Germany in Chapter 4. The analysis showed that low Rhine discharge resulted in a reduction of vessel load and more vessels had to sail to compensate for the losses, especially due to barges ceasing operation. Despite an increase in the number of vessels during periods of low river discharges, this increase was insufficient to compensate for the losses. Although there is a clear correlation between discharge levels and hinterland transport, some results may be questioned.

The data analysis for the two driest years, 2018 and 2022, did not lead to a consistent correlation between the threshold of the discharge at Lobith and fleet composition. In 2022, the cessation of 6-push barges occurred when the discharge dropped below 1,000 m^3/s, whereas in 2018, this shift began between a discharge range of 1,200 and 1,000 m^3/s. This difference could be explained by the time period in which the transition from 1,200 to 1,000 m^3/s took place, being shorter in 2022 than in 2018. Another reason may be that in 2022 more accurate measurements and decisions could be taken because more was known about the low river discharges, due to the dry period in 2018. Additionally, there was a noticeable discrepancy in the maximum load capacity of C4 vessels between 2018 and 2022, as depicted in Figures 4.4 and 4.5 in Section 4.1, indicating the utilisation of two distinct categories of C4 vessels during those years. The observed differences in fleet composition between the years may be attributed to changes in demand. However, it is important to acknowledge that these fluctuations in demand are unrelated to low river discharges, including the impact of external events such as the COVID-19 pandemic or the war in Ukraine. For instance, the reduced availability of M8 vessels in 2022, as compared to 2018, could potentially be a result of their deployment for grain transportation in Ukraine due to the ongoing conflict.

The study displayed that the total load per day reduced as a result of decreasing Rhine discharge, as found in Figure 4.18 in Section 4.3. Although the number of vessels increased during low discharges, these were not able to compensate for the load losses. A couple of reasons could explain this:

- The increase in the number of vessels may be hampered by the congestion of the river as it has already reached the maximum safe capacity for navigation.
- The availability of the required fleet sizes during low water levels may be limited, leading to a restriction in the possibility of increasing the number of vessels.
- In anticipation of the reduced load capacity that vessels could sail, companies may have already shifted their transportation to other modalities. As a result, there has been a decline in total transported cargo through IWT.

7.3. Discussion of the port processes

Based on the results of this study, it is observed that a decline in Rhine discharge levels leads to higher berth occupancy rates at the EMO loading berths. It has shown that given the terminal's sufficient capacity, these variations do not have a substantial impact on stockpile levels and significant disruptions are not evident. A few implications can still be examined within the context of port processes.

7.3.1. Cargo handling

The cargo handling capacity is based on the determination of berth occupancy, which was established by the percentage of the quay length that was occupied by the total vessel length of the served vessels at different locations. The findings of the analysis indicate that the berth occupancy of the loading berths exhibited an increase during periods of low river discharges as observed in Figures 5.5 and 5.7. In contrast, Figure 5.11 demonstrated that the berth occupancy of the unloading berths remained relatively stable. In regard to the vessels arriving at the unloading berths, the study revealed that only 50% of these vessels originate from the sea whereas the EMO terminal showed that this number is expected to be almost 100%. During the conversation with the employees of the EMO terminal, it was clarified that they did not observe significant changes in cargo handling in these dry periods except for increased barge exchange at the loading quay. They also mentioned that handling a greater number of vessels is not a problem for them and may even be beneficial as long as it does not disrupt their planning. The analysis of the berth occupancy showed that in general, the berth occupancy did not exceed 100%. Based on these results, it may be concluded that berth occupancy appears to be sufficiently determined. Nevertheless, some observations were made regarding the recorded berth occupancies, which are described in the following paragraphs.

For four occurrences, one day at the Hartelhaven and three days at the Mississippihaven in 2022 the berth occupancy exceeded 100% even though this is realistically impossible. It was observed that these exceedances were found on days when RWS data was added, for which it was infeasible to manually exclude irrelevant vessel types. On another day when the berth occupancy exceeded 100%, it is conceivable that a vessel situated next to the vessel being unloaded is inadvertently detected but is not filtered out.

It was also observed that the berth occupancy of the loading berths was still higher on the days after the period with low discharges. This phenomenon may be attributed, on the one hand, to the efforts of vessels to compensate for losses incurred during the period of low river discharges. On the other hand, the increased demand for coal during the colder months may also be a contributing factor.

A noteworthy observation was made from Figure 5.7, where the loading berth at Mississippihaven reached a berth occupancy of 0% during discharge rates below 800 m^3/s. As confirmed by the EMO terminal, this observation can be attributed to maintenance activities carried out at the loading berths and is, therefore, not directly related to the reduced levels of Rhine discharge.

Furthermore, it should be noted that vessel lengths and quay lengths lack a fully reliable source. The accuracy of the vessel lengths cannot always be guaranteed as discrepancies were observed between AIS data and dimensions found via myshiptracking.com (MyShipTracking, 2023), which were added with the GitHub script. Similarly, the accuracy of quay lengths obtained from Google Maps may be compromised due to the possibility of human errors. Hence, the berth occupancy percentages obtained should not be considered entirely precise. Nonetheless, the observed fluctuating trends during dry periods remain valid and can be used to draw meaningful conclusions.

7.3.2. Storage capacity

The sufficiency of storage capacity is determined based on the differences between the total amount of load that enters and leaves the terminal according to data provided by the EMO terminal. The volume of cargo leaving the terminal by vessels has been determined by multiplying the mean vessel load and number of arrivals. The amount of vessel cargo shipped to the hinterland as calculated with the IVS and AIS data did not fully correspond with the EMO terminal data. A potential explanation for this phenomenon, as also described in Section 7.1, is that not all arriving vessels travel along the Rhine. These vessels, not sailing along the Rhine, have on average a higher mean vessel load during low discharge than the ones sailing along the Rhine.

It was also found in Figure 6.3 that in the months with lower discharge, a greater proportion of cargo was transported by rail rather than IWT transport. However, this trend was also evident in other months when discharge was not markedly low. As rail transport was not operating at full capacity during these periods, it is expected that the terminal was still able to load vessels for IWT transport along the Rhine. It is worth noting, that during the months of September and October, the proportion of cargo transported by train decreased while transportation by IWT increased. This finding could suggest that vessels were attempting to compensate for losses incurred during the preceding months. Alternatively, the increased demand for coal during upcoming colder months may also be a contributing factor.

Figure 6.5 shows that the summation of the surpluses leads to an exceedance of maximum storage capacity when the starting capacity was already 80% full. Nevertheless, the EMO terminal has verified that the stockpile remained unaffected during the dry months, which suggests that they did not operate at 80% capacity in January 2022.

7.4. The applicability of the results to other terminals

Despite the EMO terminal not presently being affected, it is plausible that other terminals may already be facing issues. In the case of a dry bulk terminal with shorter quay walls and fewer cranes, accommodating both barges and seagoing vessels, it may not be feasible to handle an increased number of vessel arrivals that are loaded to sail in the direction of the hinterland. Due to long waiting times for vessel transportation, less cargo is being carried out of the terminal to the hinterland, resulting in increased stockpiles. Consequently, a higher demand for cargo handling capacity and storage capacity might be required. However, the degree of this demand relies on the duration of low discharges; if the period of low discharge is short, the disruption may be mitigated through a modal shift or cooperation with other terminals. Because of the increasing severity of drought, which leads to more load restrictions and limits the ability of vessels to expand their fleet size due to congestion or insufficient capacity, it may be necessary to implement adaptation measures, measures aimed at adjusting to climate change, sooner rather than later.

Since this study does not employ the analysis of container and liquid bulk terminals, an estimation can be made regarding the impact of low river discharges on these terminals based on existing literature. As liquid bulk only consists of a limited number of motor vessels, no such adaptation of shifting to other vessel types or an increase in vessels is possible. The same encounters for containers that already sail with liners for which the fleet is expected to not further expand. Consequently, while cargo loads may decrease, the capacity can not be compensated since the number of vessels will not increase. Accordingly, a modal shift to trucks or trains is preferable for liquid bulk, as also identified by Wienk (2021), and container transport compared to dry bulk. As the fleet is not able to expand, the cargo handling capacity will solely be affected by the service time which will be similarly impacted as dry bulk due to reduced cargo handling. In contrast, the number of liquid bulk and container vessel arrivals will not increase, resulting in no additional berth occupancy. However, the storage capacity may already be affected as a consequence of lacking capacity of rail or road networks, resulting in further stockpile increases and leading to a requirement for expansion or optimisation of the storage capacity. The need for these measures also depends on the duration of the low water period, as they are only expected to be needed when droughts last for longer periods.

8
Conclusions and recommendations

The objective of this research was to quantify the impact of low river levels on seaport processes by developing a method utilising vessel movement data to assess port processes. This chapter contains the conclusions and recommendations of this research by answering the research questions as stated in Chapter 1.

8.1. Conclusions

The conclusions of the current study are drawn by answering the four sub-questions, followed by the main question.

1. How can available data be processed and analysed to determine the effect of river drought on shipping at the river and port terminals?
The available data, including IVS data and AIS data, is processed and analysed to investigate the impact of river drought on shipping at the river and port terminals. Specifically, in the context of this study, which centres on the port of Rotterdam and the EMO dry bulk terminal, the IVS data is filtered to include exclusively dry bulk vessels sailing from Rotterdam to Germany. This selection allows for an assessment of the impact of the Rhine river drought on inland waterway transport of dry bulk cargo. The focus is on determining the amount of cargo carried and the number of vessels operating during periods of low river discharge.

The filtering process for AIS data is more intricate, as it involves making assumptions and conducting manual filtering to ensure that the data encompasses only vessels served at the specific terminal of interest. Once the data is filtered, service times for different vessels are obtained, and the number of arrivals is recorded. This information allows for the calculation of maximum daily berth occupancy for loading and unloading berths separately. By using the adjusted length occupancy, which is appropriate for dry bulk terminals, the impact on the cargo handling process can be analysed.

To examine the impact of river drought on the stockpile, data on the volume of cargo processed by the terminal is required, since AIS data does not provide insights into the specific cargo load carried by each vessel. Hence, by utilising data provided by the terminal, the stockpile during different months can be determined by subtracting the outgoing cargo volume from the incoming cargo volume.

2. How do low Rhine river discharge levels impact the amount of load carried and the number of vessels for the fleet navigating the Rhine?
Low Rhine river discharge levels have a notable impact on the amount of load carried and the number of vessels in the fleet navigating the Rhine. When the discharge at Lobith falls below approximately 1,400 m^3/s, a decline in the mean vessel load for dry bulk vessels is observed. This trend is even more pronounced for 6- and 4-push barges, which are not able to sail at full load capacity when discharge is below 2,000 m^3/s and 1,900 m^3/s and cease operations when the discharge reaches levels below 1,000 m^3/s and 800 m^3/s, respectively. As a consequence of the reduced load capacity per vessel,

the fleet size starts to increase as more vessels are required to transport the same amount of cargo. However, this increase in fleet size does not fully compensate for the decrease in individual vessel load capacity, since it is observed that the total load carried per day experiences a decline when the discharge falls below approximately 1,200 m^3/s.

3. How do low Rhine river discharges affect the cargo handling process for both loading of inland waterway vessels and unloading of seagoing vessels in the EMO terminal?
Low Rhine river discharges have an impact on the cargo handling process at the EMO terminal affecting the loading of inland waterway vessels. The findings indicate that as discharge levels at Lobith drop below 1,400 m^3/s, the service time for vessels being unloaded is reduced by approximately 40% compared to days with higher discharges. This suggests a decrease in the amount of cargo being loaded onto the vessels during periods of low river discharge. Furthermore, it was observed that as discharge levels fall below 1,200 m^3/s, there is an increase in the number of vessels arriving at the loading berths. This leads to an elevated berth occupancy rate, reaching a maximum of around 65% at the Hartelhaven berth when the discharge ranges between 600 and 800 m^3/s. Similarly, the maximum berth occupancy at the Mississippihaven berth is approximately 65%, but only when the discharge is between 800 and 1,000 m^3/s. The berth occupancy at the Mississippihaven starts to decrease again when the discharge falls below 800 m^3/s, which can be attributed to maintenance activities at the berth during a specific period in 2022 when the discharge was below this threshold. In contrast to this, the cargo handling process for unloading vessels remains unaffected during low river discharges. The berth occupancy at the Mississippihaven unloading berths remains relatively stable and comparable to that on days with normal discharges.

Given that a 65% berth occupancy at the loading berths indicates there is still room for additional vessels, it can be inferred that the cargo handling capacity of the EMO terminal appears to be sufficient during the low discharge conditions observed over the past 3.7 years.

4. How do low Rhine river discharges affect the storage capacity of the EMO terminal?
The storage capacity of the EMO terminal appears to be unaffected by low Rhine river discharge levels as no significant fluctuations in the stockpile have been identified during months with low discharge. It is interesting to note that the cargo leaving the terminal via IWT is not at its lowest in August, but rather in April and May 2022 when the discharge is not at its lowest point. Despite the higher proportion of cargo leaving the terminal via rail transport compared to IWT in August, the rail transport capacity is not fully utilised, thereby eliminating the need for a complete shift to rail transport and indicating sufficient slack.

The surplus of cargo, calculated by subtracting the incoming cargo load from the outgoing cargo load, is highest in the months of April and May. This indicates that during these months, a significant amount of cargo remains at the terminal, resulting in an increase in the stockpile. However, when these surpluses are cumulatively considered, it is observed that the EMO storage capacity would only reach its maximum if the stockpile were already at 80% capacity at the beginning of the year. This finding seems unrealistic and suggests that the storage capacity is deemed sufficient with no clear correlation found between low discharges and stockpiles.

Based on the conclusions drawn from the four sub-questions, the following main question will be answered:

What is the impact of low river discharge levels on seaport terminal processes?

The findings of this study indicate that low Rhine river discharges primarily affect the loading processes of barges at the EMO terminal. However, despite this impact, the terminal's substantial size ensures that it maintains sufficient cargo handling and storage capacities even during periods of low discharge. The results reveal that when discharge decreases, an increased number of vessels with reduced loads arrive at the loading berths, as they attempt to compensate for the limited cargo-carrying capacity. Consequently, this leads to higher berth occupancies at the loading berths, reaching a maximum of 65%, which still allows for additional vessels to be accommodated. However, the unloading of vessels arriving from overseas remains unaffected by low river discharge levels.

It is noteworthy that despite more vessels arriving with reduced loads during dry months, the quantity of cargo transported into barges destined for the hinterland remains consistent with other months. Furthermore, the rail transport capacity is not fully utilised during these dry months. These findings demonstrate that the stockpile at the EMO terminal is not significantly impacted by river drought, due to the large terminal capacity.

In conclusion, the extensive size of the EMO terminal mitigates the effects of river discharge on its processes, eliminating the need for expansion or optimisation measures.

8.2. Recommendations

Recommendations are proposed for future port adaptation measures concerning low river discharge. Additionally, suggestions are put forward for future research that aims to gain a better understanding of the impact of low river discharge on port processes.

8.2.1. Port adaptation measures

With the expectation of more severe droughts and the potential for low river discharges to pose a greater challenge for inland shipping, as stated in Section 2.2, adaptation measures are likely needed to mitigate the increasing impact on port processes. The current research shows that cargo handling for inland shipping is impacted primarily by the increased number of vessels and reduced cargo capacity, highlighting the need to monitor changes in the Rhine, as also recommended by the EMO terminal. This can be achieved by linking a system to estimate discharges at Lobith provided by Rijkswaterstaat (2023c). Thresholds can then be established, such as when discharge falls below 1,000 m^3/s, which indicates 6-push barges to cease operation, limited load capacity and more arrivals by other types of vessels. The mean load per vessel for different vessels already gives a rough estimate for the amount of load that can be carried and it is recommended to analyse each vessel separately with the use of terminal data to create better thresholds before incorporating them into a system. Such an approach could also optimise planning, as agents currently assume that vessels arriving should be fully loaded, but shippers later report that vessel draught restrictions prevent this and vessels can only be partially loaded. Failure to account for these changes reduces the efficiency of cargo handling, particularly with the increased number of vessel exchanges that occur when more vessels will arrive (EMO, 2023). This is not yet a significant issue given the current discharge levels but could become problematic during more severe discharges.

In a discussion with the EMO terminal, it was also mentioned that liquid bulk terminals already plan their terminal operations with the use of a digital application. This would also be recommended to apply for dry bulk to optimise terminal performance.

In terminals where inland vessel handling is already disrupted, expanding operational hours and optimising rail networks or investing in larger cranes may be necessary. Moreover, in designing new terminals that use rivers for inland waterway transport, it is advisable to ensure adequate space for increased vessel traffic during months with low discharge.

8.2.2. Future research

The research conducted on the impact of low river discharges on seaport terminal processes covers a limited scope. Hence, further research is recommended to improve understanding of the topic.

To expand the scope of the research, it is suggested to utilise the developed method and replicate the study across different terminals within the Port of Rotterdam, as indicated by the following two recommendations. These additional studies should use a larger dataset to analyse trends over multiple years. It is worth considering the utilisation of RWS AIS data, which offers a wider time range for analysis compared to the RHDHV platform. However, it should be acknowledged that filtering this data may pose challenges as manual filtering is not possible. Additionally, it is advisable to analyse complete trips, as this would provide better knowledge of the origins and destinations of loaded vessels, allowing for the analysis of IWT with IVS data for these vessels sailing along other routes.

- **Terminal size**
  In the Port of Rotterdam, there are two additional dry bulk terminal operators, namely EECV and EBS. These terminals have capacities that are two and three times smaller than that of the EMO terminal, respectively. The analysis of inland waterway transport for dry bulk vessels has already been conducted with IVS data in the current research. However, data analysis for these two terminals can be carried out using the AIS filtering method to get insights into the impact of Rhine discharges on smaller-sized dry bulk terminals. Once vessel data is retrieved, berth occupancies can be determined for both loading and unloading berths and a comparison can be made between different-sized terminals. Additionally, data on cargo throughput is required to analyse the impact of drought on the stockpile. These insights will facilitate an understanding of the impact of river drought on terminals of varying sizes.

- **Terminal types**
  For liquid bulk and container terminals within the Port of Rotterdam, a separate analysis should be conducted to examine the effect on these terminal types. The first step would involve analysing the inland waterway transport of containers and liquid bulk on the Rhine. IVS data should be filtered to select only container or liquid bulk vessels and the number of vessels, mean vessel load, and total vessel load per day should be analysed for these different fleets. Subsequently, the cargo handling process within the container or liquid bulk terminals can be analysed using similar steps employed for smaller-sized dry bulk terminals, as described above. Large container terminals such as APM, ECT or RWG, which transport cargo to the hinterland and have distinct locations for loading barges and unloading seagoing vessels, can serve as initial potential locations for analysis. To assess the impact on liquid bulk terminals, the VOPAK terminal in the Europoort, which supplies northwestern Europe and has 15 jetties for barges and 7 for larger vessels, would be an appropriate starting point. Additionally, it would be valuable to repeat these analyses for other sizes and types of container or liquid bulk terminals to quantify the impact of low Rhine discharge levels on different terminal types and to get a better understanding of the effect on various terminal types.

- **Global ports**
  Once the quantification of the Rhine's impact on terminals within the Port of Rotterdam is completed, it becomes essential to further investigate the effect on seaports situated along the remaining 7 rivers that experience navigation challenges due to river drought, as depicted in Figure 2.1. This study of ports lying along other rivers would give more insights into the effect of river drought on ports globally. It is important to note that the analysis of inland navigation using IVS data is unfeasible, as this data is solely available within the Netherlands. Hence, alternative sources of inland waterway transport data should be sought. Moreover, possible variations in fleet composition make it difficult to directly compare inland navigation on the Rhine and a literature study on the river should therefore be conducted primarily. To facilitate this research, information pertaining to river discharge for the respective river must be obtained. Additionally, the inclusion of AIS data and data provided by the terminals, alongside inland waterway data if available, is crucial for conducting this study. The methodology employed in the current study should be applied accordingly. Furthermore, when conducting research with AIS data, the adequacy of AIS coverage in these ports should first be assessed since coverage may not be as extensive as in the Netherlands.

- **Simulations for future scenarios**
  Given the limitations of the current study, it is not possible to ascertain trends or make predictions regarding future scenarios, such as the potential for lower discharge levels or prolonged periods of drought. Therefore, conducting more extensive simulations is recommended to gain a better understanding of the impacts of future river water levels on vessel fleets and port terminals. To perform such simulations, data from additional drought periods should be acquired, accompanied by information provided by the terminal. The simulation would utilise river discharge levels as input, with berth occupancy and changes in the stockpile serving as output based on average throughput and vessel arrivals for different-sized terminals. Such an approach could provide valuable insights into the challenges posed by river droughts in a port. It may also indicate the duration at which operational processes are significantly disrupted, signalling the need for port capacity expansion or optimisation.

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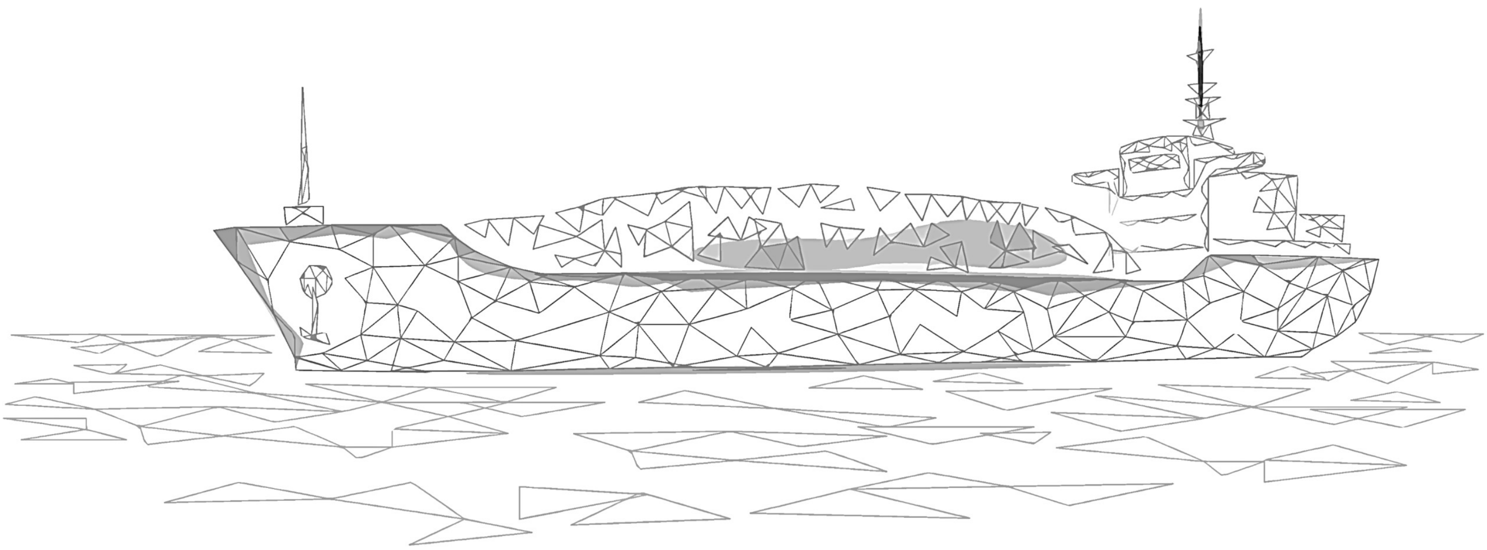
Appendices



A

Literature

This appendix contains additional information on the theoretical background described in Chapter 2. Section A.1 further elaborates on details mentioned in Section 2.1, while Section A.2 provides supplementary information on the specific drought periods and fleet compostion of Section 2.2.

A.1. Global rivers and ports affected by drought

In addition to Section 2.1, this section provides a description of the rivers that are impacted by drought worldwide but do not necessarily affect vessel navigation. Furthermore, detailed information is presented on the ports alongside rivers that have been identified as potentially being impacted by drought.

A.1.1. Rivers affected by drought, but unaffected navigability

Rivers and streams are essential sources of freshwater for many regions in the world. However, they are vulnerable to changes in climate and precipitation patterns, leading to river droughts. The following rivers are affected by drought but do not necessarily influence navigability.

In the year 2022 many rivers globally were affected by drought (Croker et al., 2022; Daily News, 2022; James, 2022; MrClain, 2021; Savannah District News Releases, 2022; Strzelecki, 2022). Croker et al. (2022) illustrates the extent of drought in six major global rivers. Among these rivers, four are navigable, but only the Loire River in France experienced no impact on its navigation as a result of the drought in 2022. Moreover, the Dnieper river in Ukraine experienced such a reduction in water levels in 2022, causing an abandoned steamship to float (Daily News, 2022). Similarly, the Elbe river in Germany experienced a period of extremely low water levels, resulting in the emergence of 'hunger stones', which centuries ago had the meaning that if they appeared it was a warning of famine in the future. However, cargo shipping could still continue during this period according to James (2022). The Oder river in Poland experienced contamination of water and fish mortality given the drought that year (Strzelecki, 2022). In contrast, the Columbia river in the United States did not face water quality issues because of meltwater, but still experienced dry periods in the spring of 2022 due to a lack of rainfall. Drought problems in Oregon also occurred due to low river basins in the Willamette river (Marine, 2022; MrClain, 2021). In the state's Georgia and South Carolina, the Thurmond Lake connected to the Savannah river entered Drought Trigger Level 1 due to low water levels in 2022 (Savannah District News Releases, 2022).

Other years also caused problems as a result of river drought. In Alabama, extreme droughts in 2016 caused 98 of the state's rivers and streams to run dry, including the Alabama river, as reported by Mosbergen (2016). In Africa, the Angolan and Malawi governments had to pay millions of dollars to respond to the impact of the Zambezi river drought in 2015 and 2016. Due to drought, people got sick from water contamination, less food was available due to poor harvests, and damages to properties occurred, leading to many losses of lives (Zambezi Watercourse Commission, 2023). Similarly, the Bio Bio river in Chile experienced a reduction in water quality during droughts between 2010 and 2015, compared to the period before droughts from 2000 to 2009 (Yevenes et al., 2018).

The Don river in Russia faced water scarcity in 2017, leading to changes in water quality and fishery stocks, which had significant impacts on the local population (Kireeva, 2018). In Canada, the Saint John river reached a low water level in 2020, exposing its bottom (Troszell, 2020). The Irrawaddy river in Myanmar suffered from a combination of drought and flood in May 2015, which destroyed crops and forced residents to leave their homes (Hansen, 2015). According to Lovgren (2019), the Mekong delta in Vietnam experienced its lowest water levels in 100 years in 2019, worsened by a combination of El Niño and climate change. The Orinoco river in Venezuela experiences annual droughts from January to April, followed by extensive flooding from June to October, especially in the Llanos regions in the west of the country (Gómez et al., n.d.). In California, the Sacramento-San Joaquin Delta is the primary water source for large regions. However, a drought emergency was declared in 2021 due to low precipitation, warm temperatures, and dry soils (California Water Boards, 2023). Moreover, climatologists predict that the streamflow of the Senegal river will decrease by approximately 10% by 2050, and the food supply for the people living in Senegal is already getting insecure due to drought in 2019 (South World, 2019) The Shatt al Arab river in Iraq suffered from low discharges, leading to human issues such as water scarcity, as reported by Almahmood et al. (2015). The droughts in the Xi river in South China are getting more frequent. Climate change and urbanisation can make this problem worse, and water management strategies should be developed to cooperate with the decrease in water availability (Wang et al., 2020).

A.1.2. Details of ports affected by drought

The ports that have been identified as having the potential to be impacted by drought, as discussed in Section 2.1.3 are presented in Table A.1. This table contains information about the size of each port based on HDX (2019), along with details obtained from S&P (2022) regarding the maximum length overall (LOA) of the vessel that can be accommodated, the maximum deadweight tonnage (DWT) that can be handled, and whether the port has container, dry bulk, or liquid bulk facilities. The maximum LOA and DWT for the port of St. Louis and Buenos Aires could not be found.

Table A.1: Additional information of ports potentially affected by river drought (HDX, 2019; S&P, 2022)

Port	River	Size	Max. LOA [m]	Max. DWT [t]	Container	Dry Bulk	LNG
Belem	Amazon	M	210	65,120	Yes	Yes	Yes
Manaus	Amazon	S	225	50,000	Yes	Yes	No
Constanta	Danube	M	300	220,000	Yes	Yes	Yes
Hai Phong	Hong red	S	351	132,800	Yes	Yes	Yes
New Orleans	Mississippi	L	366	159,150	Yes	Yes	Yes
St. Louis	Mississippi	L	-	-	No	Yes	No
Buenos Aires	Paraná	L	-	-	Yes	Yes	No
La Plata	Paraná	M	340	75,000	Yes	Yes	No
Montevideo	Paraná	M	340	134,870	Yes	Yes	Yes
Rosario	Paraná	M	240	98,700	Yes	Yes	No
Rotterdam	Rhine	L	No restriction	550,000	Yes	Yes	Yes
Montreal	Saint Lawrence	L	304	116,780	Yes	Yes	No
Quebec	Saint Lawrence	M	345	203,000	Yes	Yes	No
Sept-Iles	Saint Lawrence	M	360	225,000	Yes	Yes	No
Trois Rivieres	Saint Lawrence	M	230	63,520	Yes	Yes	No
Wuhan	Yangtze	M	-	15,670	Yes	Yes	No
Shanghai	Yangtze	L	367	300,000	Yes	Yes	Yes

The ports of Dordrecht and Europoort were also in the WPI but were not included in the selection of ports identified as ‘potentially affected by drought’, as they form part of the Port of Rotterdam. It is noteworthy that for some of the selected ports, the maximum vessel length and deadweight tonnage are not provided by Seaweb. Interestingly, the size of a port, as indicated by the WPI, does not necessarily indicate its capacity to handle the largest vessels and cargo. For instance, the medium-sized port of Quebec can handle larger vessels and more cargo than the larger port of Montreal.

As stated in Section 2.1.3, only ports of medium and large size were included in the selection along these rivers, with the exception of Manaus and Hai Phong. In Manaus, low water surcharges are already being imposed, as reported by Poel (2023). Furthermore, the port of Hai Phong is included since it is the only port located along the Hong Red river. Despite its small size, it can handle more cargo than other ports classified medium or even large-sized, such as the port of Wuhan, Trois Rivieres, La Plata, Rosario and Montreal.

A.2. Rhine corridor

A.2.1. Discharge levels

Table A.2 shows the periods that the discharge and water level are below the thresholds in Figure 2.3. The table highlights a notable occurrence of low water levels, particularly in 2018 and 2022, with a substantial number of days below the Average Low Discharge (ALD) and Average Low Water (ALW) thresholds. Conversely, in 2019, there was a scarcity of days characterised by low water levels, with no instances of discharge falling below 1,020 m^3/s.

Table A.2: Periods with discharges below ALD and water levels below ALW at Lobith (Rijkswaterstaat, 2023b)

Year	Agreed Low Discharge (<1,020 m^3/s)	Agreed Low Water level (<739 cm)
2018	30/07 - 6/09 & 10/09 - 05/12 (125 days)	23/07 - 25/07 & 29/07 - 07/09 & 09/09 - 05/12 (132 days)
2019	-	24/09 - 26/09 (3 days)
2020	30/08 - 31/08 & 01/09 - 02/09 & 22/09 - 27/09 (10 days)	06/08 & 29/08 - 03/09 & 18/09 - 28/09 & 05/12 (19 days)
2021	28/11 (1 day)	30/10 - 04/11 & 22/11 - 01/12 (16 day)
2022	16/07 - 13/09 (60 days)	16/07 - 15/09 & 27/09 - 28/09 (64 days)

A.2.2. Fleet composition

The vessel dimension classifications of Rijkswaterstaat and Koedijk (2020) classes are given in Table A.3.

Motor vessels, except for container vessels, most often travel laden to their destination and empty during their return. The barges indicated by a ‘B’ in Table A.3 are a combination of a push boat and push barges and are called a push convoy. The BII-6l class is for example a 6-barge pushed in a long formation, while BII-6b is a 6-barge pushed in a wide formation. A coupled convoy, indicated by a ‘C’, is a motor cargo vessel combined with another vessel or push barge attached in front of alongside. A C3l vessel is for example a CEMT class Va motor vessel (M8 or M9) with a Europa II long barge in front, these are the same barges that are pushed by a BII-1, BIIa-1 and BIII-1 pushed convoys.

It is noteworthy that each vessel does not have a unique length and width, but that classifications are made. This means that when the length and width of a vessel are known but the appearance is not, it can be classified as multiple vessels. For instance, a vessel with a length of 130 m and a width of 12 m, can be an M11, BIIL-1 and C3l vessel. However, when the appearance of a vessel is known, a distinction can easily be made between motor, pushed convoy or coupled convoy, since motor vessels are single vessels, a pushed convoy consists of a push boat and push barge and a pushed convoy is a combination of a motor vessel and another vessel or a barge.

Table A.3: Inland navigation fleet classification (Rijkswaterstaat & Koedijk, 2020)

CEMT class	RWS class	Length [m]	Width [m]	Loaded draught [m]	Load capacity [t]
I	M1	≥ 38.01	$5.01 - 5.10$	2.5	$251 - 400$
II	M2	≥ 38.01	$5.11 - 6.70$	$401 - 650$	
III	M3	≥ 38.01	$6.71 - 7.30$	2.6	$651 - 800$
III	M4	$38.01 - 74.00$	$7.31 - 8.30$	2.7	$801 - 1050$
III	M5	≥ 74.01	$7.31 - 8.30$	2.7	$1051 - 1250$
IVa	M6	$38.01 - 86.00$	$8.31 - 9.60$	2.9	$1250 - 1750$
IVa	M7	≥ 86.01	$8.31 - 9.60$	3.0	$1751 - 2050$
Va	M8	$38.01 - 111.00$	$9.61 - 11.50$	3.5	$2051 - 3300$
Va	M9	≥ 111.01	$9.61 - 11.50$	3.5	$3301 - 4000$
VIa	M10	$38.01 - 111.00$	$11.51 - 14.30$	4.0	$4001 - 4300$
VIa	M11	≥ 111.01	$11.51 - 14.30$	4.0	$4301 - 5600$
VIa	M12	≥ 38.01	≥ 14.31	4.0	≥ 5601
I	B01	all	≤ 5.20	1.9	$0 - 400$
II	B02	all	$5.21 - 6.70$	2.6	$401 - 600$
III	B03	all	$6.71 - 7.60$	2.6	$601 - 800$
III	B04	all	$7.61 - 8.40$	2.7	$801 - 1250$
IVa	BI	all	$8.41 - 9.60$	3.0	$1251 - 1800$
Va	BII-1	≤ 111.00	$9.61 - 15.10$	3.5	$1801 - 2450$
Va	BIIa-1	≤ 111.00	$9.61 - 15.10$	4.0	$2451 - 3200$
Va	BIIL-1	$111.01 - 146.00$	$9.61 - 15.10$	4.0	$3201 - 3950$
Vb	BII-2l	≥ 146.01	$9.61 - 15.10$	$3.5 - 4.0$	$3951 - 7050$
VIa	BII-2b	≤ 146.00	$15.11 - 24.00$	$3.5 - 4.0$	$3951 - 7050$
VIb	BII-4	$146.01 - 200.00$	$15.11 - 24.00$	$3.5 - 4.0$	$7051 - 12000$
VIc	BII-6l	≥ 200.01	$15.11 - 24.00$	$3.5 - 4.0$	$12000 - 18000$
VIc	BII-6b	all	≥ 24.01	$3.5 - 4.0$	$12000 - 18000$
I	C1l	all	≤ 5.10	2.5	≤ 900
I	CIb	≤ 80.00	$9.61 - 12.60$	2.5	≤ 900
IVb	C2l	all	$5.11 - 9.60$	3.0	$901 - 3350$
Vb	C3l	≥ 80.01	$9.61 - 12.60$	$3.5 - 4.0$	$3351 - 7250$
VIa	C2b	≤ 136.00	$12.61 - 19.10$	3.0	$901 - 3350$
VIa	C3b	≤ 136.00	> 19.10	$3.5 - 4.0$	$3351 - 7250$
VIb	C4	≥ 136.01	> 12.60	$3.5 - 4.0$	≥ 7251

B

Additional information on AIS data processing

This appendix provides additional information on the AIS data processing steps as described in Section 3.4. The first section further elaborates on the limitations of AIS data. The second, third and fourth sections contain additional information on the three stages taken during the data processing, while the last section shows the data reduction due to filtering.

B.1. AIS limitations

Table B.1 presents the proportion of AIS messages not showing values ('NaN') with respect to the total number of messages, derived from AIS data obtained in the EMO terminal during the year 2022, after eliminating certain rows.

Table B.1: Limitations in AIS data in the EMO terminal in 2022 after removing irrelevant vessel types

Parameter	Number of messages [-]	Share of missing messages of total [%]
Total messages	4,722,856	-
Number of messages without vessel type	3,027,497	64.1%
Number of messages without speed	275,040	5.8%
Number of messages without length	3,144,673	65.9%
Number of messages without DWT	3,850,313	81.5%

The table verifies that for numerous messages, information regarding vessel type, length and dead weight tonnage is unavailable. This makes it more complicated to conduct a comprehensive analysis.

B.2. Data filtering and trip creation

This section further elaborates on the data filtering and trip creation as presented in Section 3.4.2.

B.2.1. AIS Terminal data

Figure B.1 depicts the polygon utilised to extract data from the EMO terminal. As described in Subsection 3.4.2, the polygon encompasses a larger region beyond the berth locations themselves, thus enabling the visualisation of complete vessel trips.

Figure B.1: Polygon of the area defined as EMO terminal (Royal HaskoningDHV, 2018)

As a result of this polygon, 5,334,949 messages with 2,122 unique mmsi numbers are extracted for the year 2022. It should be noted that each unique mmsi number generates a trajectory consisting of multiple messages within the polygon, and may also appear on different dates. Subsequently, after discarding all messages pertaining to vessels identified as non-dry bulk (i.e., those with a vessel type other than ‘NaN’), the data set is reduced to 4,722,856 messages, representing an 11% reduction in total messages, and 1,816 unique vessels, reflecting a 14% decline.

As each vessel generates a path, Movingpandas is utilised to create trajectories that can be plotted, an example of a random trajectory is illustrated in Figure B.2.

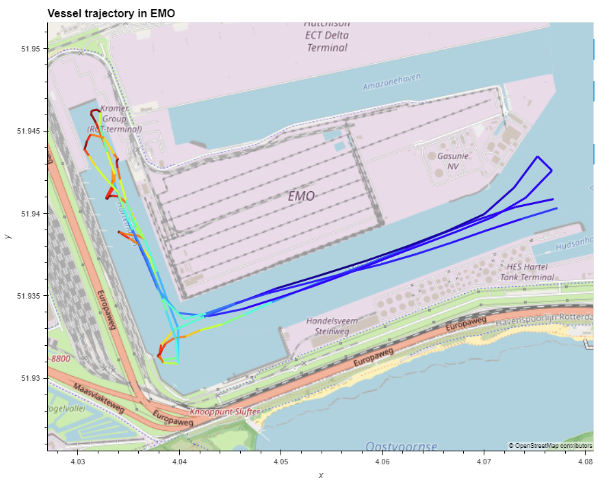


Figure B.2: Trajectory created by MovingPandas

In the year 2022, a total number of 1,529 trajectories were generated, each expected to correspond to a unique vessel. However, it was observed that the data set was reduced to only 4,648,415 messages, representing a decline of 1.6% messages, and so 15.8% fewer unique vessels were in the trajectories. Although Movingpandas can create trajectories of unique vessels with only one message, which needs to be removed before creating trips, it is now apparent that the reduction in the number of unique vessels during trajectory creation implies that Movingpandas occasionally removes messages of a unique vessel with a single message. Therefore, not all unique vessels are in the dataset when creating trajectories. Moreover, no trajectories were created with only one message in 2022, thus the step of removing trajectories with a single row is unnecessary in that year. Using the 1,529 trajectories, trips were created following the gap restriction of 12 hours, resulting in 12,490 trips for 2022. Figure B.3

illustrates two trips created from the trajectory depicted in Figure B.2.

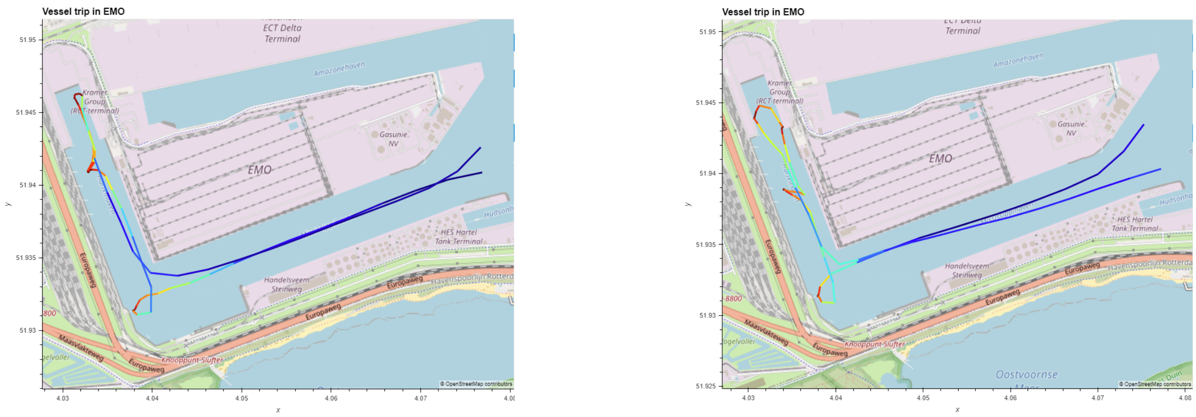
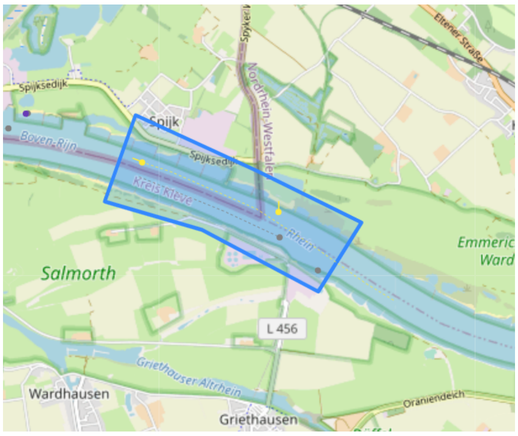


Figure B.3: Two trips created from the trajectory in Figure B.2 by Movingpandas

B.2.2. AIS Rhine and sea data

Figure B.4 shows the established polygon to generate AIS data on the Rhine and in the sea.



(a) Polygon to detect Rhine vessels at Lobith (Royal HaskoningDHV, 2018)

(b) Polygon to detect sea vessels at sea (Royal HaskoningDHV, 2018)

Figure B.4: Polygons to detect vessels coming from the Rhine and from the sea (Royal HaskoningDHV, 2018)

B.3. Defining vessels lying idle

This section further elaborates on the assumptions made during the steps in Section 3.4.3 to find out which vessels lie idle at the terminal.

B.3.1. Speed filtering

This speed limit of 0.3 m/s is chosen by analysing speed over time. It was found that for the majority of trips which stayed in a single location for a longer duration, the speed values remained below 0.3 m/s. In a later stadium of the research, the service time is analysed, therefore the time it takes to moor is reduced as much as possible by filtering on a low speed.

To gain insights into the number of messages with a speed below 0.3 m/s, a histogram of all trips merged in 2022 is shown in Figure B.5. The continuous red line indicates the cumulative distribution function (CDF). This CDF shows that 88% of the speed messages of all trips are below the limit of 0.3 m/s, which is indicated by the dashed red line.

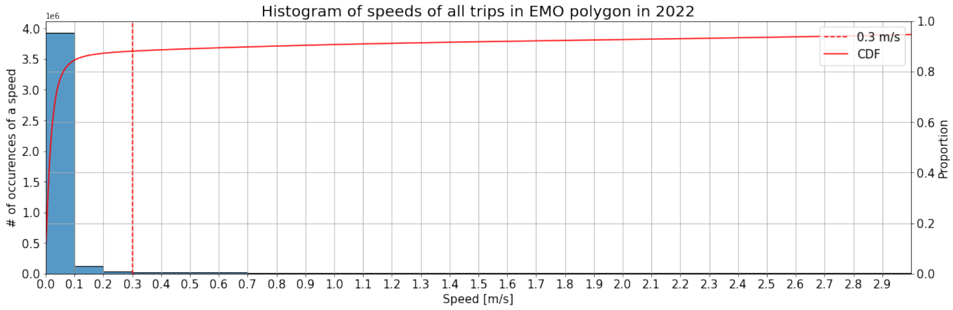
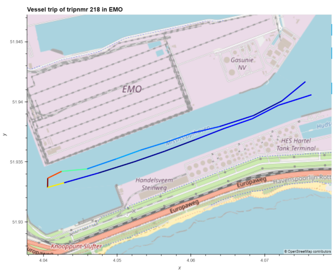
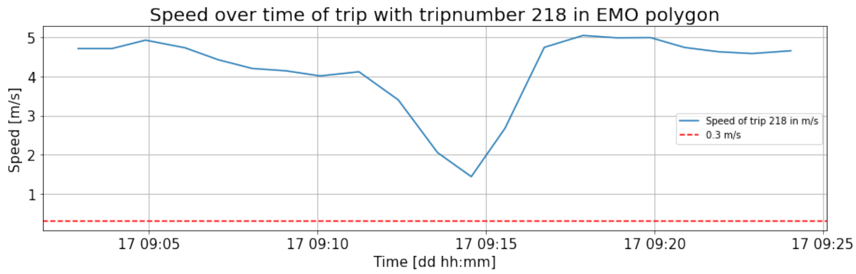


Figure B.5: Histogram and CDF of speed for all trips made in EMO polygon in 2022

As described in Subsection 3.4.3 a few trips end up empty after filtering on speed. For the year 2022, this was 1.6% of the trips, which is 203 of the 12,490 trips. An example of an empty and which is therefore not further taken into account is shown in Figure B.6b. The left figure shows that the vessel only enters the polygon and then turns around and leaves again. The vessel probably continues its trip in a different direction. The speed over time plot on the right shows that the trip only has speed values above 0.3 m/s.



(a) Trip number 218 in 2022

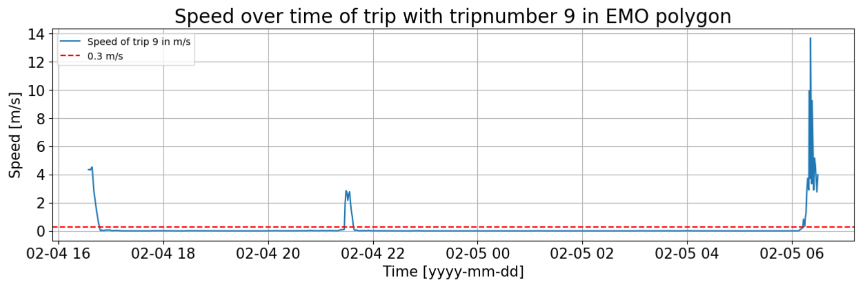


(b) Speed over time of trip number 218 in 2022

Figure B.6: Speed and trip of vessel not stopping in EMO polygon

In addition to the speed over time showed in Figure 3.10b, the trip and speed of a vessel that stops at multiple locations is depicted in Figure B.7. The left figure shows the course of the vessel before filtering, while the right figure shows the speed over time. When analysing the speed it is found that the vessel first lies still for a little more than 4 hours at the east side of the EMO terminal, then the vessel starts to sail with a speed higher than 0.3 m/s and then arrives at the opposite of the Hartelhaven, where it lies for approximately 8 hours, where after the vessel the polygon leaves again. Moreover, it confirms that when a vessel is lying still, the speed values are below the limit of 0.3 m/s.

(a) Trip number 9 in 2022



(b) Speed over time of trip number 9 in 2022

Figure B.7: Speed and trip of vessel stopping at two locations in EMO polygon

B.3.2. Create clusters

Similarly to the speed filter, the distance of two successive messages for the EMO trips in 2022 is merged and plotted as a histogram in Figure B.8. The histogram shows that a high share of messages is below the limit of 40 m.

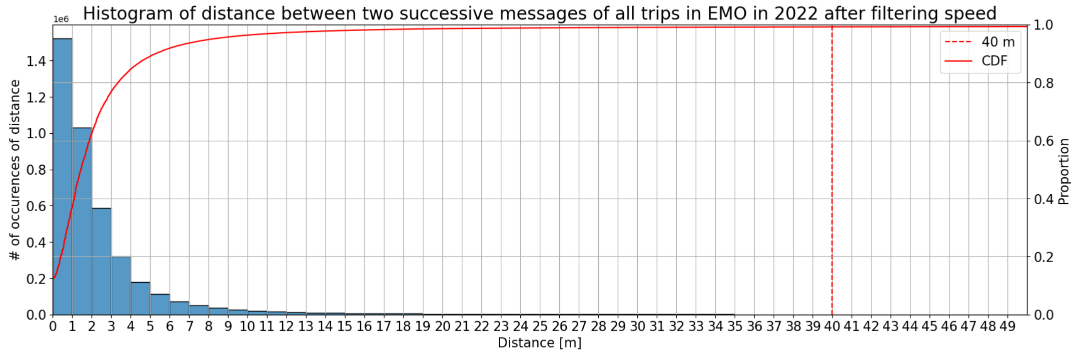
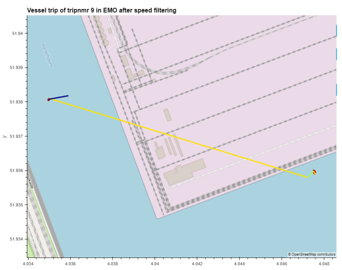
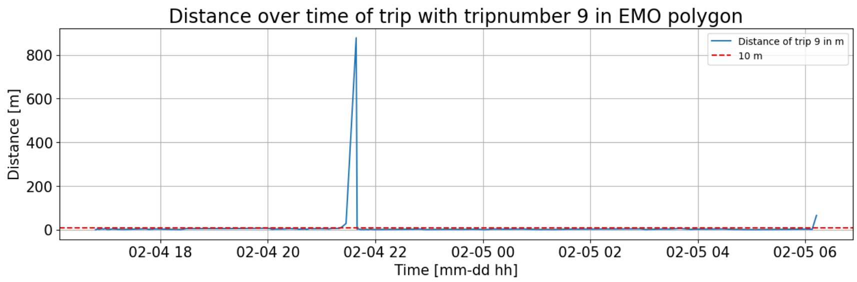


Figure B.8: Histogram and CDF of distance for all trips made in EMO polygon in 2022 after filtering on speed

As indicated in Subsection 3.4.3, the route of the trip is narrowed down following the application of speed filtering. Figure B.9a illustrates the same trip as presented in Figure B.7a post-speed filtering. As observed in Figure B.9b, the distance between two successive messages once increases to 800 m, during vessel movement between locations.



(a) Trip of Figure B.7a after filtering on speed



(b) Distance between two successive points over time of trip number 9 in 2022

Figure B.9: Trip after filtering and distance between two successive points for the trip of Figure B.7a

As a result of creating clusters, a new column with the name *clustnr* is added to the existing trip DataFrames. An example of a few messages of the DataFrame from the trip in the figure above is illustrated in Figure B.10. It shows that when the distance becomes larger than 40 m, a unique value cluster number, in this case, number 40, is created. The cluster with the number 39 is the cluster on the right side in Figure B.9a and cluster 41 is the cluster on the left.

	date	speed	distance	time	clustnr
45	2022-02-04 21:22:49	0.070890	12.703899	179.0	39.0
46	2022-02-04 21:27:20	0.104859	28.468069	271.0	39.0
47	2022-02-04 21:38:39	0.073850	878.325118	679.0	40.0
48	2022-02-04 21:39:40	0.033715	2.063181	61.0	41.0
49	2022-02-04 21:40:40	0.066807	4.011573	60.0	41.0
50	2022-02-04 21:41:40	0.055890	3.355650	60.0	41.0
51	2022-02-04 21:42:40	0.031526	1.892775	60.0	41.0

Figure B.10: Few messages of the DataFrame of the trip depicted in Figure B.9

B.3.3. Filter on location and duration

To find the optimal duration limit, first, a filter is applied on location and a duration of 0.1 hours. This ensures that single clusters, given a duration of 0 hours, are removed. Cluster number 40 in Figure B.10 is an example of such a cluster. This filter steps results in 41.0% of all trips being empty. Figure B.11 shows the histogram and CDF of the durations of all unique clusters in EMO in the year 2022 after filtering on speed, location and duration of 0.1 hours. Although the maximum duration is 189 hours, the histogram is cut off at a duration of 8 hours, since the number of durations thereafter is getting more stable and the smallest duration is of most interest. It moreover shows that there is a strong peak in number of durations below 0.7 hours.

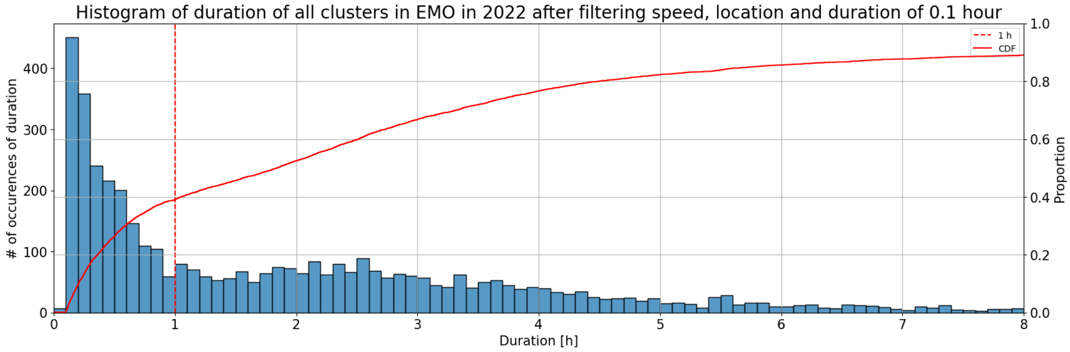
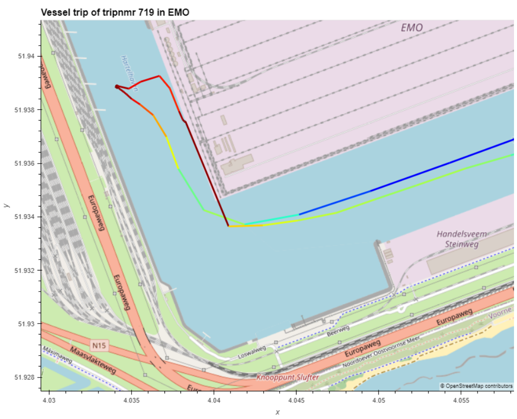


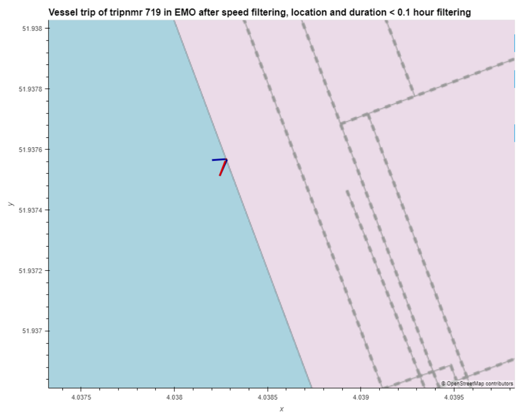
Figure B.11: Histogram and CDF of the durations of all clusters

Although there is an apparent rise in the number of clusters with durations under 0.7 hours, the analysis encompasses all trips with cluster durations less than 1 hour to ensure a wider scope of analysis. Additionally, trips are analysed at the Hartelhaven barge loading berths of the EMO terminal, since this takes less time than sea vessel unloading, these specific locations are determined within the next step.

The figures below give an example of trips with a cluster duration below 1 hour. On the left-hand side of Figure B.12, the trip is depicted before filtering, while on the right-hand side, the filtered portion of the trip is presented. The trip shows that the vessel first arrives at the waiting berths opposite of the EMO terminal where it is for 15.4 hours, subsequently, it manoeuvres towards the exit of the polygon, and in between it has a cluster of 18 minutes at the quay. The assumption is made that a loading time of fewer than 18 minutes is inadequate and that the vessel is either making space for an arriving vessel or waiting until it can berth at its designated area.



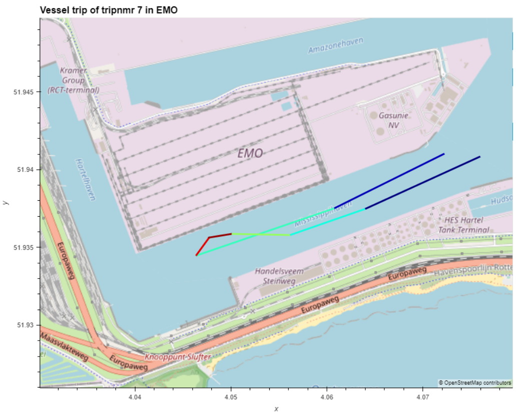
(a) Entire trip before filtering



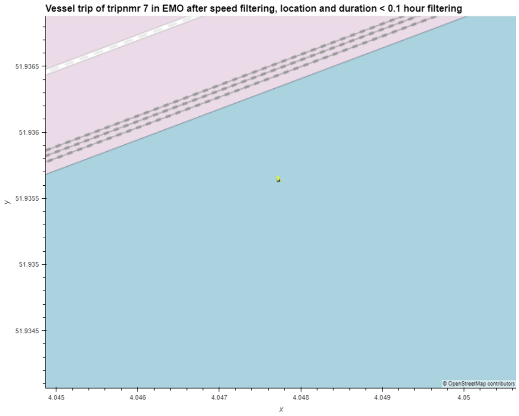
(b) Trip of Figure B.12a after filtering on location and duration of 0.1 hours

Figure B.12: Trip arriving at Hartelhaven with cluster duration 0.3 hours

Figure B.13 shows an example of a trip with a duration shorter than 1 hour in the Mississippihaven. The figure on the right depicts the filtered section of the trip, which is at the terminal for 0.9 hours. The plot indicates that only a few messages are transmitted during this interval, suggesting that the vessel may be using this location to manoeuvre. Moreover, it is unlikely that the unloading of a sea vessel can be completed within an hour.



(a) Entire trip before filtering



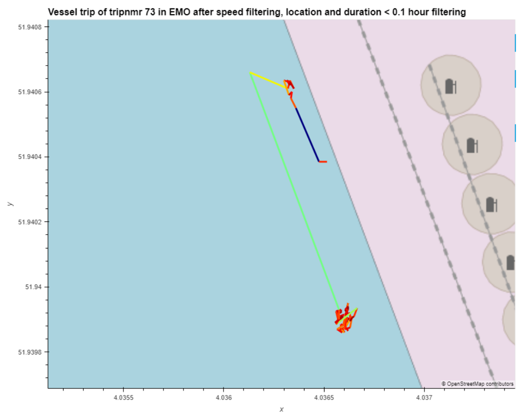
(b) Trip of Figure B.13a after filtering on location and duration of 0.1 hours

Figure B.13: Trip arriving at Mississippihaven with cluster duration shorter than 0.9 hours

Additionally, trips are analysed with more than one cluster after applying a filter on location and duration. A trip may consists of multiple clusters for several reasons. For instance, a push boat may couple with a barge and transport it to an (un)loading location, followed by sailing to another location for a similar task. Alternatively, a vessel may need to unload cargo before loading a new commodity or load for a different location. Additionally, some trips may have clusters located close to one anothher. In such cases, the vessel may have completed loading but is required to wait for approval to leave, as another vessel is required to load at that location. The same can occur for arrival, when the berth is still occupied when the vessel arrivals. Finally, it may be necessary for a vessel to receive assistance to maneuver in the desired direction.

The trip depicted in Figure B.14 first arrives at the location with many messages and lies there for 3.6 hour, additionally it seems to sail backwards and then manoeuvres away. This might be done to avoid other vessels mooring at the quay or it is waiting for approval to leave. The second cluster has a duration of 0.85 hours, but is assumed as not loading, since it is also for a shorter duration than the other cluster.

(a) Entire trip before filtering



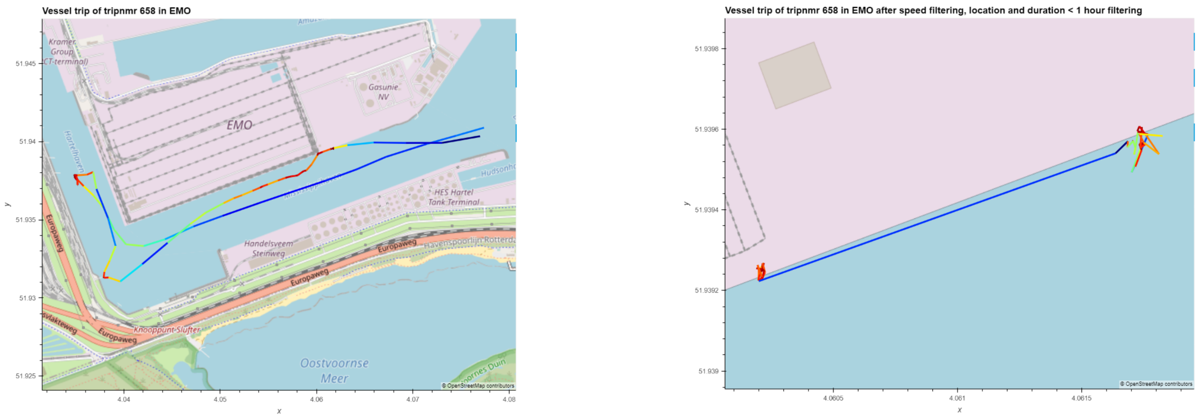
(b) Trip after filtering on location and duration of 0.85 hour

Figure B.14: Trip arriving at Hartelhaven with multiple clusters with duration's 3.6 and 0.85 hours.

As a result of the analysis, the duration limit is set to 1 hour. From Figure B.11 it can be seen that approximately 40% of all clusters are disregarded and 18.6% more trips are totally empty after changing the filter from duration 0.1 hour to 1 hour for the data of 2022.

B.3.4. Multiple berth

As described in the previous step, trips may consists of multiple clusters. The clusters at multiple berths in a single trip are distinguished. A trip can arrive at different quay locations, Hartelhaven and Missippihaven, but there are also trips that arrive at both the loading and unloading berth of the Missis-sippihaven. Figure B.15 shows a trip that first arrives at the unloading berth, where it is for 1.5 hours and then sails further to the loading berth where it lies for 2.0 hours. It is assumed that the vessel thus does make two actions: first unload and then load. This however, does not have to be reality, therefore more information should be required.



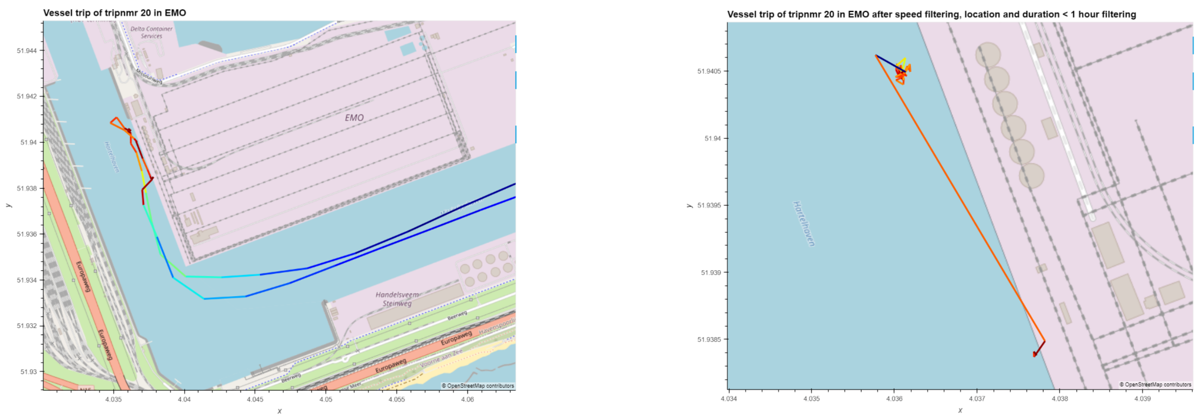
(a) Entire trip before filtering

(b) Trip after filtering on location and duration of 1 hour

Figure B.15: Trip that has multiple clusters at Missisipphaven loading and unloading berth

B.3.5. Create new trip numbers

New trip numbers are created to split up clusters that have multiple distinct berth locations, however, there are also trips that do have multiple clusters but do not berth at two distinct berths. These clusters then get the same new trip number. Figure B.16 shows an example of a trip that has multiple clusters at the Hartelhaven quay. Initially, the vessel arrives at the far end of the quay and remains there for 1.91 hours before moving forward slightly and staying for 1.33 hours. Since both clusters have a duration exceeding 1 hour, none are discarded, while most other trips with multiple clusters are reduced to just one cluster, since these have a duration shorter than 1 hour. Additionally, it is assumed that the vessel can only load at one location, although this may not be accurate for this specific trip, which could entail loading at two distinct berths. Consequently, when generating new trips, the clusters for this trip are merged into one trip.



(a) Entire trip before filtering

(b) Trip after filtering on location and duration of 1 hour

Figure B.16: Trip that has multiple clusters at Hartelhaven with durations 1.91 and 1.33 hour

Moreover, the creation of new trips results in 3.6% more trips, while not taking into account the empty trips for the year 2022.

B.3.6. Create DataFrame for all trips

Figure B.17 illustrates an example of the final DataFrame created for the vessels arriving at EMO in 2022. The column with mmsi numbers is left out due to privacy sensitivity. The preceding steps led to a total DataFrame comprising 3722 unique vessels arriving at the EMO terminal in 2022.

start_date	start_time	end_time	trip_dur	trip_nr	trip_nr_clust	longitude	latitude	vesseltype	maincat	berth	quay	LOA	width	DWT
2022-06-09	2022-06-09 05:28:50	2022-06-13 23:27:01	113.969722	0	1.0	4.058035	51.938526	bulk carrier	Bulk Carriers	missi_sea	missi_tot	292.00	45.00	179895.0
2022-11-08	2022-11-08 19:17:31	2022-11-08 21:28:00	2.174722	1	2.0	4.037132	51.939375	NaN	NaN	hartel	hartel	NaN	NaN	NaN
2022-05-10	2022-05-10 19:48:17	2022-05-11 12:36:34	16.804722	5	3.0	4.048452	51.935972	NaN	NaN	missi_sea	missi_tot	NaN	NaN	NaN
2022-07-02	2022-07-02 18:04:51	2022-07-03 06:20:51	12.266667	6	4.0	4.048181	51.935906	NaN	NaN	missi_sea	missi_tot	NaN	NaN	NaN
2022-07-28	2022-07-28 11:53:15	2022-07-28 12:47:13	0.899444	7	5.0	4.047725	51.935638	NaN	NaN	missi_sea	missi_tot	NaN	NaN	NaN
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2022-01-29	2022-01-29 12:17:58	2022-02-02 14:20:33	98.043056	12485	4583.0	4.058028	51.938539	bulk carrier	Bulk Carriers	missi_sea	missi_tot	260.37	43.00	121448.0
2022-03-15	2022-03-15 16:08:41	2022-03-18 02:32:47	58.401667	12486	4584.0	4.049198	51.936480	bulk carrier	Bulk Carriers	missi_sea	missi_tot	260.37	43.00	121448.0
2022-03-21	2022-03-21 13:26:41	2022-03-22 00:15:46	10.818056	12487	4585.0	4.049207	51.936498	bulk carrier	Bulk Carriers	missi_sea	missi_tot	260.37	43.00	121448.0
2022-09-27	2022-09-27 08:53:29	2022-09-30 02:58:23	66.081667	12488	4586.0	4.058049	51.938540	bulk carrier	Bulk Carriers	missi_sea	missi_tot	260.37	43.00	121448.0
2022-09-27	2022-09-27 16:02:00	2022-10-01 05:56:50	85.913889	12489	4587.0	4.053730	51.937651	bulk carrier	Bulk Carriers	missi_sea	missi_tot	229.00	32.26	82000.0

Figure B.17: Example of end DataFrame

B.4. Vessel filtering and adding features

Due to the steps in Subsection 3.4.4, a few adjustments to the DataFrame are made. As a result of filtering on a duration of 1 hour 2.3% of the trips in 2022 are removed. Moreover, lengths are added, prior to this step 74.6% of all trips did not have a length given, after adding and replacing the length information only 1.0% of the trips do yet not have a length. Additionally, the number of trips is further reduced by 6.9% after filtering on a vessel length of 38 m.

B.4.1. Add origin of the trips

By incorporating origins into the data frame using the Rhine and sea polygon, as well as Seaweb, Table B.2 displays the number of messages recorded for the year 2022. It clearly shows that most vessels in the EMO terminal come from the Rhine.

Table B.2: Number of trips per origin after adding origins to trips

rhine	seaweb	sea_poly	# of trips
True	False	False	2321
False	False	False	387
	True	True	50
		False	219
	False	True	95
True	True	False	7
	False	True	4

B.4.2. Check vessel types and remove manually

As mentioned in Subsection 3.4.4, data is analysed by checking individual mmsi numbers for vessels with varying origins based on the columns *rhine*, *sea_poly* and *seaweb*. The steps being taken and the results for data for the year 2022 are therefore described in detail.

First, the sea vessels are analysed for which vessels are both in Seaweb and the sea polygon. For these vessels, it is almost sure that they come from the sea since most of these vessels come from countries overseas. It was found that only 4% of the trips in 2022 does not have a vessel type and may therefore not be a dry bulk vessel. This 4% of the trips consist of 5 unique mmsi numbers, which are checked manually on marinetraffic.com (Marine Traffic, 2023). As a result, one of the vessels is indicated as a tanker by Marine Traffic (2023). This vessel is probably used for bunkering. Consequently, this mmsi number is required to be removed since it is not a vessel which is served for (un)loading dry bulk. This reduced the data set by 0.03%.

Additionally, vessels with the value 'True' in the *seaweb* column and 'False' in *sea_poly* column are analysed. It shows that 91.6% of these trips do not have a vessel type, moreover, most vessels are sailing under Dutch, German and Belgium flags. The trips without vessels type consist of 38 unique mmsi numbers. After checking a few of these vessels on marinetraffic.com, it seems that all vessels are tankers according to Marine Traffic (2023). Consequently, also the few trips that have a vessel type given are manually checked. Although these vessels are indicated as dry bulk by their vessel type, these vessels also seem to be a tanker according to Marine Traffic (2023). As a result, it is assumed that all vessels that are not found in the sea polygon but are in Seaweb, are not dry bulk terminal vessels and are therefore not included in this research. This further reduces the data set by 6.7%. Since it is now known what tankers are, the dimensions of the vessels are saved separately.

Furthermore, the trips which are not in Seaweb but are found in the sea polygon are analysed. It is found that 35.5% of these trips do not have a vessel type, each of these trips has as origin country the Netherlands, while all vessels with vessel types come either from the Netherlands or countries overseas. Therefore it is assumed that the vessels with vessel type are indeed vessels being served for dry bulk. Additionally, the vessels without vessel type are checked. In the year 2022, these trips are actually two unique mmsi numbers making multiple trips, which are both inland dry bulk vessels. Since these are served at the terminal, no vessel types are removed from the data set.

The preceding steps result in a refined data set for sea vessels, for which the Seaweb data is removed and a new column, called *sea*, is created for the vessels in the sea polygon. This reduces the number of trips to the values in Table B.3.

Table B.3: Number of trips after adjusting sea vessel trips

rhine	sea	
True	False	2321
False	True	435
	False	387
True	True	4

Additionally, the trips with origin from the Rhine are analysed. In the data set for 2022, 4 trips, made by one vessel, are both found in the Rhine and in sea. This is a dry bulk vessel and therefore retained in the data set.

Subsequently, the largest share of the data set is analysed, the vessels which are sailing over the Rhine but not in sea. For the year 2022, 71.7% of the trips do not have a vessel type. Almost all trips are found have vessels sailing under the flag of the Netherlands, Germany and Belgium. The vessels without vessel types are further analysed. These trips consist of 327 individual mmsi numbers, which is too much to all check manually. Therefore a few are randomly checked manually on marinetraffic.com. The findings show that all vessels checked through Marine Traffic (2023) are dry bulk vessels. Moreover, a double check is done for the vessels with the same length as the tankers found in the previous search. It is found that these are also dry bulk vessels, indicating that tankers and dry bulk vessels share the same dimensions.

Vessels which are neither in the Rhine nor in Sea are checked. 95% of the trips in 2022 does not have a vessel type. These trips consist of 39 unique vessels. The first vessel checked is already a tanker, therefore all 39 are checked manually and it is found that 25.6% (10 vessels) in this data are tankers. These are manually removed. This reduces the data set by 1.4%. Finally, the DataFrame consists of 3,103 trips with 746 unique vessels for the year 2022.

B.5. Result of method application

Table B.4 shows the total number of vessels after retrieving data from the AIS platform, the number of trips created and the number of vessels after applying the method described in Section 3.4. The fifth column shows the percentage of reduction for the extracted number of vessels from the AIS platform after taking all data filtering steps.

Table B.4: Percentage of data set reduction after applying the method to the retrieved data from the AIS platform for the EMO terminal

Year	Number of vessels start	Trips	Number of vessels end	% of vessel reduction
2022	2,122	12,490	746	64.8%
2021	2,691	14,306	746	73.9%
2020	4,965	14,069	569	88.5%
2019	4,367	10,025	450	89.7%

C

Additional results on inland waterway transport

This appendix provides information and outcomes in addition to the results found on the impact of low Rhine discharge levels on inland waterway transport, presented in Chapter 4.

C.1. Seasonality

Figure C.1 shows three figures that are based on IVS data of years for which the entire year has a discharge above the Agreed Low Discharge of 1,020 m^3/s. These years are found to be 2012, 2013, 2014, 2019 and 2021. The mean value per day for each year is plotted as a blue line, the upper figure shows the mean daily vessel load, the second figure illustrates the total number of vessels per day and the lowest figure depicts the total daily load. The red line indicates the Savitzky-Golay filter to create a smoother gradient of the blue lines.

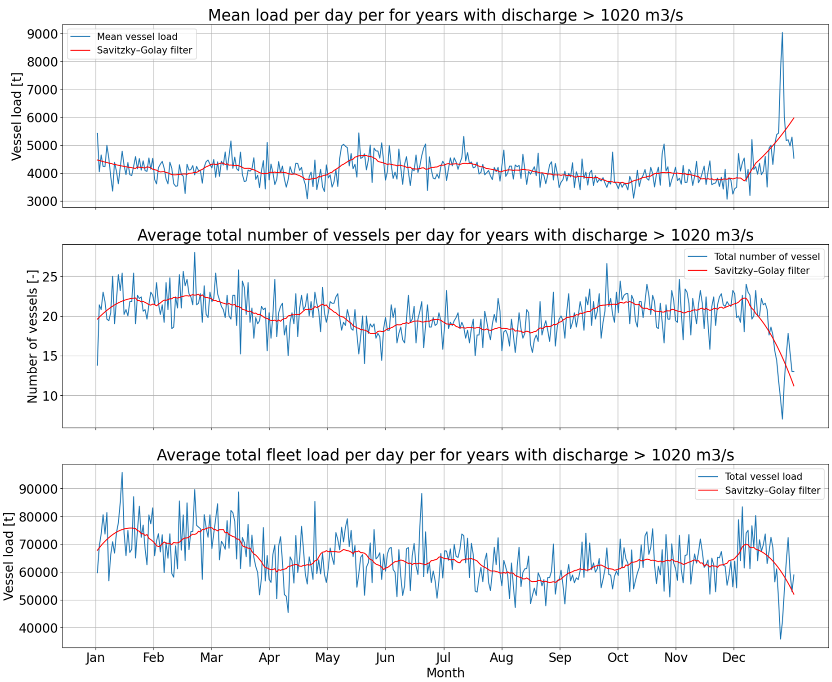


Figure C.1: Average total number of vessels, mean load and total load for years with discharge levels higher than 1,020 m^3/s

The figures show that the number of vessels and the total load, in the lower two figures, are lowest during the months of April, June and August. Therefore, the total load is assumed to be dependent on the number of vessels, and since the mean vessel load does not clearly show a reduction during these months, it is assumed that vessels did not have to adapt their load as a result of discharges during these months.

Furthermore, remarkable is the gradient in December. The number of vessels and total load strongly decrease, while the mean load increases. This occurred during the period of Christmas and New Year's Eve when fewer shippers sail, but probably the vessels that sail have a larger load capacity, leading to a higher mean load, than vessels that sail more often on most days of the year.

C.2. Discharge distribution

As the discharge is the primary focus of this study, Figure C.2 presents the number of days with a specific discharge level. The plot indicates that the discharge at Lobith typically ranges from 1,200 to 1,400 m^3/s during the years 2012-2023, followed by a discharge between 1,800 and 2,000 m^3/s. Additionally, the cumulative distribution function (CDF), represented by the red line, reveals that 75% of the days from 2012 to 2023 have a discharge lower than 2,200 m^3/s.

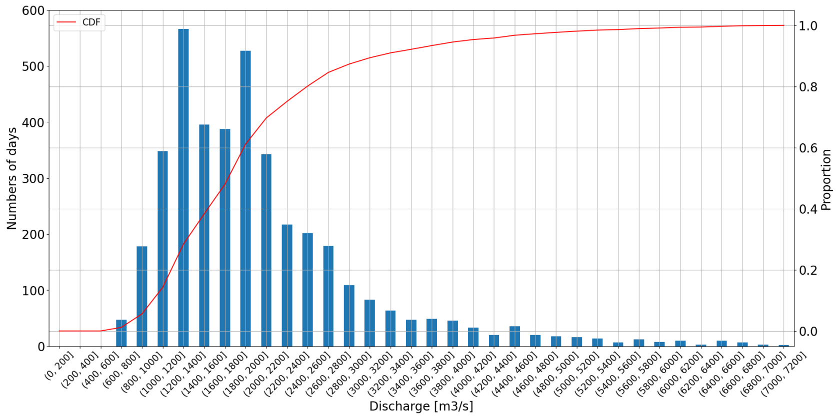


Figure C.2: Discharge distribution at Lobith for the period from 04-2019 to 01-2023

It is found that days with discharges below 1,000 and above 2,200 m^3/s do not occur that often as discharges in between 1,000 and 2,200 m^3/s. As stated in Section 2.2, 2018 and 2022 have the most days of low discharges in the period from 2018 to 2022, while this IVS data also includes the years from 2012 to 2018. Analysing the number of days per year per discharge bin reveals that a discharge range of 600 to 800 m^3/s occurs solely in the years 2018 and 2022. These years also exhibited the highest number of days with a discharge between 800 and 1,000 m^3/s. Further details regarding the occurrence of days per discharge bin, are listed in Table C.1. This table shows the number of days for each year per discharge bin, until 1,600 m^3/s, as depicted in Figure C.2.

Year	600-800 m^3/s	800-1,000 m^3/s	1,000-1,200 m^3/s	1,200-1,400 m^3/s	1,400-1,600 m^3/s
2012	0	0	4	32	48
2013	0	0	3	18	13
2014	0	0	14	47	47
2015	0	19	69	45	14
2016	0	6	62	40	12
2017	0	18	12	93	53
2018	30	89	24	20	8
2019	0	0	13	45	58
2020	0	5	60	111	49
2021	0	0	48	35	33
2022	17	41	39	80	61

Table C.1: Number of days per year per discharge from 600 to 1,600 m^3/s in bins of 200 m^3/s

The days for which a discharge between 600 and 800 m^3/s occurs, is in 2018 from the 18th of October until the 31st of October 2018, the 9th of November until the 11th of November and from the 20th of November until the 2nd of December, which are 30 days in total. In 2022 this period of 17 days is from 7 August until 23 August. Additionally, the table demonstrates that during days that discharge ranges from 800 to 1,000 m^3/s, the majority of days occurred in 2018 and 2022. Furthermore, it verifies that the years examined for the seasonality, as mentioned in Section C.1, occur null days during discharges below 1,000 m^3/s. The table further shows that discharges higher than 1,000 m^3/s transpire in every year, albeit with varying frequency across years.

C.3. Load over discharge for various vessel types

Figure C.3 shows the mean vessel load per discharge of various vessel types, as also depicted in Figure 4.1. Solely vessel types are depicted that are considered as being affected by low discharge levels. It moreover shows that 6 and 4 push barges have the best correlation between discharge and load since the points in the scatterplot are closely concentrated in one pattern. Additionally, a vessel that has the sk code C3l or C4 seems to consist of two maxima, this could be caused by the fact that these are coupled barges that can be coupled in two different manners, for instance, one type with one barge and the other one with two barges.

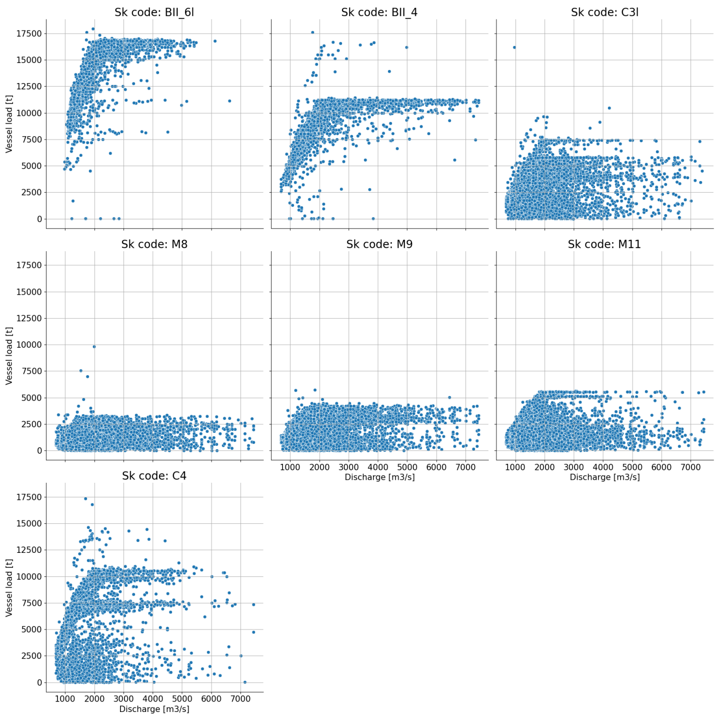


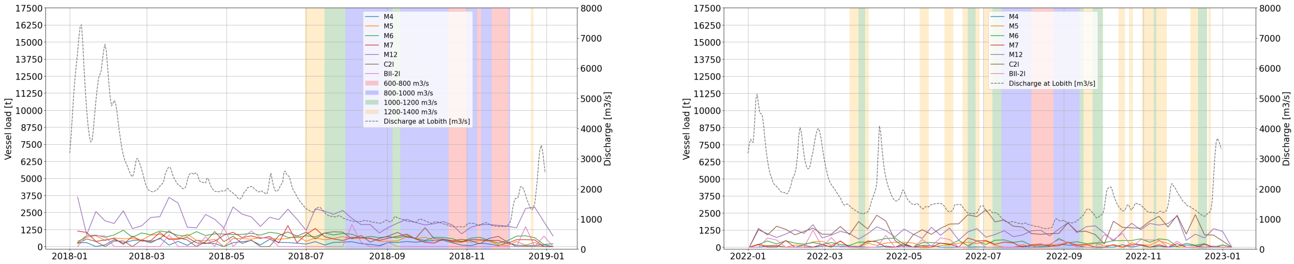
Figure C.3: Vessel load per discharge for different vessel types

C.4. Additional vessel types sailing along the Rhine

This section consists of the vessel types that do have more than 20 vessels in the year 2022, but where the effect of low discharge levels is not that significantly observable. For each of these vessel types, the mean vessel load, the number of vessels per day and the total vessel load per day are averaged over a week and plotted for the years 2018 and 2022.

C.4.1. Mean load

The mean load per week over time of the additional vessel types are illustrated in Figure C.4. The figure displays no significant difference in mean vessel load for these vessel types. However, the mean vessel load of M12 vessels in 2018 is comparable to M9 and M11 vessels illustrated in Figure 4.4. Remarkably, this amount is lower in 2022, however, all vessel types, except for C2l vessels, carry less cargo in 2022 compared to 2018.

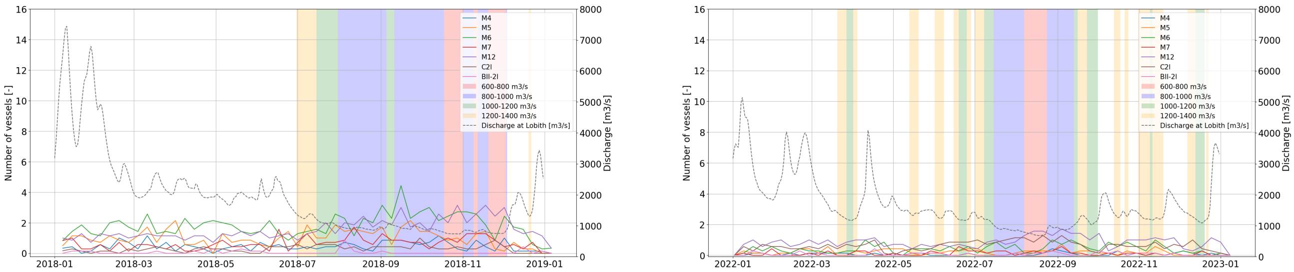


(a) Average weekly load of other vessel types in 2018 (b) Average weekly load of other vessel types in 2022

Figure C.4: Average weekly load of other types of dry bulk Rhine vessels passing Lobith from RTM to GRM in both 2018 and 2022

C.4.2. Number of vessels

Figure C.5 presents the number of vessels of the vessel types in addition to the ones plotted in Figures 4.9 and 4.10. Similarly, a small increase is visible when discharge is below 1,400 m^3/s, however, this is not as significant as the vessel types visualised in Figure 4.9 and 4.10.

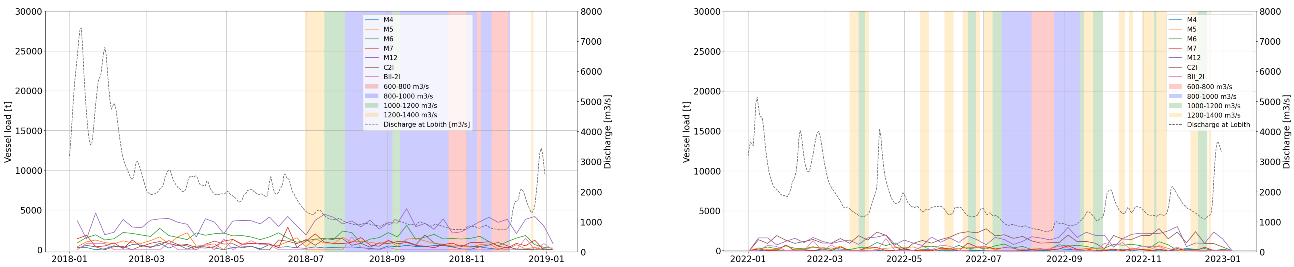


(a) Total weekly number of other vessel types in 2018 (b) Total weekly number of other vessel types in 2022

Figure C.5: Total weekly number of other types of dry bulk Rhine vessels passing Lobith from RTM to GRM in both 2018 and 2022

C.4.3. Total load

Figure C.6 illustrates the total vessel load per day averaged over a week for the vessel types in addition to Figures 4.14 and 4.15. It moreover shows that M12 vessels carry the most load, approximately 3,000 tonnes per day in 2018. This is carried constantly over the entire year. In 2022, it is demonstrated that C2l vessels have most of the time the largest total capacity. The findings show that it slightly fluctuates but not only during the low discharge between 600 and 800 m^3/s but also at the beginning of May, which is when its discharge strongly decreases after a peak to approximately 2,000 m^3/s. This difference, compared to the vessel types in Figure 4.14 and 4.15, is so small that is not taken into consideration.



(a) Total weekly load of other vessel types in 2018 (b) Total weekly load of other vessel types in 2022

Figure C.6: Total weekly load of other types of dry bulk Rhine vessels passing Lobith from RTM to GRM in both 2018 and 2022

D

Additional results on cargo handling process

This appendix presents additional results to the findings in Chapter 5 regarding the impact of low Rhine discharge levels on the cargo handling process.

D.1. Vessel types

The determination of the different vessel types within the AIS data was based on the 14 selected sk codes within the IVS data. The classifications for all vessel types are listed in Table A.3. It was determined that many vessels are classified as vessel type C3l, as shown in Figure D.1. However, upon manual inspection, this classification appears to be inaccurate, as many of the vessels appear to be motor vessels. The reason for this is that the classification criteria for C3l vessels specify a width between 9.61 and 12.60 m and a vessel length greater than 80.08 m. Meanwhile, the M8 vessel type is classified with a width between 9.61 and 11.5 m and a length ranging from 38.01 to 111 m, which falls within the range of the C3l classification. Therefore, the misclassification of many motor vessels as C3l vessels can be attributed to the overlap in classification criteria between the two types. The same issue arises for M9 vessels, which have the same width restrictions as M8 vessels but have a length classification exceeding 111 m. This misclassification is not limited to these vessel types but extends to others such as the M12 and C4.

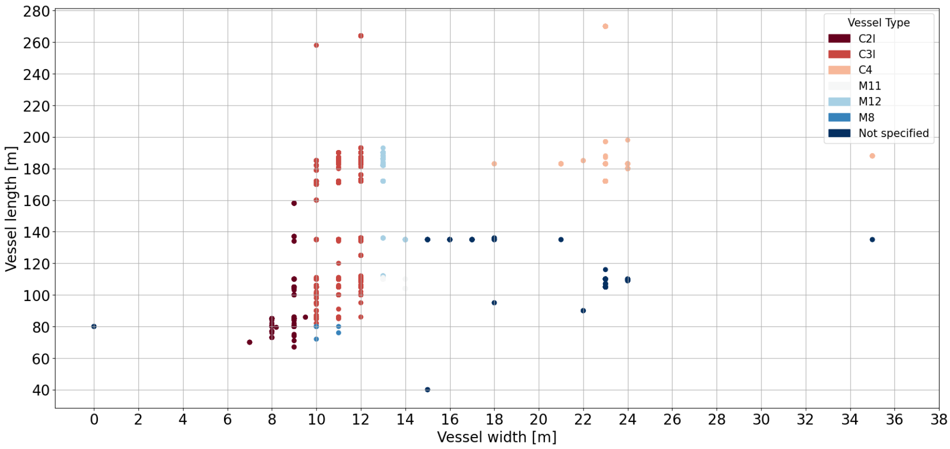


Figure D.1: Determined vessel types as a result of vessel length and width classification for Rhine vessels arriving at EMO from April 2019 to 2023

Another factor that affects the determination of vessel types according to the RWS classification is the presence of push barges and coupled convoys, which consist of multiple barges that may be loaded separately using the dimensions of a push boat that pushes each barge in the direction of the loading berth. These barges may then be coupled after loading to the appropriate motor vessel or push boat to create the vessels as indicated in the IVS data.

D.2. Discharge distribution

Before analysing the vessels, the discharge distribution is determined for the study period and shown in Figure D.2. It demonstrates that during this period most days have a discharge between 1,200 and 1,400 m^3/s followed by a discharge between 1,400 and 1,600 m^3/s. In comparison to the 10-year time span, utilised to analyse the Rhine vessel navigation, 75% of the days were below a discharge of 2,200 m^3/s, while for this time span of 3.5 years 75% of the days are below 2,000 m^3/s.

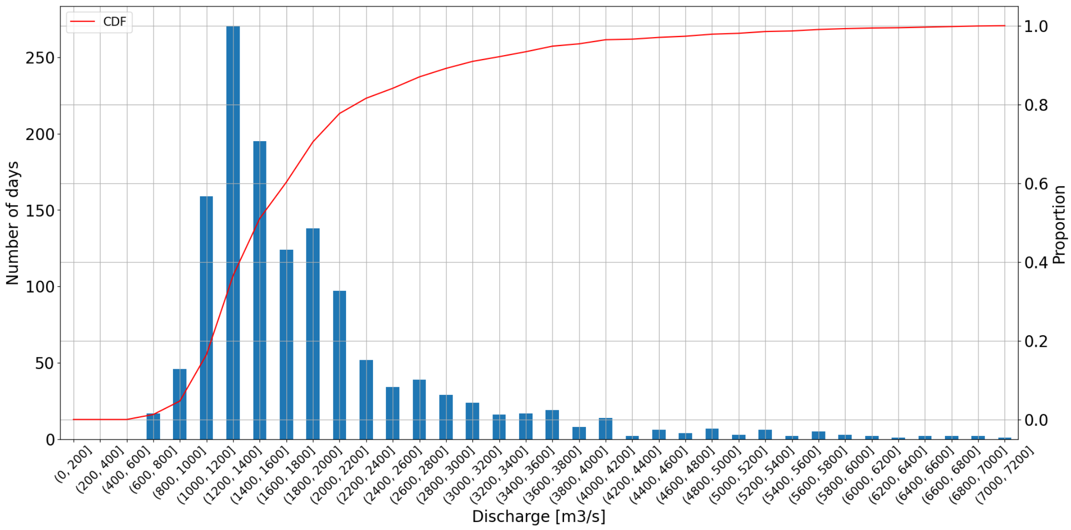


Figure D.2: Discharge distribution at Lobith from April 2019 to 2023

It should be noted that, due to the relatively short time span of 3.7 years, as much as 92% of the days with discharge below 1,000 m^3/s occurred in 2022. Furthermore, even in 2022 alone, there were days with discharge below 800 m^3/s. Table C.1 shows the number of days with these discharges.

D.3. Service time distributions

The service time distribution of the loading berths and unloading berths is presented in the following sections.

D.3.1. Service time loading berths

Figure D.3 shows the service time distribution of the loading berths. The left graph depicts all service times per vessel, while the right graph illustrates the distribution for service times shorter than 20 hours, which corresponds to approximately 97% of the vessels. It is evident that 60% of the vessels have a service time that is shorter than 3 hours.

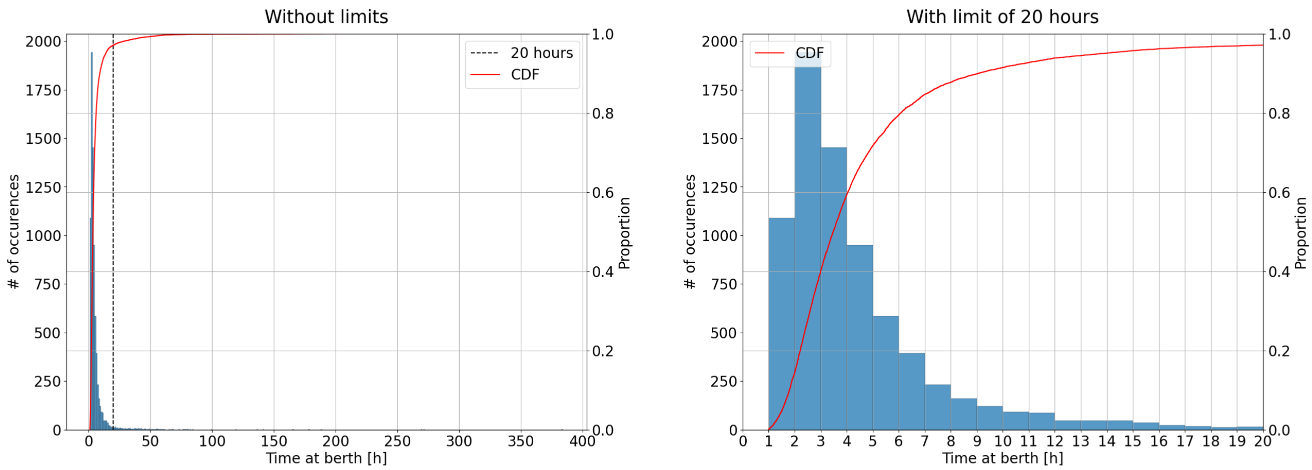


Figure D.3: Service time distribution of EMO loading berths without a limit and with a limit set to 20 hours

D.3.2. Service time unloading berths

The service time for the unloading berths is depicted in the figure below. Similar to the loading berths' service time, the left graph of Figure D.4 represents the service time without constraints, whereas the right graph shows the service time when the maximum limit of 150 hours is imposed. As a consequence of this limit, 1.5% of the vessels' service times are disregarded.

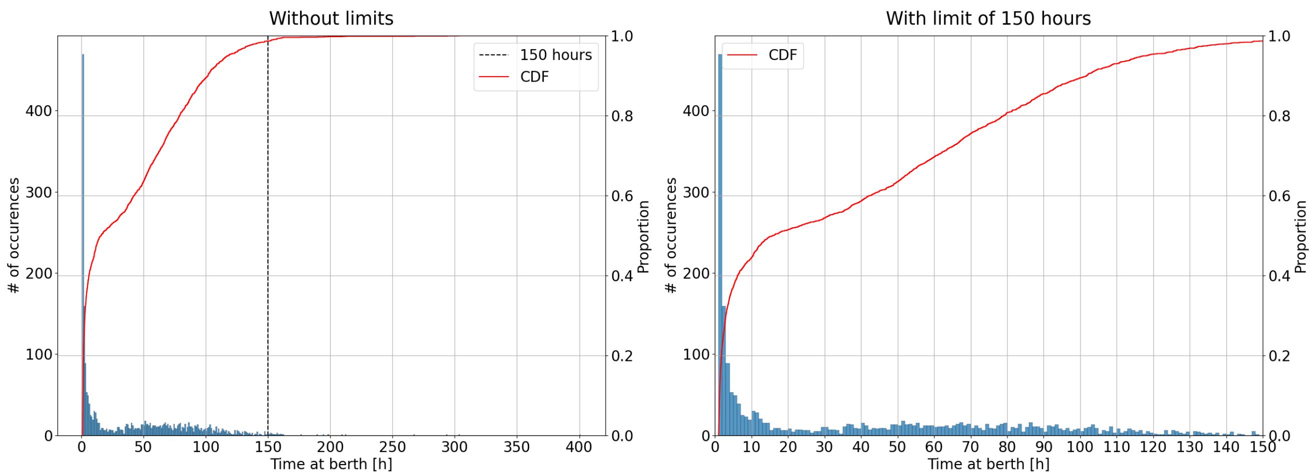


Figure D.4: Service time distribution of EMO unloading berths without a limit and with a limit set to 150 hours

D.4. Comparison between all vessels and Rhine vessels arriving at EMO loading berths

This section makes a comparison between all vessels arriving at EMO loading berths and solely vessels arriving that are sailing in the direction of the Rhine for both the service time and the number of arrivals.

D.4.1. Service time

Figure D.5 shows the mean service time per day as a result of all vessel arrivals at the EMO loading berth, indicated by the blue line and smoothed with the red line, and the service times for vessels that sail in the direction of the Rhine, represented with the yellow line and smoothed with the green line. As it is not possible to indicate the origin of the vessels for days on which RWS data is added, those days are outlined with the grey-coloured background in the figures below.

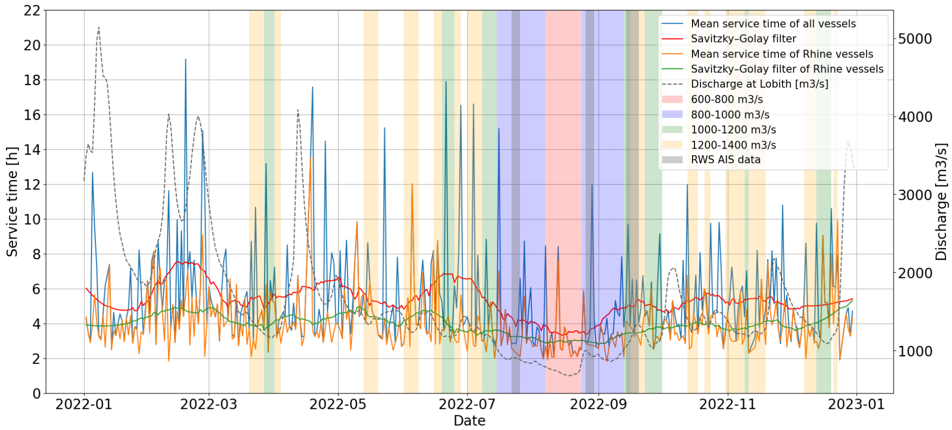


Figure D.5: Mean daily service time of both Rhine vessel arrivals and all vessels arrivals at EMO loading berths in 2022

The figure presented indicates that the average service time for Rhine vessels during non-dry months is approximately 4 hours, whereas, for all vessels, it is approximately 6 hours, owing to a few days with an extended service time. Upon observing periods with low discharge, it appears that the mean service time decreases for both Rhine vessels and all vessels. The minimum service time observed during the lowest discharge period is 3 and 3.5 hours for Rhine vessels and all vessels, respectively. Given that a substantial proportion of all vessels are Rhine vessels, a discharge below 800 m^3/s results in an average 40% reduction in service time for all vessels.

D.4.2. Number of vessels

The number of arrivals per day for all vessels and solely Rhine vessels in 2022 is depicted in Figure D.6.

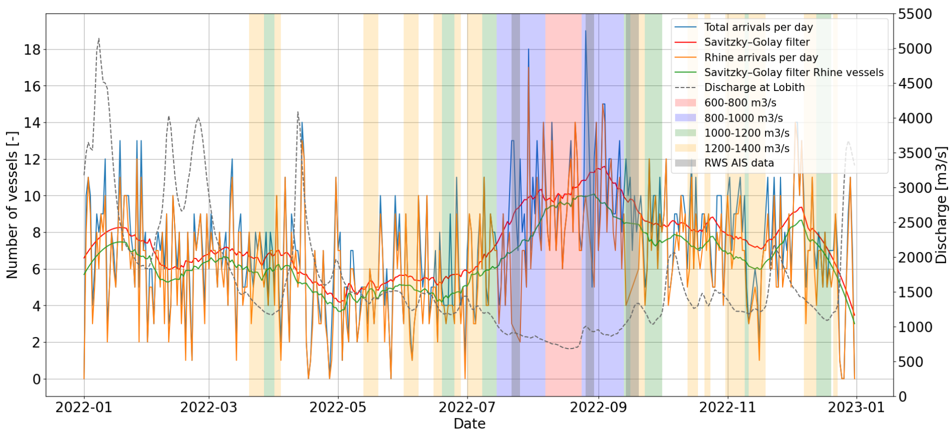


Figure D.6: Total number of arrivals per day of both Rhine vessel arrivals and all vessels arrivals at EMO loading berths in 2022

The red line, which represents the smoothed trend of all vessel arrivals, exhibits a similar pattern to that of the smoothed number of Rhine arrivals, depicted by the green line. This indicates that nearly all vessels arriving at the port originate from the Rhine, with only one vessel from other origins arriving daily. However, there are some exceptions to this trend, specifically on the days when RWS data is included, during which it is not possible to distinguish Rhine vessels from others.

Overall, the analysis reveals that the service time for vessels arriving from the Rhine is slightly lower than the average service time for all vessel arrivals. However, as the Rhine vessels constitute a substantial portion of all arrivals, a decrease in river discharge results in a 40% reduction in service time for all vessels. Additionally, no significant differences between the Rhine vessels and all vessels are observed during low discharge periods. It is worth noting that the inability to identify the origin of vessels on days when RWS data is included is another reason to rely solely on all arrivals in this analysis.

D.5. Total service time per day at EMO loading berths

In order to analyse the total effect of drought on the service time and whether the number of vessels or the mean service time is most dominant, the total service time per day is determined. As mentioned earlier, service times solely shorter than 20 hours are taken into consideration. Figure D.7 shows the total time at the loading berths per day for 2022. An increase in September 2022 can be found when discharge was between 800 to 1,000 m^3/s.

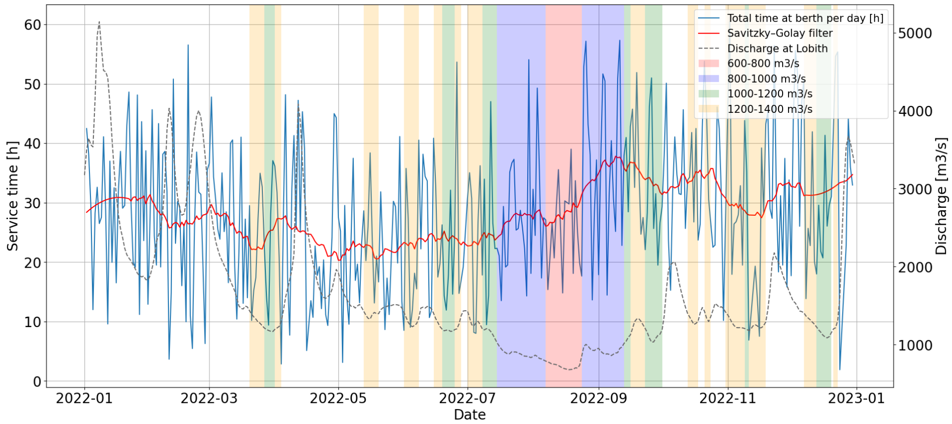


Figure D.7: Total service time per day for vessels at EMO loading berths in 2022

Figure D.8 shows the total time per day per discharge bin for both EMO loading berths over a three-and-a-half-year period.

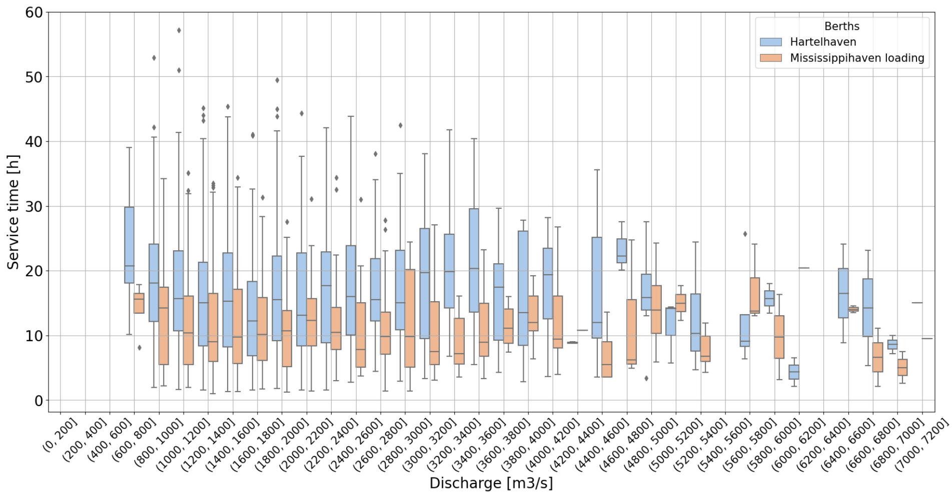


Figure D.8: Total service time day for vessels at different EMO loading berths from April 2019 to 2023

The boxplots of the Hartelhaven show that the total time at berth is largest when discharge is between 600 and 800 m^3/s and the mean reduces when discharge increases until a discharge is higher than 1,000 m^3/s. This is partly in line with the number of vessels, which starts to increase when the discharge is below 1,200 m^3/s already. Therefore, it is confirmed that the total number of vessels has more effect on the total service time than the mean service time of a vessel since the mean service time decreases when discharge is below 1,400 m^3/s. The Mississippihaven has approximately the same gradient, except that the total time at berth for the lowest discharge bin is considerably high compared to the number of vessels and mean service time but this discharge bin consists only of 4 arrival days of vessel arrivals.

The figures show that the total time at berth slightly increases when discharge is below 1,200 m^3/s and that thus the number of vessels is the dominating factor in determining the total service time per day. This might be a result of the time at berth still including time for other activities in addition to loading and as a result it is more difficult to relate the service time to the vessel load.

D.6. Vessel lengths of vessels arriving at loading berths

This section presents an analysis of vessel lengths for various discharge levels to investigate whether they have any impact on berth occupancy.

Boxplots of the vessel lengths of vessels arriving at the Hartelhaven during various discharges are depicted in Figure D.9. The figure shows that vessels are on average 150 m long and no deviation can be found for smaller discharges.

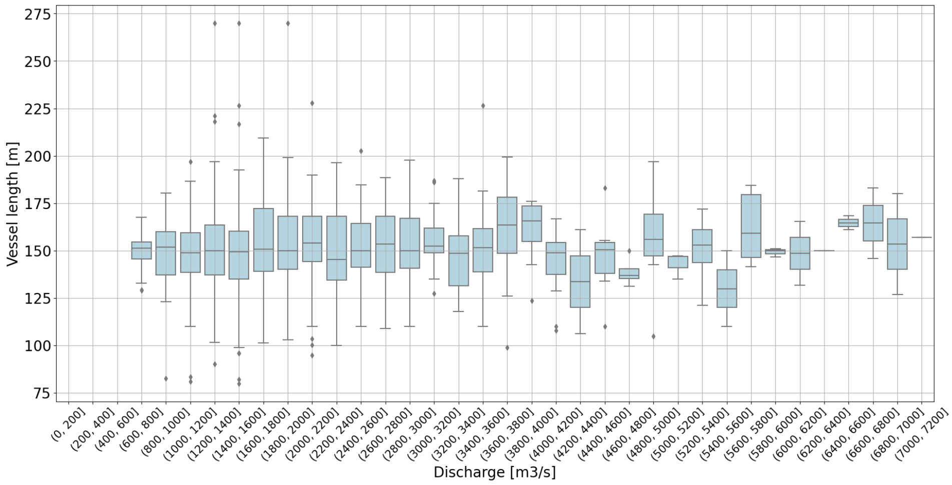


Figure D.9: Boxplot showing variation in vessel lengths per discharge bins of vessels arriving at Hartelhaven loading berth from April 2019 to 2023

Figure D.10 shows the various lengths of vessels arriving during different discharges. It is evident that the vessel lengths of arrivals remain consistent regardless of changes in river discharge. The boxplots also indicates that, on average, the vessels arriving at Mississippihaven are longer compared to those arriving at Hartelhaven. This observation further supports the longer service time at Mississippihaven.

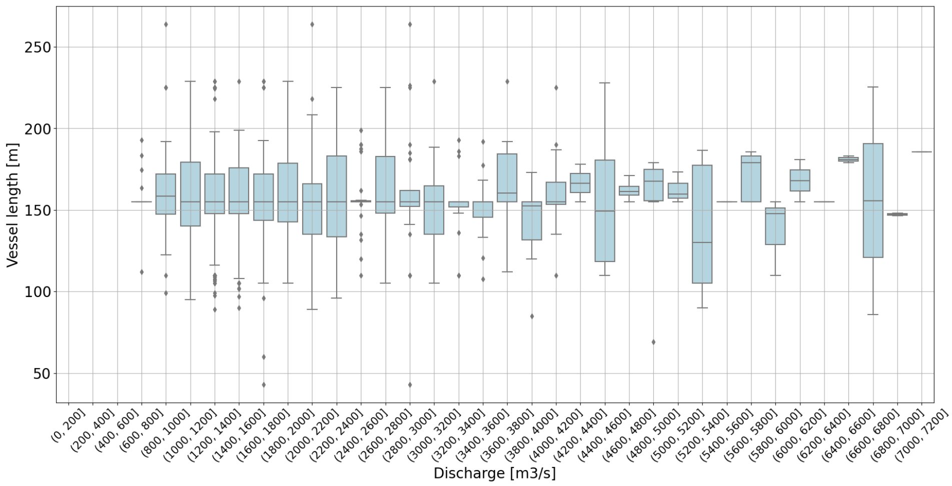


Figure D.10: Boxplot showing variation in vessel lengths per discharge bins of vessels arriving at Mississippihaven loading berth from April 2019 to 2023

E

Additional results on storage process

This appendix offers supplementary data and outcomes in addition to the results presented in Chapter 6, pertaining to the impact of low Rhine discharge levels on the storage process.

E.1. Determination of total load with crane capacity

In addition to the total load computed by the mean vessel load and number of vessels, the total load being handled is in this section computed by using the crane capacity and service time. Firstly, this is done for the amount of cargo that is being loaded, and this is moreover compared to the total load as presented in Section 6.1. Secondly, the same is done for the cargo entering the terminal, but solely a comparison with the EMO data is possible for this cargo flow.

E.1.1. Volume of cargo loading inland vessels

Two methods were used to estimate the volume of cargo loaded onto inland waterway vessels at the EMO loading berths and illustrated in Figure E.1.

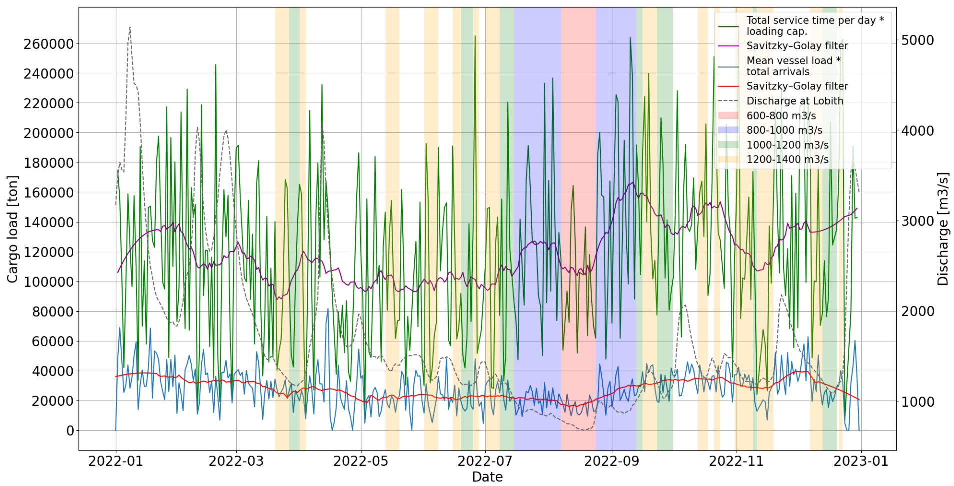


Figure E.1: Amount of dry bulk cargo leaving EMO per day based on two different sources in 2022

The first method involved calculating the total load using the service time per day and the loading capacity of the conveyor belts for the cranes at Mississippihaven and Hartelhaven, separately represented by the green line in Figure E.1. The green line was smoothed with the purple line to provide a clearer representation of the total load. The maximum loading capacity of the Hartelhaven cranes was found to be 3,500 tph, while Mississippihaven had a capacity of 6,000 tph. The second method, represented by the blue line, and smoothed by the red line, in Figure E.1, involved determining the total load per day using the mean vessel load based on IVS data and the number of arrivals at the loading berths, as previously illustrated in Figure 6.1.

An analysis of the two estimation methods revealed that the first method yielded an estimate of the total load that was almost three times higher than the estimate obtained using the mean load and number of vessels. Furthermore, it was observed that the peak of the total load computed using the crane capacity occurred during discharge levels between 1,000 and 1,200 m^3/s in September. In contrast, no noticeable reduction of the total load was observed for this method during discharges between 600 and 800 m^3/s, as depicted in the lower plot.

To establish the accuracy of the determined load quantities mentioned above, a comparison is made with the authentic EMO data that provided the total amount of load leaving the terminal per month. Subsequently, the monthly values depicted in the above figure are summed up to formulate monthly data. The resulting outcomes are displayed in the upper portion of Figure E.2. Upon examining the upper figure, it was ascertained that the load capacity of 3,500 tph and 6,000 tph differed considerably from the other two sources. Consequently, the belt load capacity was decreased by 30%, which corresponds more closely with the EMO data and the combination of the mean vessel load and the number of vessels. These lines are then further enlarged in the middle section of Figure E.2.

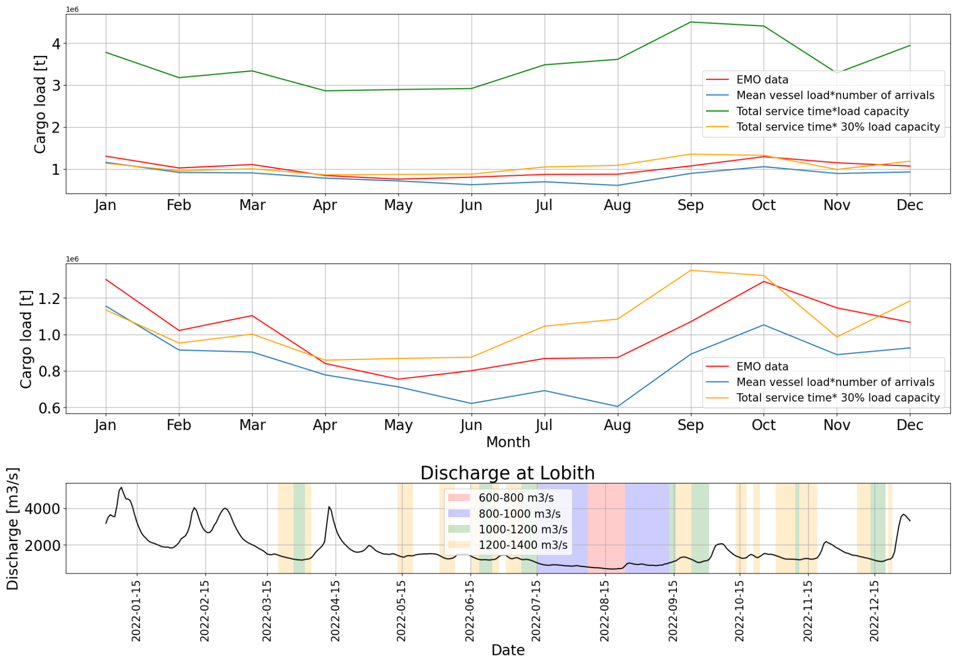


Figure E.2: Amount of cargo leaving EMO per month in 2022 compared with data provided by the EMO terminal

The reduction of the load capacity by 30% leads to an overlapping total load in April and October, as found in the middle graph in the figure above, however in the months before April and in November, an underestimation with the actual situation is observed, while in the other months, an overestimation is found. Compared to the total load computed by the IVS and AIS data, the determination of the total load by crane capacity of 30% still leads to higher values.

E.1.2. Volume of cargo unloading sea vessels

The total load that is unloaded at the EMO unloading berths is determined by multiplying the total service time per day by the crane capacity of 1800 tph, as illustrated in Figure E.3.

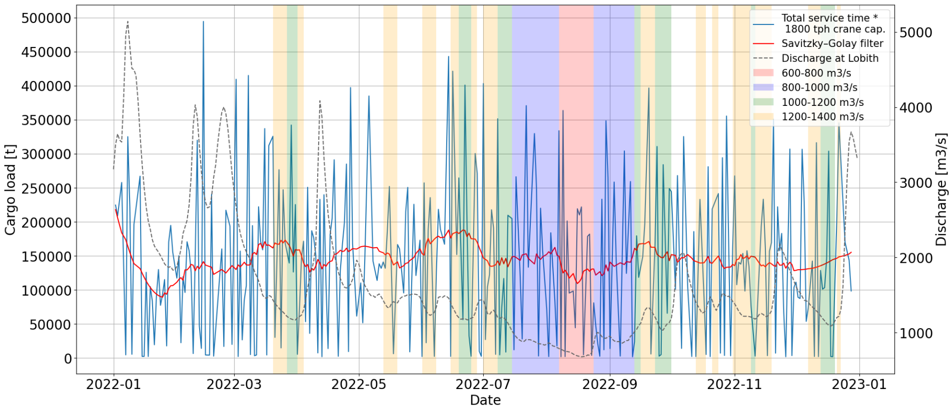


Figure E.3: Amount of dry bulk cargo entering EMO per day in 2022 based on total duration and unloading capacity

By aggregating the daily load values presented in the figure above into monthly totals, the green line in Figure E.4 is obtained. However, since the green line is not consistent with the actual quantity of cargo unloaded, which is indicated by the blue line, the crane capacity is adjusted downwards by 33% to 1,200 tph. The resulting trend is then comparable in magnitude to the actual values, as demonstrated by the yellow line.

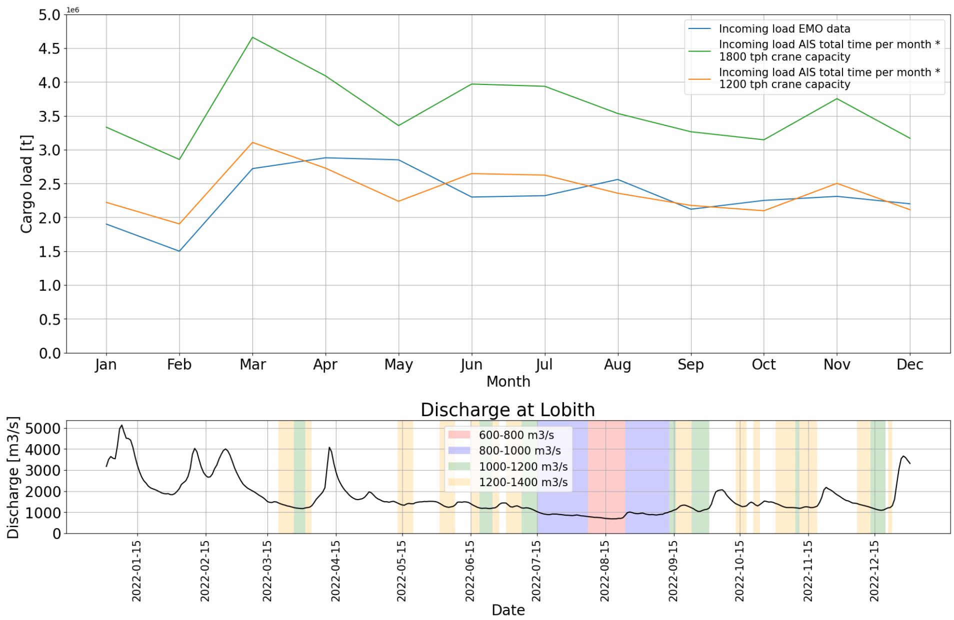


Figure E.4: Amount of cargo entering EMO per month in 2022 compared with data provided by the EMO terminal

E.2. Determination of the mean vessel load

The mean vessel load for the entire fleet of vessels arriving in a month is determined for the outgoing vessels and for the incoming vessels. In both cases, this mean vessel load is determined by dividing the total handled load per month according to the EMO data by the number of vessel arrivals according to the AIS data. Moreover, for the outgoing vessels, it is possible to compare this with the outcomes of the IVS data.

E.2.1. Mean outgoing vessel load

The number of vessels arriving at the EMO loading berth per month in 2022 according to the AIS data are depicted in bar plots, as well as with the red line in Figure E.5. As was also evident from Figure 5.3, the number of arrivals is highest when discharge is lowest in the month of July, August and September.

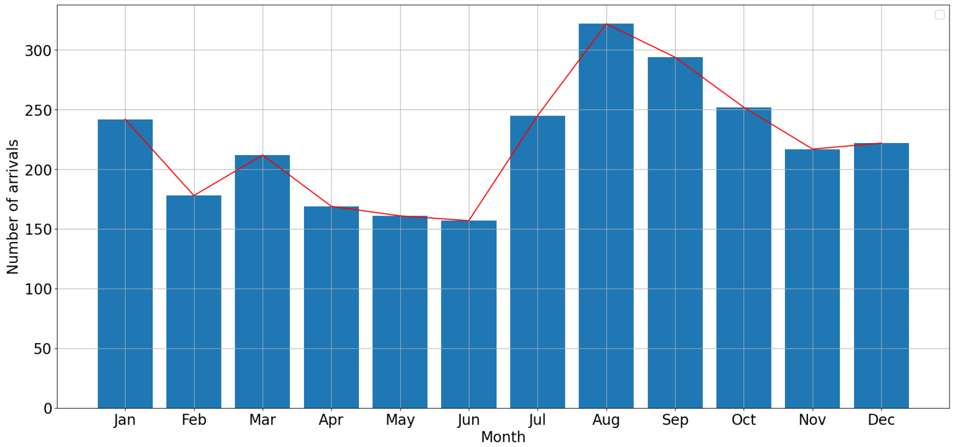


Figure E.5: Number of vessels arriving at EMO loading berths per month in 2022

Using the number of arrivals from the figure above, can give an indication of the mean vessel load according to the EMO data and compare that with the monthly mean vessel load according to IVS data. This monthly value is determined by the summation of the daily mean vessel load for the entire fleet in 2022 as found in Figure 4.7. Figure E.6 shows the mean vessel load per month for both the IVS data, as indicated by the orange barplot, and determined by the mean vessel load of the entire Rhine fleet of Figure 4.7 summed up per month and the mean vessel load by dividing the total amount of cargo loaded into vessels sailing to the hinterland, as represented with the red line in Figure 6.2, by the number of vessels from Figure E.5.

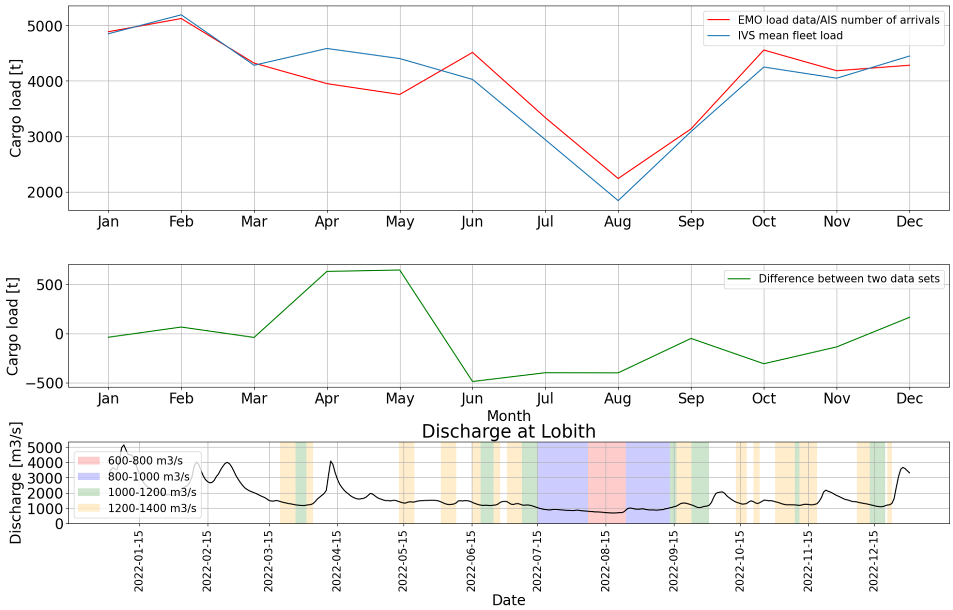


Figure E.6: Mean vessel load per month for loading vessels computed with EMO data/number of arrivals from Figure E.5 in 2022

In most months the IVS mean vessel load is an underestimation of the mean vessel load according to EMO and AIS data, except for February, April, May and December. Whereas in April and May the difference is large. This indicates that also vessels arrive with more load capacity than the capacity of vessels sailing on the Rhine. However, in the months when IVS mean vessel load is assumed higher, it can also be that the mean vessel load for EMO and IVS is lower due to an overestimation of the number of vessels arriving, resulting in a smaller mean vessel load than in reality. All these uncertainties are further described in Chapter 7.

E.2.2. Mean incoming vessel load

The number of vessels arriving at EMO unloading berths per month is depicted in Figure E.7. In March an April a peak in number of vessels can be observed compared to the other months.

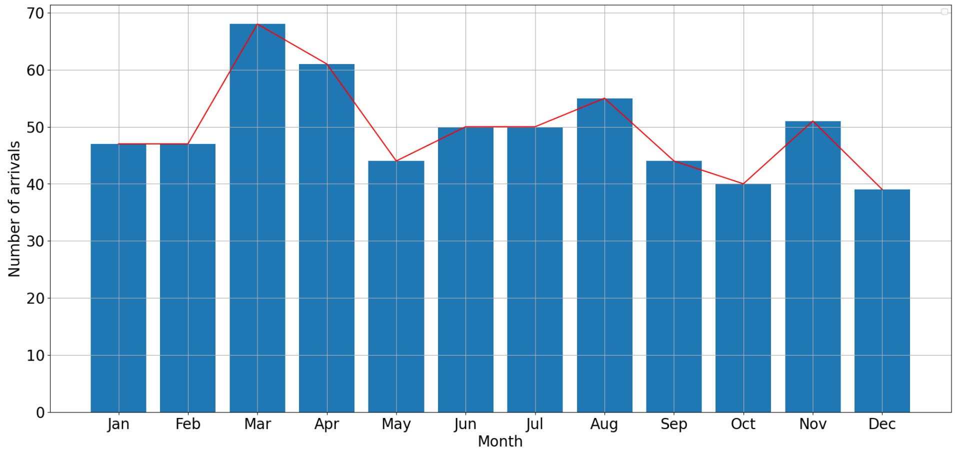


Figure E.7: Number of vessels arriving at EMO unloading berths per month in 2022

Dividing the number of vessels per month from the figure above by the total volume of cargo unloaded per month, as found by the blue line in Figure 6.4, results in the mean vessel load as illustrated in Figure E.8. It is found that vessels arriving in February, carrying only around 30,000 tonnes, were on average smaller compared to the mean vessel load in the other months. In May it seems that way larger vessels arrived, carrying approximately 65,000 tonnes. These large discrepancies may also be a result of the filtering of AIS data.

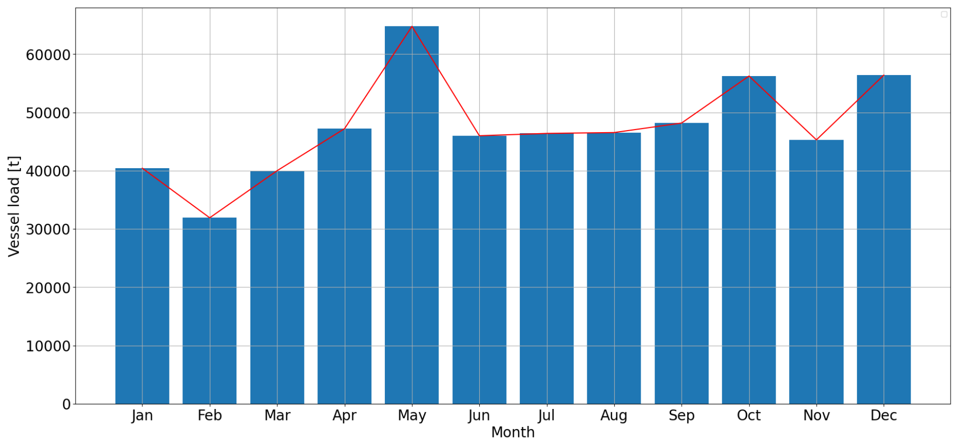


Figure E.8: Mean vessel load per month for unloading vessels computed with EMO data/number of arrivals from Figure E.7 in 2022

It can be concluded that also smaller vessels arrive, as the large seagoing vessels carry on average 180,000 to 200,000 tonnes, according to EMO (EMO, 2023).

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