Effects of drought on the traffic capacity of the river Waal and the occurrence of congestion.

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by

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Preface

This thesis is the final product to obtain the title Master of Science in the field of Hydraulic Engineering at the faculty of Civil Engineering and Geosciences of the Delft University of Technology. The research on inland waterway traffic capacity during low river discharge appealed to me because inland waterway transport has always played a part in my live. As a student, I lived close to the Zuid-Willemsvaart and every morning during breakfast I watched the ships passing by. On may way to school I tried to read the names on the ships. The drought of 2018 and its impact on inland navigation, has encouraged me to graduate in the field of Ports and Waterways.

I would like to thank the members of my graduation committee Mark van Koningsveld, Henk Verheij, Dick ten Hove, Otto Koedijk, Kees Sloff and Frederik Vinke for their enthusiasm and involvement during my research. Furthermore, I would like to express my gratitude to Henk Verheij for his patient way of supervising and for his endless inspiration and feedback. Beside my graduation committee I would like to thank Noortje Hobo for helping me understand the SIMDAS software and analyse the results at the Maritime Research Institute Netherlands, MARIN. Working at the MARIN students facility in Wageningen has been a great pleasure for me. Additionally, I would like to thank Rolien van der Mark from Deltares, for her recommendations regarding the hydraulic data gathering and analysis. Her recommendations have greatly accelerated the hydraulic data gathering phase of my thesis.

During the last months of my graduation the Coronavirus (COVID-19) outbreak changed my way of working completely. Working at MARIN as well as the university was no longer an option. Studying at home never had my preference, as I have always been much less productive there. During the Pandemic I realized, more than before, how important it is to be connected with family and friends. I realized I have been blessed with the people around me, like my boyfriend Frank, who supports me and motivates me. Being isolated at home, during the COVID-19 pandemic, has been a struggle but also provided me with some valuable insights.

Finally, I would like to give special thanks to my sister, Lisanne Verschuren, for the feedback during the writing process of my thesis. With my dyslexia it has always been a challenge to structure my thoughts and format them correctly, so the help and support of family and friends has always been very valuable.

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Abstract

This research focuses on the impact of extreme low river discharges, meaning discharges below 1200 m^3/s at Lobith. In 2018 extreme low river discharges in the river Rhine led to congestions in the main Dutch part, called the river Waal. The river Waal is an important river for inland navigation, but during low discharges the vessel draught reduces and consequently the transported cargo volume per shipment reduces. To compensate the loss of transport volume, the total number of shipments increases, leading to an increased traffic intensity on the river Waal.

The purpose of this study was to investigate the effects of extreme low discharges on the traffic flow and traffic capacity in the river Waal. The study consisted of two elements: a study combining fleet data and hydraulic information and a traffic simulation study. During this research IVS90 data was used as the source for inland waterway transport data. Based on literature and previous river Waal studies the river section between the Pannerdensche Kop and the Maas-Waal canal was selected as the river section to investigate in more detail. Multi-beam measurements in combination with water level data were used to generate cross-sectional profiles in order to carry out the simulations. The cross-sectional profiles were highly variable. From these cross-sectional profiles the navigable river width was determined. It was found that a river depth of 2.80 m was no longer available at all cross-sections from a discharge of 900 m^3/s and lower. Therefore, the navigable width was determined at a river depth of 2.0 m for the discharges 1020, 900, 800, 700 and 600 m^3/s. Also, it was found that with reducing discharge the navigable width of the cross-sections reduced.

The fleet composition was determined in detail for four weeks representing the drought of 2018. These four weeks in 2018 represented weeks with average discharges around 1020(2x), 800 and 700 m^3/s. The river Waal fleet composition was determined based on the Rijkswaterstaat vessel classification system (RWS-class) and categorised in three groups: coupled units (all RWS-classes with index C), push-tow units (all RWS-classes with index B) and motorised vessels (all RWS-classes with index M). It was found that the number of passages by coupled units and push-tow units was effected largely during the drought of 2018. The number of passages by push-tow units reduced significantly from October 2018 as the discharge dropped below 1500 m^3/s and the number of passages remained low until the discharge raise above the 1020 m^3/s at the end of 2018. The number of passages by coupled units increased already before the discharge reached the 1020 m^3/s limit and continued to increase throughout the period of drought. The number of passages by coupled units started to decline only after the discharge rose above the 1020 m^3/s again. Even though the daily average number of passages increased during the drought of 2018, the total transported cargo volume per day decreased. There was a strong relationship between discharges below 1200 m^3/s and the transported cargo volume per day.

Within this study special attention was given to the occurrence of congestion in the river Waal. The occurrence of congestion was investigated using the traffic simulation model SIMDAS. As indicators for congestion a fluency and safety limit of 8% was used to evaluate the simulated traffic, as well as simulations of the traffic flow. As safety parameter the penetration of the safety margin of a vessel in percentage of the total number of vessel interactions was used. While the percentage of the number of vessels that need to reduce their speed fully during their passages was used as the fluency parameter. With SIMDAS also the impact of increased traffic intensity and reduced navigable width were analysed. The simulation results showed that the reduced navigable width had more impact on the delay time, the fluency parameter and the safety parameter than the increase of the daily intensity. During the simulations large congestions occurred for discharges of 800 m^3/s and lower, but small harmonically moving congestions already occurred for a discharge of 1020 m^3/s. Harmonically moving congestions, meaning seven or more vessels travelling behind one larger or slower vessel while awaiting room to overtake, were observed in the traffic simulations. Permanent congestions with ten or more vessels were observed in the simulation of the river width with a 800 m^3/s discharge. The data analysis and the traffic simulations clearly showed the effects of the extreme low discharges on the traffic flow and traffic capacity. The conclusion of this study is that the traffic capacity of the river Waal is at its limit at discharges of 800 m^3/s and lower.

This study made also clear the need for correct fleet data and river bed levels. The limited available fleet data reduced the accuracy of the results. The river bed should be monitored regularly in order to know the actual water depth particularly during low discharges. Furthermore, it is recommended that highly variable river profiles are implemented in the traffic simulation model SIMDAS to improve the simulation of the vessel's sailing trajectories. Also, the validation of the vessel trajectories in SIMDAS with AIS data is recommended in order to evaluate the traffic intensity on the traffic lanes in the river.

Contents

List of abbreviations & terminology

Abbreviations

AIS	Automatic Identification System.
BIVAS	Inland navigation analysis system (Binnenvaart Analyse Systeem).
CCNR	Central Commission for the Navigation of the Rhine.
CEMT	European Conference of Ministers of Transport (de Conférence Européenne des Ministres de Transport).
dep-file	Wizard Dependency file.
GPS	Global positioning system.
IPS	Input preparation program for SIMDAS (Invoer preparatie SIMDAS).
IVS Next	Tracking system for inland navigation (Informatie- en Volgsysteem voor de Scheepvaart, 2019).
IVS90	Tracking system for inland navigation (Informatie- en Volgsysteem voor de Scheepvaart, 1990).
IWT	Inland waterway transport.
KNMI	The Royal Netherlands Meteorological Institute (Koninklijke Nederlandse Meteorologisch Instituut).
LAT	Lowest astronomical tide.
LAD	Least available depth (Minst gepeilde diepte).
MARIN	Maritime Research Institute Netherlands.
MDTC	Minimun distance to collision.
NAP	Normal Amsterdam Water Level.
nc-file	Unidata Network Common Data Form Format file.
OLA / ALD	Agreed Low Discharge for the Rhine at Lobith.
OLR / ALR	Agreed Low River level for the Rhine at Lobith.
OLW / ALW	Agreed Low Water level, transition level at Gorinchem based on LAT and ALR.
RWS	Rijkswaterstaat.
SIMDAS	General inland navigation simulation software (Simulatie DVK Algemeen Scheepvaartmodel).
SIVAK	Simulation software package for capacity studies of locks and bridges (Simulatie pakket voor Verkeers Afwikkeling bij Kunstwerken).
SLR	Sea level rise.
WVL	The department of water, mobility and environment of RWS (Water, verkeer en leefomgeving).

Terminology

Coupled units	A combination of barges or ships (koppelverbanden).
Draught	The depth of a vessel.
Depth	The river depth / depth of the fairway.
Harmonically moving congestion	Seven or more vessels travelling behind one larger or slower vessel while awaiting room to overtake.
Push-tow units	A combination of a push-boat with one or multiple barges (duwvaart).
Rijkswaterstaat	Part of the Dutch Ministry of Infrastructure and Water Management and responsible for the main infrastructure in the Netherlands.
Traffic capacity	The maximal number of vessels that can safely pass the river section, per time unit.
Traffic flow	The smoothness of individual vessel movements in the fairway, as well as ship-ship interaction, expressed in delay time and overtaking manoeuvres.

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1 Introduction

In 2018, there was a prolonged drought that caused severe water shortages and the water level of the river Rhine dropped to a record low level (Atkins, 2018 and Schuetze, 2018). These record low levels, forced shipping companies to reduce freight volumes and increase the number of shipments in order to fulfil the freight transport demand (Van t' Verlaat, 2019a). In the Netherlands, an increase in the number of shipments lead to an increase in the number of vessels on a part of the river Rhine, called river Waal. During the drought in 2018 congestion occurred in the river Waal (Van t' Verlaat, 2019a). The occurrence of congestion in the river Waal in 2018 has been the motivation for this study and forms a fundamental part in this research. As Rijkswaterstaat (RWS) has to facilitate inland waterway transport (IWT) in the river Waal during periods of extreme low discharge, knowledge is required on the effect of a reduced fairway width on the traffic flow and traffic capacity in the river. Previous river Waal studies mainly focused on the navigational depth during low river discharges (Bosschieter, 2005, Hetzer, 2005, Jonkeren et al., 2007 and Roex, 2018), whereas this research concentrates on the impact of reduced fairway width on the traffic flow and traffic capacity.

In the remainder of this chapter the research motivation and general information on the river Rhine system is provided. This chapter also contains the problem statement, the research objective and the scope and relevance of this research. Additionally, a reading guide briefly summarises the structure of this report.

1.1. Research motivation

The river Rhine is an important European river for IWT, but IWT cargo volumes are highly variable due to fluctuations in the Rhine river discharge (Amos et al., 2009). Due to the absence of locks in the river Rhine between the North Sea and Southern Germany, ship dimensions in the river Rhine are hardly restricted. In order to encourage European inland navigation, the Central Commission for the Navigation of the Rhine (CCNR) guarantees a minimal fairway depth in the river Rhine. To guarantee a minimal fairway depth during low discharges the corresponding water level in the river is determined and set at an Agreed Low River level (ALR). Currently the ALR stands at 2.80 m. During the drought of 2018 extreme low water levels in the river Rhine were recorded and the ALR level could not be maintained (Van t' Verlaat, 2019a). More precisely, in 2018 the water level was 156 days below ALR and became insufficient for the larger vessels in the fleet on the river Rhine (Van Hussen et al., 2019).

The drought of 2018 was an extreme event, but due to climate change extreme low discharges will occur more frequent and last longer (Figee, P. & Volker, W., 2016). In 2014, the Dutch national weather service (KNMI) developed eight climate scenario's for a maximum temperature increase of 2.4 degrees by the year 2050 and 4.2 degrees by 2085 (KNMI, 2015). The general conclusion from these scenarios is that warming of the Dutch climate will continue. Warming of the climate will cause astronomical summers to be warmer and dryer more frequently and astronomical winters to be more gentle but wetter with more extreme rainfall events (KNMI, 2015). The general conclusion of all KNMI climate scenarios is that the river Rhine discharge will increase in winter and decrease in summer. During periods of low discharge the width of the river channel is limited, which influences the traffic capacity of the river for navigation (Van der Mark, 2019a). The drought in 2018 showed that extreme low discharge in the river Rhine changes the IWT traffic capacity (Van t' Verlaat, 2019a). With future increase in transport volumes, increasing ship sizes and more frequent droughts, maintaining the IWT traffic capacity of the river Rhine is a major concern (Arnold et al., 2011, Figee, P. & Volker, W., 2016, KNMI, 2015, Özlem et al., 2019 and Schuetze, 2018).

In the river Rhine system, future climate change and extreme low river discharge could potentially have major consequences for IWT. As research by Van Dorsser (2015) has indicated that the middle section of the river Rhine, located in Germany, may no longer remain all year round navigable in case of the most extreme climate scenario towards the year 2100. Hence, it is important to look at the river Rhine system and analyse the Dutch river Rhine sections that are potentially limiting IWT in case of extreme low river discharges. The river Rhine finds its origin in Switzerland and enters the Netherlands at the German border. In the Netherlands the discharge in the river Rhine is often referred to as the discharge at the gauging station Lobith (see figure 1.1). At Lobith the water supplied from, among others, the Rhine and Moselle is measured. The Dutch part of the river Rhine divides into the river Waal and the Pannerdensch canal at the Pannerdensche Kop. The river Waal is an important river, because it is one of the main IWT corridors in Europe and is intensively used for navigation (Van Winden et al., 2010).

At Lobith the ALR is set at 739 cm above the Normal Amsterdam Water Level (NAP) and the corresponding discharge, the Agreed Low Discharge (ALD), for the Dutch part of the river Rhine is fixed at 1020 m^3/s (Kroekenstoel, 2009). The river Waal is the most important Rhine effluent in the Netherlands, containing 64% of the river Rhine discharge under average discharge conditions (2300 m^3/s) (Hermeling, 2004). During ALD the discharge distribution at the Pannerdensche Kop changes, resulting in 818,3 m^3/s (80%) in the river Waal and 201,7 m^3/s (20%) in the Pannerdensch canal (Sloff et al., 2014). Moving downstream of the Pannerdesche Kop, the river Waal meets the Maas-Waal canal, the Amsterdam-Rhine canal, the channel of Sint Andries, and finally reaches the city of Woudrichem. Near Woudrichem the river Waal merges with the Afgedamde Maas, which is a branch of the Meuse, to form the Boven-Merwede. To guarantee a smooth transition from the ALR level at Lobith to the river outflow at sea, an Agreed Low Water level (ALW) is set at Gorinchem. The ALR level operates as a upstream boundary condition for the water level in the river Waal, whereas the ALW functions as a downstream boundary condition. The ALR, ALW and ALD values are redefined every ten years and currently stand till 2022 (Jans et al., 2018). After 2022 the ALD, ALR and ALW values are redefined, taking into account climate change and sea level rise to guarantee future IWT in the river Rhine during extreme low discharges.

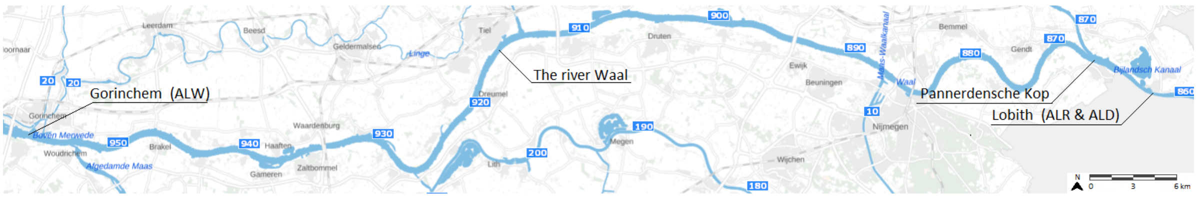

Figure 1.1: The river Waal flows from the Pannerdensche Kop (at the right), to the Boven-Merwede near Gorinchem (at the left) (Rijkswaterstaat, 2013).

1.2. Problem statement

In the Netherlands IWT has a market share of 34% in terms of transported tonnage of goods (CBS, 2019). Since, the market share of IWT is high, maintaining IWT capacity is of major importance for the Netherlands (Van Dorsser, 2015). As the river Rhine is the busiest river in the world (Figee, P. & Volker, W., 2016), extreme low discharges in the river Rhine have great impact on the Dutch transport sector. As the river Waal is the main branch of the Dutch river Rhine, extreme low discharge in the river Rhine have great impact on the IWT capacity of the river Waal. For example, when the water level at Lobith reduces to 850 cm relative to NAP, navigational safety measures forbid the use of push-tow units with six barges (in Dutch: zesbaksduwvaart)(Commissie voor de Rijnvaart, 1994). A water level of 850 cm relative to NAP corresponds to a discharge of approximately 1600 m^3/s. When push-tow units with six barges are taken out of operations, more vessels are required to transport the same amount of freight upstream. Initially less cargo is transported at once and four instead of six barges are used, but when the discharge reduces for a longer period of time, push-tow units will be replaced by coupled units (in Dutch: koppelverbanden): barges with smaller inland vessels (Van Hussen et al., 2019 and Van t' Verlaat, 2019a). The use of coupled units instead of push-tow units leads to a larger amount of vessels and, consequently, to a higher traffic intensity in the fairway. Moreover, during low discharge the fairway dimensions change, leading to a reduction in fairway width and depth. With higher traffic intensity but less navigational width, it will become increasingly difficult to overtake slower vessels. When overtaking is no longer possible, congestion occurs and the traffic flow of the fairway is limited by the slowest vessel using the river. This phenomenon was observed during the drought in 2018, the reduced fairway width caused congestions in the winding parts of the river Waal (Van t' Verlaat, 2019a). Though congestions in the river Waal have been observed in 2018, it is still unknown to what extend congestions in the river Waal influence the IWT traffic flow and traffic capacity (Van Hussen et al., 2019). Rijkswaterstaat has to facilitate inland navigation now and in the future, also in periods with extreme low discharges but little research has been done into extreme low discharges in the river Waal and the extent of their impact on the IWT traffic flow and traffic capacity.

1.3. Research objective

This research focuses on the following research question:

"What are the effects of extreme low river discharges on the traffic flow and traffic capacity of the river Waal fairway?"

During this research traffic capacity is expressed as the number of vessels per time unit that can safely pass a river section. Traffic flow refers to the smoothness of ship movements in terms of the number of overtaking manoeuvres and the delay times. Lastly, the discharges below ALD were considered as extreme low discharges.

In order to provide an answer to this research question, a traffic simulation model was used. Evaluating the performance of a network of waterways with a traffic simulation model is a proven method (Huang et al., 2013).

The following sub-questions were addressed to answer the research question:

1. Which river Waal discharges are most relevant to simulate in a IWT traffic simulation model?
2. What are the locations with limiting dimensions in the current river Waal fairway, at various discharge levels?
3. How does a extreme low river discharge affect the IWT fleet characteristics?
4. What was the relationship between fairway traffic flow and fairway width in the river Waal during the drought of 2018?
5. What is the impact of a change in traffic intensity on the river Waal traffic flow during extreme low river discharges?
6. What is the economical impact of congestion, based on the delay time?
7. Are congestions during low discharges in the river Waal triggered by the traffic intensity, the dimensions of the fairway, or both?

1.4. Scope and relevance of the study

The research methods and their limitations will be discussed first, and after that the scientific contribution and social relevance will be explained. To provide an answer to the research questions IVS90 data and discharge data were analysed and traffic flow simulations were carried out. Multi-beam measurements and water level data were used to generate the river profiles for extreme low discharges. The multi-beam measurements were measured in 2017. The water level data was generated by Deltares using SOBEK on the basis of an extrapolation of historic water level measurements at moments of extreme low discharge. During the extrapolation, water withdrawals and additions were estimated based on historic observations. Resulting in a known water level deviation of 5 to 10 cm on the river Waal. There were more locations with bed level data than locations with water level measurements. An interpolation method was used to fill the lacking water level data, increasing the uncertainty of the local water levels.

Recent IWT data for extreme low discharges were only available in the form of IVS90 data. IVS90 data is manually entered by the vessel's skipper, giving room to amongst others typing errors. Regression analyses were preformed on the IVS90 data. The IVS90 data was linked with the discharge data, filtered for a maximum daily discharge below 1200 m^3/s and a minimum of 40 observations per vessel class. Outliers in the date were excluded during the RWS-class vessel draught and loading percentage analyses. Also, the section of the river Waal that was analysed during this research was limited to approximately 21 km of the river Waal. The total length of the river Waal is approximately 82 km, which is about 4 times the investigated river section. Not all parts of the river Waal encounter the same problems during extreme low discharges. The conclusions drawn from this research do not take local effects into account that are of relevance outside the analyzed river section.

Little research has been done into extreme low discharges in the river Waal and the extent of their impact on the IWT capacity, especially, focussing on river width. More detailed knowledge was required concerning the impact of extreme low discharges on the IWT fleet composition (Van der Mark, 2019b). This research tries to cover this knowledge gap by the performance of low river discharge traffic simulations. With these simulations a first estimate of the delay time costs due to extreme low river discharge in the river Waal is provided. The economical impact of the drought of 2018 has been investigated before, but focuses on the transportation of one cargo type, or on the IWT sector as a whole. First indications of what the 2018 drought has cost the Dutch economy were available by (Van der Mark, 2019b) and (Van Hussen et al., 2019), but these reports focus on the entire IWT sector and the economic effects over longer time periods. The economical impact of IWT traffic related problems during drought remained untreated. Having rough estimates of the delay time cost of drought can help the Dutch authorities to investigate if improving navigability during extreme low river discharges is economically justifiable.

1.5. Reading guide

A brief summary of the structure of this report is provided to enhance readability. The report is divided in eight chapters and the chapters two to eight are summarised below.

Chapter 2, evaluates several traffic simulation models and the model requirements. The selection of the traffic simulation model has been clarified. Also, the chosen traffic simulation model SIMDAS is explained. This chapter describes the input and output files from the simulation model.

Chapter 3, contains the analyses of the gathered data. The river Waal fairway and the IWT fleet characteristics were determined in the hydraulic and transport analyses. The hydraulic analysis and the transport analysis provided insight in the data selection and processing required for modelling. An analysis of the economical effect of extreme low discharge on the IWT data, was preformed. Furthermore, the analysed data provided the answers to the first three sub-questions.

Chapter 4, discusses the sensitivity of the traffic simulation model to various parameters. The effect of changes in the river width on the traffic simulation results were analysed. Also, the sensitivity to increasing traffic intensity was investigated. More general model parameters that were tested were: the radio range, initial vessel position, the fraction of the loaded versus empty vessels and the vessel draught.

Chapter 5, treats the results of the traffic simulations. The remaining sub-questions were answered, resulting in an answer to the main question. Furthermore, the IWT delay times and fleet characteristics were linked with a rough estimate of the cost assuming a constant price per vessels class and delay time.

Chapter 6, evaluates the analysed data and the effect of data corrections and uncertainties on the results. This chapter also discusses the simulation results in relation to the observations during the drought of 2018. The results were placed into perspective.

Chapter 7, is the concluding part of this research, in which all research questions were answered.

Chapter 8, discusses the opportunities to apply the knowledge gained by the traffic simulation model in practice. Recommendations for further research on extreme low discharges and SIMDAS improvements were given. Therewith, the research on the effects of reduced discharge on the traffic flow and capacity of the river Waal was concluded.

2 Traffic simulation model

This chapter discusses the traffic simulation model selection. The model selection was based on model availability and literature. After the selection of the traffic simulation model, the general inland navigation simulation software (SIMDAS), the SIMDAS principles are explained.

2.1. Model selection

Multiple models were evaluated for the selection of the traffic simulation model for this research. In the last decade many studies have investigated the capacity of harbours, locks and waterway bottlenecks with computer models (Chen et al., 2013). These models were developed for specific situations, which resulted in a wide variety of traffic simulation models (Fischer et al., 2014). Most of these models, however, are still oversimplified and only suited for one specific research topic (Hekkenberg et al., 2017). The simplicity and specificity of existing traffic simulation models limits their applicability for other studies.

2.1.1. Model requirements

The model selection was based on four primary requirements. For the research on traffic flow and traffic capacity in the river Waal during extreme low river discharges the first two requirements were based on the representation of traffic in inland waterways. To represent IWT in a intensively used river the traffic simulation model must be able to, firstly, represent ship-ship and, secondly, represent ship-waterway interactions. The third requirement was based on the rivers hydraulic conditions. Because the river Waal cross-sectional dimensions are nonhomogeneous, the model must be able to, thirdly, represent location-varying waterway dimensions. The fourth requirement is that in order to represent the entire fleet on the river Waal, the traffic simulation model must be able to represent all occurring vessels. To represent the fleet on the river Waal during extreme low discharges, vessels were categorised in loaded and empty states, as their draught differs significantly. The RWS-classification system recognises 33 different ship classes, whereas the classification system determined by the European Conference of Ministers of Transport (CEMT) contains only 13 classes. To maintain the highest resolution in the fleet characteristics the RWS-classification system has been selected, resulting in 33 ship-classes with loaded and empty vessel dimensions. Therefore, lastly, the model must be able to distinguish 33 different vessel types in loaded and empty state. Summarised, the model requirements for the research in this report contains the representation of ship-ship interactions, ship-waterway interactions, location-varying waterway dimensions and the representation of 33 different vessel types in loaded and empty state.

2.1.2. Model comparison

To study congestions in the river Waal during extreme low discharge, it is important that the traffic simulation model uses vessel movements as a traffic parameter instead of transport volumes. Considering that the occurrence of congestions during extreme low discharge has been the main motivation for this research topic, models developed for lock scheduling, analysis of harbour waiting times or tow scheduling were not included in the model comparison. Due to the existence of narrow stretches, sharp bends and nonhomogeneous cross-sections in rivers, maritime open-water traffic simulation models were not considered suitable for research on inland waterways (Watanabe et al., 2008). As a result, maritime open-water traffic simulation models were not included in the model analyses. Table 2.1 shows all traffic simulation models using vessel movement as a traffic parameter available in literature, to the authors best knowledge. The considered models were evaluated based on the four model requirements: representation of ship-ship interactions, ship-waterway interactions, location-varying waterway dimensions and the representation of 33 different vessel types in loaded and empty state.

Table 2.1: Comparison of traffic simulation models, without model alterations, based on the four model requirements.

Model	**Ship-Ship interaction**	**Ship-Waterway interaction**	**Represent fairway** [1]	**33 different vessel types** [2]	**References**
AWESIM model [3]	No	Limited	Yes	Yes	Köse et al. (2003), Ulusçu et al. (2009)
IWTS [4]	Yes	Yes	Unkown	Yes	Watanabe et al. (2008)
SIMDAS	Yes	Yes	Yes	Yes	Bekendam et al. (1988), De Boer & Bilinska, (2016), Waterloopkundig - laboratorium (1994)
NetLogo Multi-agent	Yes	Yes	Yes	Yes	Xiao et al. (2013)
PIANC'14 [5]	Yes	Yes	Unkown	No	Fischer et al. (2014)
SIVAK	Limited	Limited	Limited	Yes	Chen et al. (2013), Ten Hove et al. (2015)
VTMIS	No	Yes	Yes	Yes	Ince and Topuz (2004)
Tagus model [6]	Yes	Limited	Unkown	Yes	Rong et al. (2015)

[1] Represent the fairway in terms of location-varying fairway dimensions.

[2] Distinguish 33 different vessel types in loaded and empty state.

[3] Simulation model developed with AWESIM software tools by Köse et al. (2003).

[4] Short for Inland Waterway Traffic Simulator.

[5] Model package introduced at the 2014 PIANC World Congress in San Francisco.

[6] Model package designed for the Tagus River Estuary by Rong et al. (2015).

As illustrated in table 2.1, only the SIMDAS and the NetLogo Multi-agent model meet all four model requirements. SIMDAS evaluates the safety and capacity of waterways and has been designed for RWS to simulate IWT in straight river sections, river bends, bifurcations, confluences or crossings.

SIMDAS is spatially limited by the number of crossings in the river system. The software is available at RWS for research purposes.

Xiao et al. (2013), developed a multi-agent simulation model for autonomous ships in the NetLogo environment, using AIS data as the input data-source to include human decision making, nautical regulations and the nautical environment in the simulation. The model uses a geographical scale smaller than 1:10 kilometres (Xiao et al., 2013). The NetLogo platform is an open source platform for simulation software and is accessible for research. Due to the restricted spacial scale and the incompleteness of the river Waal 2018 AIS data, the NetLogo Multi-agent simulation software has not been selected for this research. SIMDAS was chosen as the traffic simulation model for this research.

2.2. Introduction to SIMDAS

SIMDAS was developed in the eighties of the last century by TNO-IWECO in collaboration with RWS and the latest model update was executed in 2000 (De Boer et al., 2016). SIMDAS is a dynamic traffic simulation model for fairway sections and simulates traffic flow at individual ship level, as a function of time. The manoeuvrability and ship steering in SIMDAS was updated and validated for the RWS-classification system by the Maritime Research Institute Netherlands (MARIN) in 2016 (De Boer et al., 2016). The validation by De Boer et al. (2016) mainly focused on the improvement of the ship parameters for RWS-classes categorised as coupled units and push-tow units. In 2017 SIMDAS was used by Ten Hove & Bilinska (2017) to analyse the river Waal in the context of studies for the new waterway guidelines ”Richtlijnen Vaarwegen” (Koedijk, 2020). Ten Hove & Bilinska (2017) studied the transport intensity and fleet composition on the river Waal during ALD levels. The SIMDAS traffic simulation output requires post-processing before the simulated traffic can be analysed. At MARIN post-processing tools were developed in the programming language MATLAB. The post-processing tools gather all information from the SIMDAS output files and transport the generated simulation data into one excel file. Also, MATLAB tools were developed to visualise the traffic simulated in SIMDAS. The input data in SIMDAS requires pre-processing, which makes a detailed study of the river data and IWT data crucial for a correct representation of a river and corresponding river fleet.

With SIMDAS changes in waterways and their influence on the traffic flow can be analyzed, using traffic safety and fluency as the main model characteristics. The SIMDAS model simulates the individual ship position, direction and speed in the waterway as time-dependent variables. The waterway layout is described by the ship route, the depth contour along the route and the position of buoys. The composition of the simulated traffic is specified by the number of vessels per class. Of each ship-class the manoeuvring characteristics and vessel dimensions need to be specified. The traffic intensity per ship-class has to be specified per route and per time interval for the total duration of the simulation. If a conflict arises an interaction model is activated. A conflict can arise in the form of overtaking, encounter or crossing in the individual shipping routes (Hobo, 2019). The SIMDAS model solves conflicts by allowing ships to divert or slow down, using traffic and manoeuvring rules. The hydraulic representation in SIMDAS is less developed than the traffic representation, meaning that the discharge and flow velocity within a river section are considered stationary. Fluctuations in the discharge and flow velocity are neglected in SIMDAS, resulting in a oversimplification of the river dynamics. The simplification of the river hydraulic characteristics was considered acceptable for the research on the effects of extreme low river discharges in the river Waal on the traffic flow and traffic capacity.

2.2.1. SIMDAS files

For SIMDAS a data-preparation program, called Invoer Preparatie SIMDAS (IPS), was developed to reduce the complexity of the SIMDAS model (De Boer et al., 2016). It resulted in the input files: *Waterway file* with the extension *(.vwb)*, *Shipping file (.sch)*, *Navigator file (.nav)* and *Simulation file (.sim)*. The left side of figure 2.1 shows the relationship between the files containing the input data and the SIMDAS run files. In the waterway file *(.vwb)* the waterway was schematised using reference lines. At each reference line the depth-profile and X- and Y-coordinates were set. The shipping routes were defined in the waterway file whereas the ship-classes and characteristics were defined in the shipping file

(.sch). Once defined, the shipping parameters were used for all subsequent simulations. The navigator file *(.nav)* contains all parameters related to ship steering and decisions making. In the simulation file *(.sim)* all control data for the simulation was programmed. For the analyses of multiple traffic flow scenarios only the simulation files were modified, all other data files could remain unchanged. However, this method was only useful for the traffic related variables, because changes in the hydraulic parameters requires alterations in the waterway file. For a complete system analyses including hydraulic and ship parameters, the *.vwb*, *.sch*, *.nav* and *.sim* files need to be modified.

Besides the IPS program, the SIMDAS model contains the programmes called SIMDAS50 and SIMDAS60 as well as several tools to analyse the model output. The centre of figure 2.1 shows the order of programming in SIMDAS. SIMDAS50 is the traffic simulation executable of SIMDAS and SIMDAS60 is the programme that stores the traffic simulation results. IPS uses the four text files; *.vwb, .sch, .nav* and *.sim*, to generate the input for SIMDAS50. SIMDAS60 requires the output of SIMDAS50 as an input file, together with the *x.stuur*, *.voork* and *x.hist* files. The *x.stuur* file contains the models stirring parameters. Whereas, the histogram variables are registered in the *x.hist* file and additional parameters regarding the incoming fleet and waterway data in the *.voork* file. SIMDAS60 produces eight output parameters. Two of these output parameters are the number of cancelled overtaking manoeuvres and forced overtaking, per ship class. Also, the delay, per ship class and direction are SIMDAS60 output parameters. The delay time in SIMDAS is defined as, the difference in the time it takes to travel a certain distance and the time that is required if using the ships maximal given speed. SIMDAS60 counts the number of vessels per direction that needed to slow down to avoid conflicts during the simulation. The model also registers, per ship class, when ship safety margins are compromised. Furthermore, the model counts the number of times the ships position in the waterway changes. Herewith, a ships position in the waterway is registered in terms of distance from the reference line. Lastly, the total number of ships per class and direction are not only part of the model input but also the model output parameters. The right side of 2.1 summarized the 8 output parameters of SIMDAS.

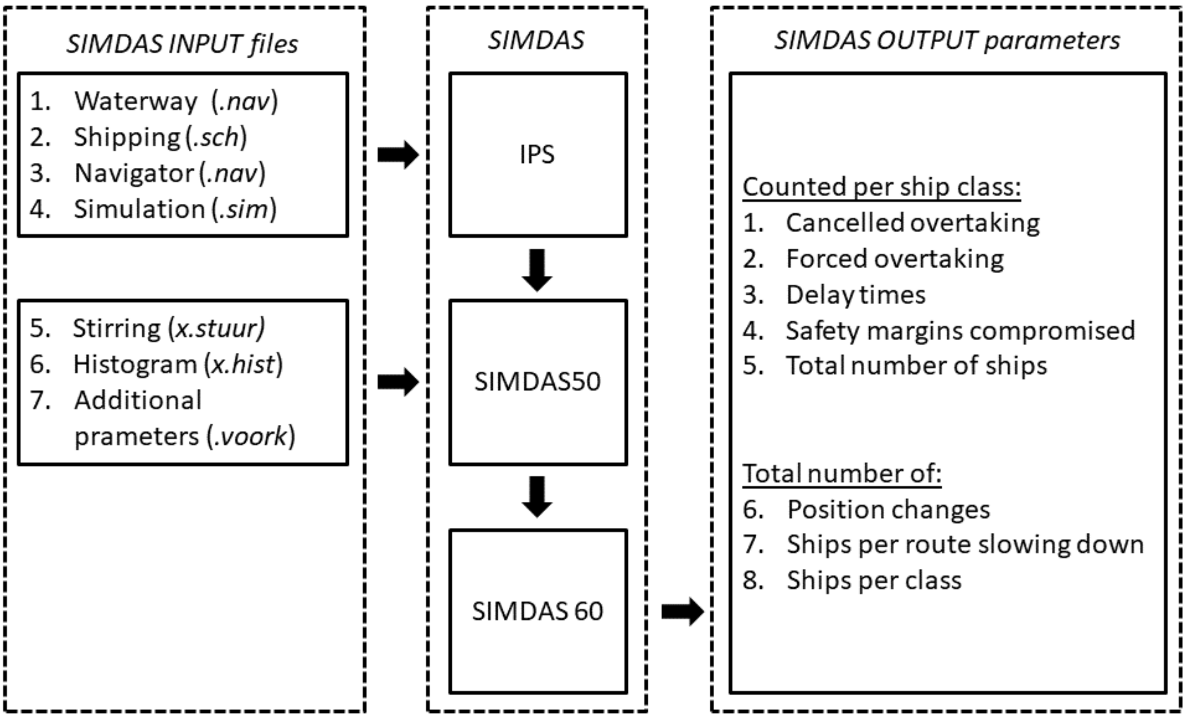

Figure 2.1: An overview of the input files for SIMDAS, the order of running SIMDAS and the output parameters.

2.2.2. SIMDAS programming

SIMDAS is build on the keep-your-lane principle, which means that when the waterway dimensions change, the vessel's position will change as a fraction of the distance between the reference line and the margin of the fairway. The change of position relative to the reference line has been illustrated in figure 2.2. The outer boundaries of the fairway are d_{max} and d_{min}, and the waterway boundaries are w_{max} and w_{min}. The model accounts for the position, direction and speed of every simulated ship at each time step.

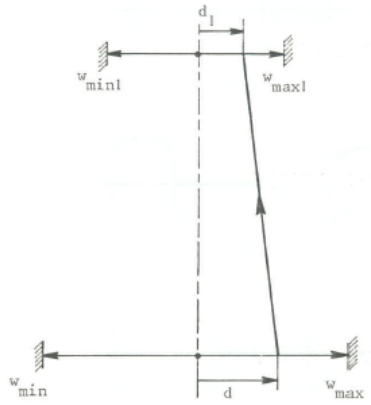

Figure 2.2: Changing ship position according to the relative distance from the reference line (Bekendam et al., 1988).

The SIMDAS model can be classified as an interaction model due to the conflict detection and program options. If a conflict arises a deviation from the ships course or a change in operational speed becomes necessary. The program uses different conflict handling options. Changes in the ship's course are initiated by changing the relative distance to the reference line. A minimal distance to the fairways outer borders has to be maintained at all times. When the course of a ship is changed the programme always takes the minimal distance to collision (MDTC) and the drift angles into account. SIMDAS handles conflicts with the following rules:

1. A reduction in sailing speed is only considered when a conflict cannot be solved by course diversion.
2. Overtaking is only permitted on the port side. However, when overtaking is not possible, the speed is adjusted to that of the ship in front. The ship is diverted as far as possible to the starboard side, to make room for other vessels.
3. With a deviation to starboard side, oncoming traffic is avoided. If space is limited and it is not possible to avoid oncoming traffic the overtaking manoeuvre is interrupted. Reducing the speed of the vessel to overtake, can speed up the procedure, whereas reducing the speed of the overtaking vessel will abort the manoeuvre.
4. Ships deviate, so that at crossings priority ships are passed at the rear. If passage at the rear is not possible speed is reduced, whereby in the most extreme case the priority giving ship comes to a halt.

SIMDAS facilitates the simulation of special traffic rules, like sailing with a blue sign or white flashing light (Ten Hove, 1996). A blue sign indicates that an upstream sailing vessel sails on the opposite side of the fairway. The blue sign as well as a white flashing light has to be placed on starboard side of the vessel. Additionally, ships will adapt their speed according to the radius of curvature of the following river section (Ten Hove, 1996). It may occur that large vessels, like push-tow units, are not able to encounter other vessels in sharp bends, due to a large drift angle. The model recognises large vessel bottleneck locations and solves encountering issues by reducing the speed of the vessel downstream of the bottleneck. If slowing the vessel down does not resolve the conflict, the program will let the vessel downstream of the bottleneck await passage at a non-bottleneck location. In theory a fairway is divided into navigation lanes, normally one for every direction with a total maximum of four lanes, but in practice inland vessels use the total available width of the fairway. Navigation lanes are not indicated in the waterway. In SIMDAS the model accounts for only two navigation lanes, one for both directions relative to the reference line. Even though SIMDAS has not been validated for the use of the available fairway width by inland vessels, it is assumed that SIMDAS represent the reality fairly well.

Most of the traffic related parameters were incorporated in SIMDAS, but many of the parameters involving the ships environment were not included. In SIMDAS the effect of wind on the ship movement and the river flow were not accounted for. The horizontal and vertical variations in the rivers flow velocity were not included, because SIMDAS sets a constant flow velocity at each cross section. Nonetheless, the model is validated for its ship steering capabilities and the way it represents ship manoeuvring in 2016 by MARIN (De Boer et al., 2016).

3

Data collection, processing and analysis

A deeper understanding of the river Waal IWT system was obtained with the hydraulic data analysis and the IWT data analysis. The hydraulic data analysis was used to select a section of the river Waal to focus on for the simulations. The IWT data was used to determine the fleet characteristics for the traffic simulations. A brief literature study was used to indicate the transport costs corresponding to low discharges due to delay times. Consequently, this chapter provides an answer to the first three research questions:

1. *Which river Waal discharges are most relevant to simulate in the IWT traffic simulation model?*
2. *What are the locations of limiting dimensions of the current fairway, at various discharge levels?*
3. *How does a low river discharge affect the inland waterway transport fleet characteristics?*

3.1. Hydraulic analysis

In order to simulate IWT on the river Waal, hydraulic data and transport data were required. Hydraulic data of the river Waal had been gathered from projects executed by Deltares and from RWS Waterinfo (Rijkswaterstaat, 2020). The IWT data was gathered from the RWS department for Water, mobility and environment (WVL). The collected data needed processing before implementation in SIMDAS, because the format of the gathered data was not compatible. Also, SIMDAS can simulate only two crossings, T-junctions, confluences or bifurcations. Whereas, the river Waal contains several crossings, starts as a bifurcation of the river Rhine and ends with a confluence downstream in the Boven-Merwede. For a correct representation of the river Waal fairway in SIMDAS, only a part of the river Waal was selected. During the transport analyses the IWT on the selected river section has been analysed, resulting in the fleet composition and the number of passages during extreme low discharge.

The hydraulic data obtained from Deltares, was based on the calculation of the momentum equation and the continuity equation for flow in SOBEK. SOBEK describes physical processes in a one-dimensional (1D) network while using a two-dimensional (2D) horizontal grid. The level of accuracy was considered suitable for the desired application because the discharge in the traffic simulation model has been taken as a constant in time. The discharge distribution along the branches and the bed level were considered as constant in time. The computation of the hydraulic properties of the river Waal was not the main objective of this study and therewith the use of available data was justified.

The hydraulic analysis begins with addressing the first sub-question:

"Which river Waal discharges are most relevant to simulate in the IWT traffic simulation model?"

Historic data analysis provided a first indication on extreme low discharges at Lobith and their occurrence. The river Waal discharge data at Lobith was available from RWS Waterinfo. The requested data-set contained discharge and water level data, measured at Lobith from 1901 till 2018. The lowest recorded river discharge from the acquired dataset was measured in February 1929 at a discharge of 575 m^3/s. In 2018 the lowest recorded discharge was measured in October at 709 m^3/s. In 2018 the discharge was 138 days below 1200 m^3/s, placing it at the seventh place in the top 15 of years with extreme low discharges (Scheijven, 2019). The top 15 of years with extreme low discharges averaged between September and November, has been illustrated in figure 3.1. The 2018 discharges from August till December were measured around and below the ALD line. The average discharge in 2018 between September and November was 859 m^3/s (Scheijven, 2019). In figure 3.1 the extreme low discharge period between the first of August and the first of December shows that 2018 was not the year with the most extreme low discharge in this period. Hence, for this research more relevant discharges had to be considered alongside the discharges measured in 2018.

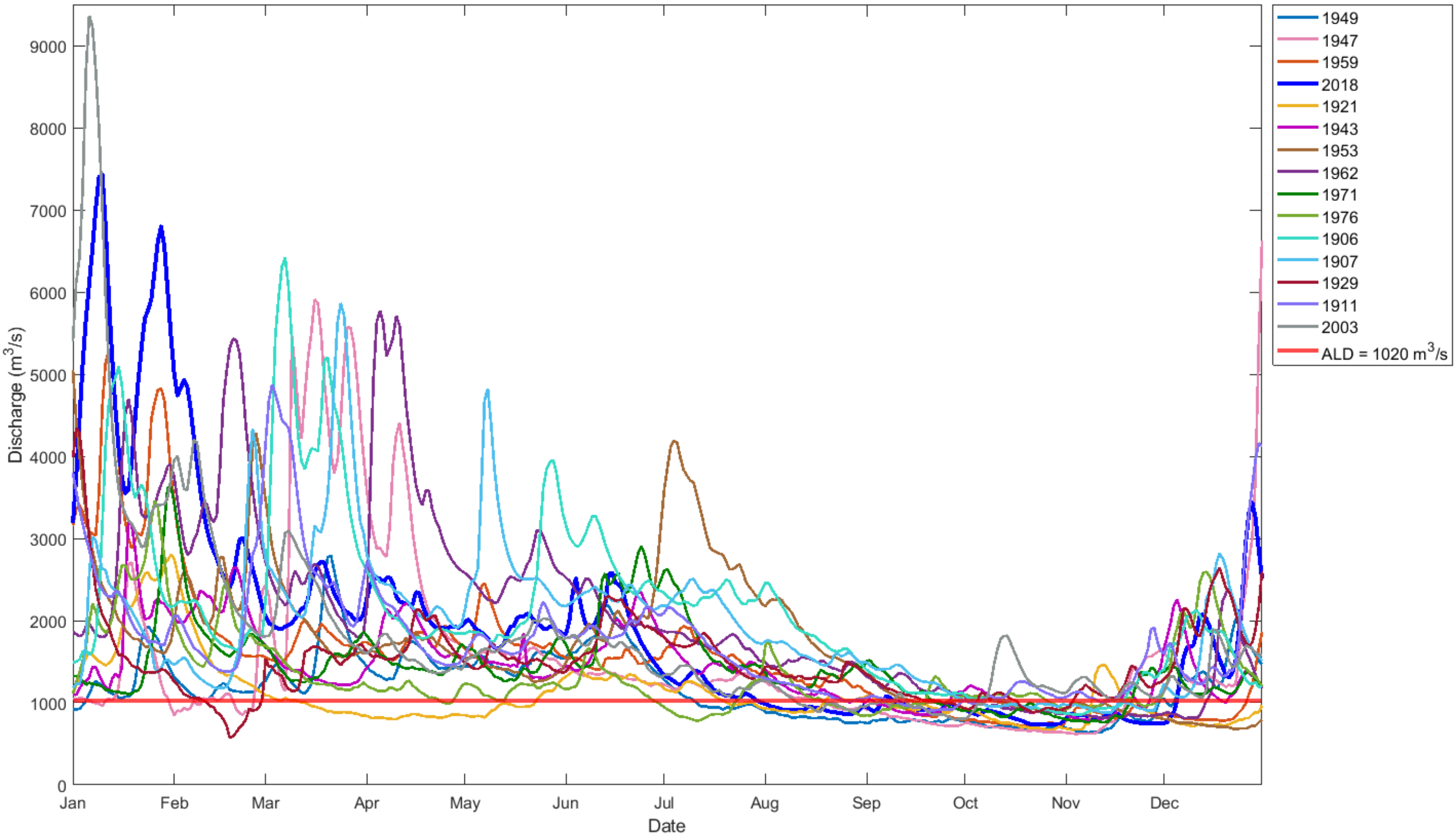

Figure 3.1: Top 15 years with extreme low discharges, averaged from September to November. Rijkswaterstaat data measured at Lobith in 1900 up to 2018. The agreed low discharge (ALD) has been highlighted in red.

After the historic discharge data at Lobith was analysed, the selection of relevant extreme low discharges for the future was based on the study of Van der Mark (2019a). For two of the eight KNMI climate scenarios (W_H and $W_{H,dry}$), Van der Mark (2019a) predicted ALD values for the years 2050 and 2085, table 3.1. For the more extreme scenario, the $W_{H,dry}$ scenario, the future ALD value for the year 2085 was calculated at 791 m^3/s. The future ALD values were used to select representative discharges to include future ALD values and future extreme low discharge values in the traffic simulations.

Table 3.1: Future agreed low discharge values calculated with the W_H and $W_{H,dry}$ KNMI climate scenario's by Van der Mark (2019b).

KNMI climate scenario	2050	2085
W_H	1013 m^3/s	985 m^3/s
$W_{H,dry}$	866 m^3/s	791 m^3/s

In order to select the most relevant discharges of the river Waal, the historic discharge data and the future ALD values were combined. The historic extreme low discharge measured at Lobith was 575 m^3/s and to include this extreme value, the discharge modelling range was set at 1020 to 600 m^3/s. The lower boundary was not set at exactly 575 m^3/s, because hydraulic data was available for a discharge of 600 m^3/s whereas no data was available for a discharge of 575 m^3/s. Between these boundary values a range of discharges was selected in order to simulate the impact of extreme low discharges on IWT. The lower ALD value predicted for the year 2085 was 791 m^3/s and the lowest recorded discharge in 2018 was 709 m^3/s. Therefore the discharges to include in the traffic simulation model scenarios were 700 and 800 m^3/s. Given the available data, the discharges to model are 1020, 800, 700 and 600 m^3/s and thereby the sub-question about the most relevant river Waal discharges for the IWT traffic simulation model, has been answered.

The following paragraphs will continue with the analysis of the system, in order to provide an answer to the second sub-question:

What are the locations of limiting dimensions of the current fairway, at various discharge levels?

The study by Van der Mark (2019a) was used to indicate the area's where future ALD discharges create bottlenecks. The study takes scenarios with sea level rise (SLR) into account as well as scenarios without SLR. The study by Van der Mark (2019a) focuses on a guaranteed depth of 2.80 m and than on the remaining fairway width. Currently, the advised river Waal fairway width is 170 m (Ten Hove & Bilinska, 2017 and Fischenich et al., 2002), though the actual fairway maintenance width is 150 m at ALD (Sloff et al., 2014). During extreme low discharges the fairway width can reduce to smaller values than the maintenance width. For the ALD levels for the year 2050 the study by Van der Mark (2019a) already observed bottleneck locations where the fairway width was less than the required 150 m. Including SLR in the depth analysis of future extreme low river discharges lead to larger depths. Van der Mark (2019a) highlighted that scenario's where SLR was not included resulted in more conservative future fairway dimensions. The study shows that the river Waal fairway dimensions between Weurt and Druten, as well as downstream of Sint Andries, were the first places affected during extreme low discharges. When considering the river Waal ALD discharge of the $W_{H,dry}$ scenario for the year 2085, the study by Van der Mark (2019a) indicated several locations where the depth over the whole cross-section was below 2.80 m. Figure 3.2 shows the locations indicated by Van der Mark (2019a) where the river cross-sectional depth was below 2.80 m. Therefore, figure 3.2 indicates the locations in the river Waal with limiting dimensions during extreme low discharge.

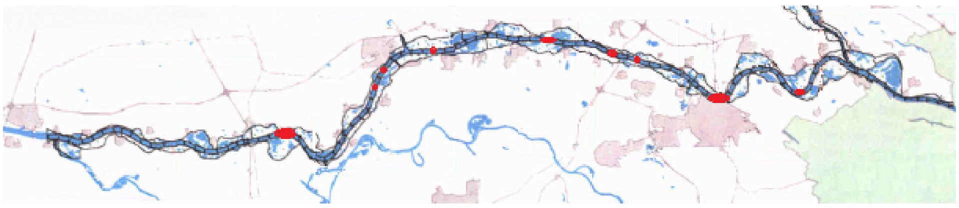

Figure 3.2: Bottleneck locations where the depth is less than 2,80 m in 2085 for the KNMI $W_{H,dry}$ climate scenario, indicated with red. The figure is based on the report by Van der Mark (2019b).

The bottleneck locations in figure 3.2 were located in the more winding parts of the river as well as the relative straight river sections. Observations during the extreme low discharge of 2018 were used to select the river section that has the most valuable contribution to this research. Observations by Van t' Verlaat (2019a) indicated that congestions occurred in 2018 in the river Waal bends. Due to these observation the further analysis was more concentrated on the river sections with numerous bends. More specifically, Van Hussen et al. (2019) stated that during the drought in 2018, bottlenecks arose near the city of Nijmegen. Combining the locations indicated in figure 3.2 with the findings of Van t' Verlaat (2019a) and Van Hussen et al. (2019), the river section from the Pannerdensche Kop to the Maas-Waal canal has been chosen as the section with limiting dimensions. Therewith an answer has been provided to the second sub-question.

After the selection of a river Waal segment for modelling, the section's fairway dimensions for varying discharges need to be determined. Considering that the ALD discharges for the years 2050 and 2085 were calculated based on the assumption that the discharge distribution at the Pannerdensche Kop remains unaltered (Briene et al., 2018), the unaltered discharge distribution has also been assumed for this study. Meaning that 80% of the discharge measured at Lobith, flows to the river Waal and 20% to the Pannerdensch canal. 3.4.

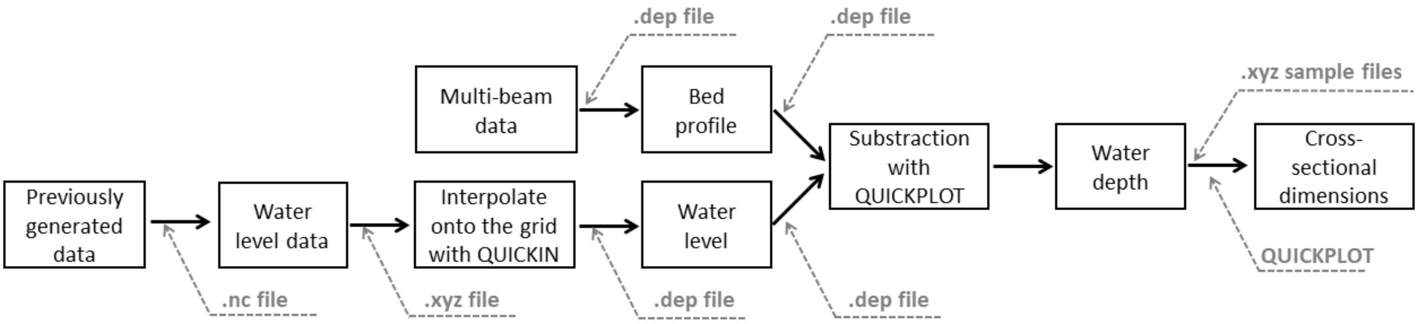

Figure 3.3: Hydraulic data processing to obtain the cross-sectional dimensions.

To obtain the cross-sectional river dimensions at the selected discharges, several data transformations were needed. Figure 3.3 illustrates the performed data transformations. Firstly, the multi-beam measurements from the river Waal of 2017 were used to compute the river bed profile. Secondly, *.nc* files containing the river data during the research by Roex (2018), were obtained from Deltares. Often multidimensional science-related data is stored in Unidata Network Common Data Form formats (File.extension.info, 2020), also called *.nc* files. These river data *.nc* files were used to create *.xyz* files containing the water levels. These *.xyz* water level files relate the water level, Z, to the coordinates, X and Y. The X- and Y-coordinates were defined in the Rijksdriehoek (RD) coordinate system. The RD-coordinate system is illustrated in figure 3.4. RD-coordinates are national triangle coordinates and are used at national level in the geodetic coordinate system (De Bruijne et al., 2005). The RD-coordinates are used on maps of the land registry and for geographical indications. In the RD-coordinate system the X axis runs from west to east and the Y axis runs from south to north. The coordinates are always positive and the X-coordinate is always smaller than the Y (De Bruijne et al., 2005). Thirdly, a Wizard Dependency (*.dep*) file containing the water levels for the river Waal was generated using QUICKIN. QUICKIN is the interpolation module of the Delft3D-suite software. In QUICKIN the water level *.xyz* files were uploaded as sample files and assigned to the cell centres. Then the water level data was interpolated over the entire river grid and exported, resulting in the water level *.dep* file. Fourthly, the bed profile *.dep* file was combined with the water level *.dep* file, to compute the water depth along the river Waal. To generated the water depth, QUICKPLOT was used. QUICKPLOT is a Delft3D tool to visualise and animate numerical results. The water depth was computed by subtracting the bed profile *.dep* file from the water level *.dep* file. Lastly, the computed water depth at every cross-section was exported from QUICKPLOT as *.xyz* sample files.

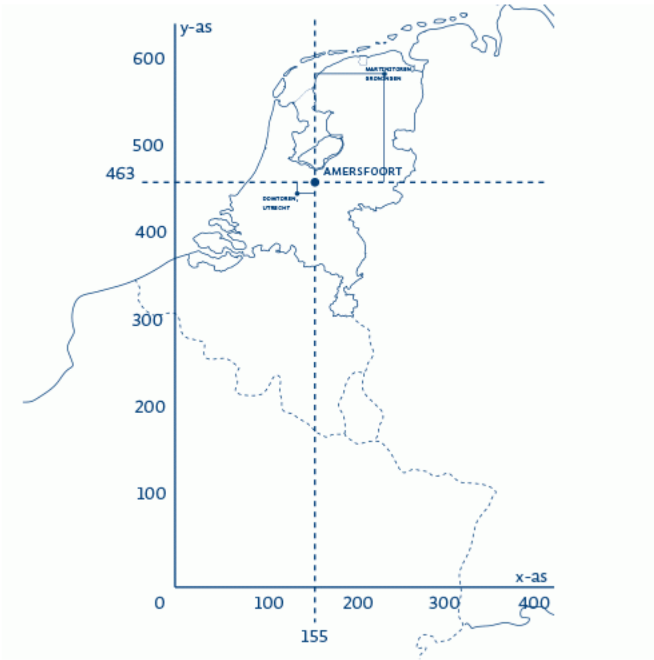

Figure 3.4: The Rijksdriehoek coordinate system (Kadaster, 2019)

Because the RD-coordinates were used to determine the cross-sectional profile, additional data was also gathered in RD-coordinates in order to combine all the hydraulic data for the simulations. In order to define the waterway in SIMDAS a reference line was needed, separating the fairway into an upstream travelling and downstream travelling traffic lane. The reference line of the river Waal was not situated in the middle of the fairway. The river Waal is a trained river, as groynes and longitudinal training dams were used to generate better navigational conditions. In the cross-sectional data these training works were not indicated. Beacon line data was used to indicate the port and starboard boundaries of the navigable river. At every computed cross-section, the reference line and beacon lines were determined in RD-coordinates. A general distance of 30 m from the beacon line is advised for the calculation of the navigable width in rivers (Koedijk, 2020). However, the distance of 30 m is only required for onshore beacons, buoy beacons only require a 5 m passing distance. The difference between both beacon types was not clear from the beacon line data, therefore the calculated cross-sections do not incorporate the required minimal distance from the beacon line. In SIMDAS a distance factor for the passage along the fairway boundary was used to represent a minimal passing distance from the beacon line. All cross-sectional files were combined in MATLAB to generate the cross-sectional river dimensions, illustrated in figure 3.5. From there 5 data-points left and 5 data-points right, of the reference line were selected to form the cross-sectional input for SIMDAS. To select the 5 data-points a linear interpolation was used between one side of the beacon line and the reference line.

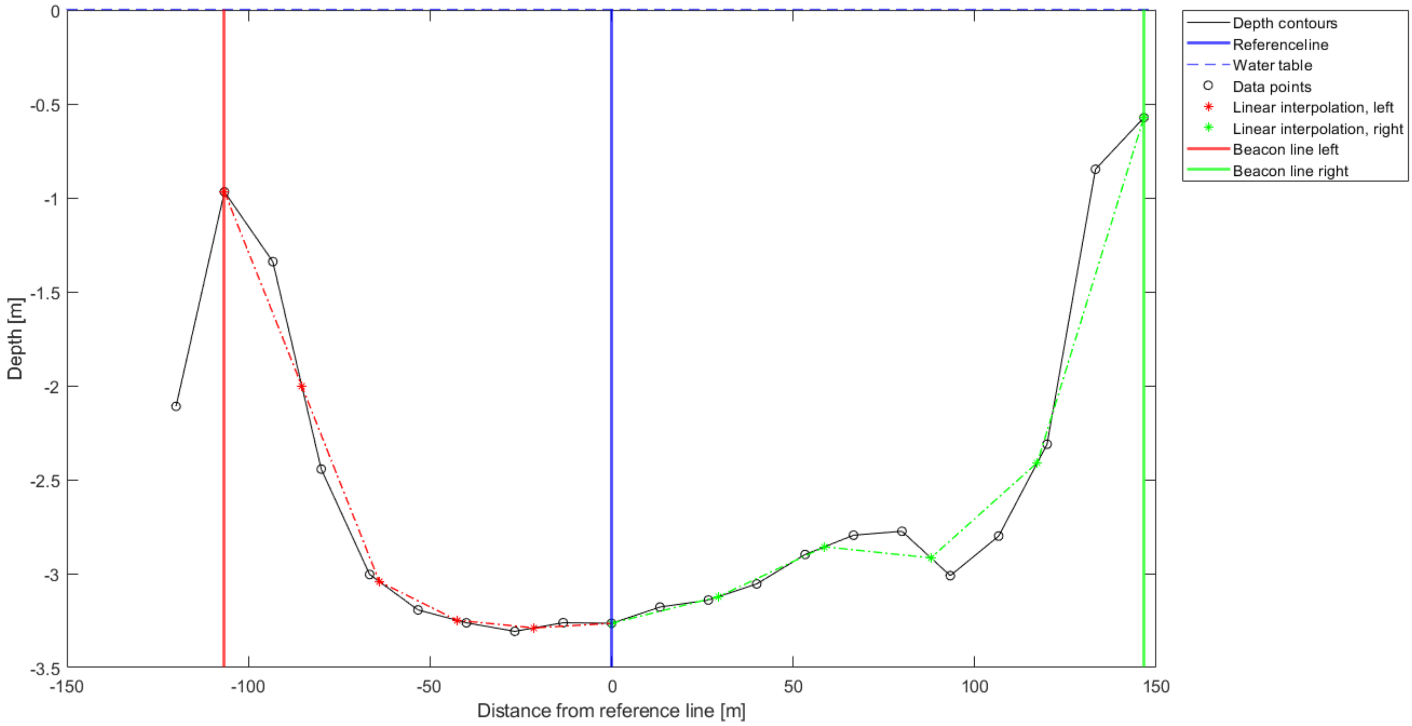

Figure 3.5: The cross-sectional files were combined to determine the river dimensions using only 10 points, for the cross-sections from the Pannerdensche Kop (55) to the Maas-Waal canal (140).

From the Pannerdensche Kop, cross-section number 55, till the Maas-Waal canal, cross-section number 140, the width of the river was determined (figure 3.7). The extreme low discharges at Lobith considered during the study on the available river width were 1020, 900, 800, 700 and 600 m^3/s. These discharges were based on available data and historical data analysis. Table 3.2 and figure 3.6 summarises the average navigable width of all the cross-sections, from 55 till 140, at a river depth of 2.0 m. With a decreasing discharge, the navigable river width reduces. The 2.80 m river depth criteria at ALD was not possible to maintain during the discharge of 900 m^3/s because the depth was insufficient for some of the cross-sections. Therefore, the width at a depth of 2.0 m was determined for all discharges at all cross-sections. A vessel draught of 2.0 m during extreme low discharge was assumed to be reasonable based on the averaged vessel draught during the four observed weeks. Between profile 114 and 120 the river width is strongly reduced, representing the river bend near Nijmegen, see figure 3.7. Cross-section 114 has a width of only 28 m for discharges of 800 m^3/s and lower. More detailed data on the calculated navigable width per cross-section is available in appendix B.1 and C.4.

Table 3.2: Average navigable river width determined at a river depth of 2.0 m for the discharges 1020, 900, 800, 700 and 600 m^3/s

Discharge profiles	1020 m^3/s	900 m^3/s	800 m^3/s	700 m^3/s	600 m^3/s
Average width	200 m	170 m	152 m	151 m	123 m
Standard deviation	23 m	33 m	44 m	44 m	46 m
Maximum value	242 m	228 m	228 m	228 m	223 m
Minimum value	145 m	89 m	28 m	28 m	28 m

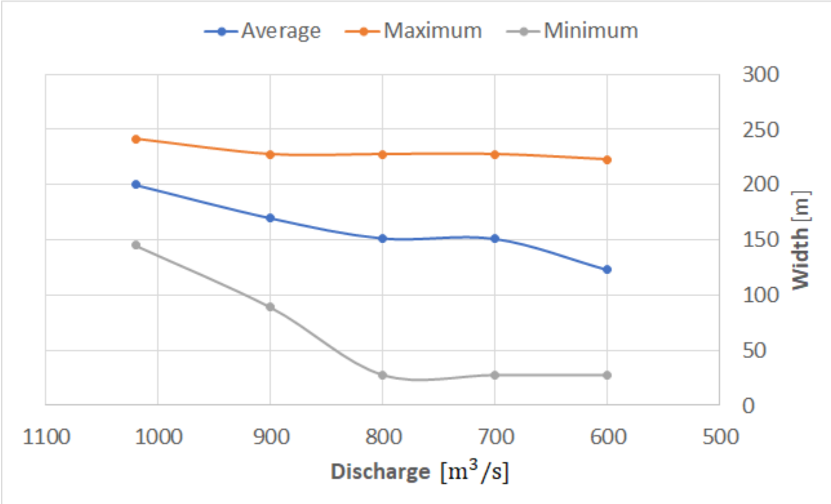

Figure 3.6: The average, maximum and minimum river widths plotted against the discharge.

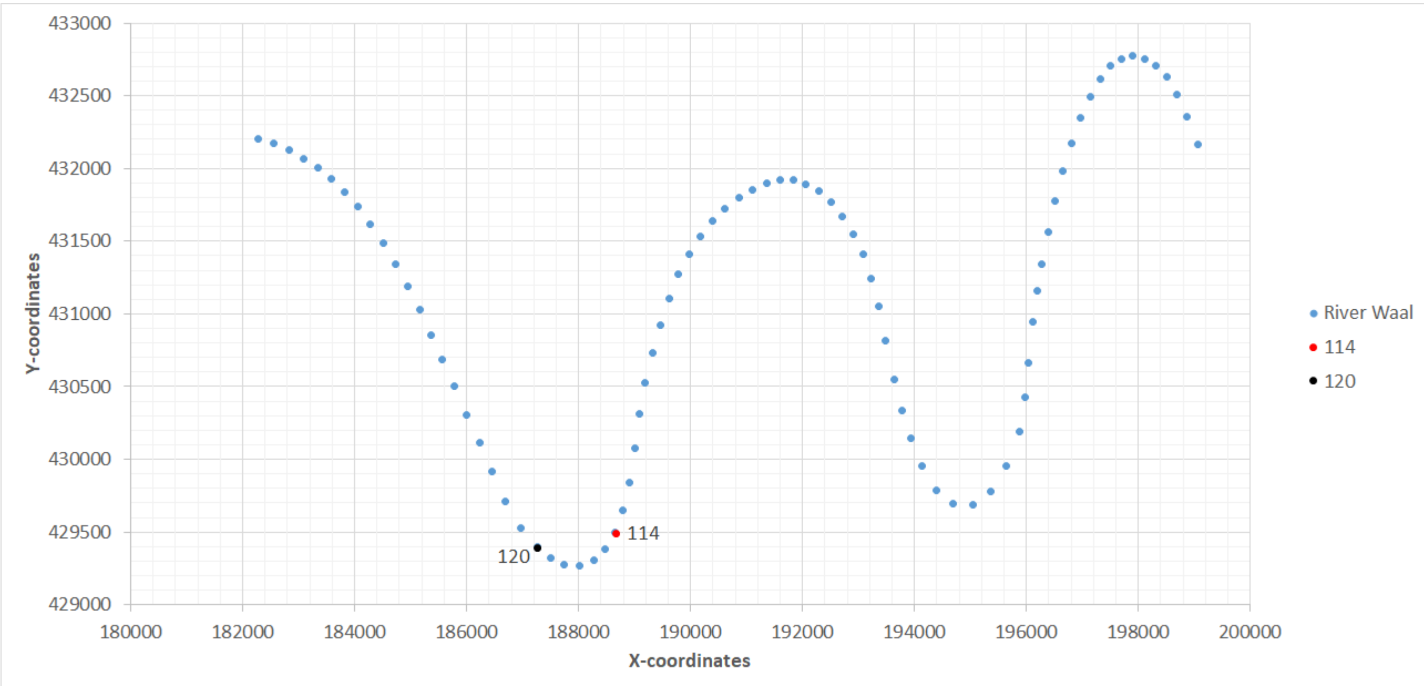

Figure 3.7: The cross-sectional profiles with their coordinates.

Finally, SIMDAS requires radial data for non-straight river sections. So, all cross-sectional files were combined in MATLAB to generate the curvature of the river between cross-sections, illustrated in figure 3.8. The curvature was calculated based on the orientation of two subsequent cross-sections. Next, the point were the extension of the orientation lines of these subsequent cross-sections intersect was calculated. This intersection point is equal to the centre point of the circle on which both reference points of the cross-sections are situated. The orientation lines are represented by a blue and pink line in figure 3.8. The distance from the reference points (highlighted in red in figure 3.8) to the centre point of the circle is equal to the radius of the circle. Based on the orientation of the first of the two subsequent cross-sections, the direction of rotation of the curvature was determined.

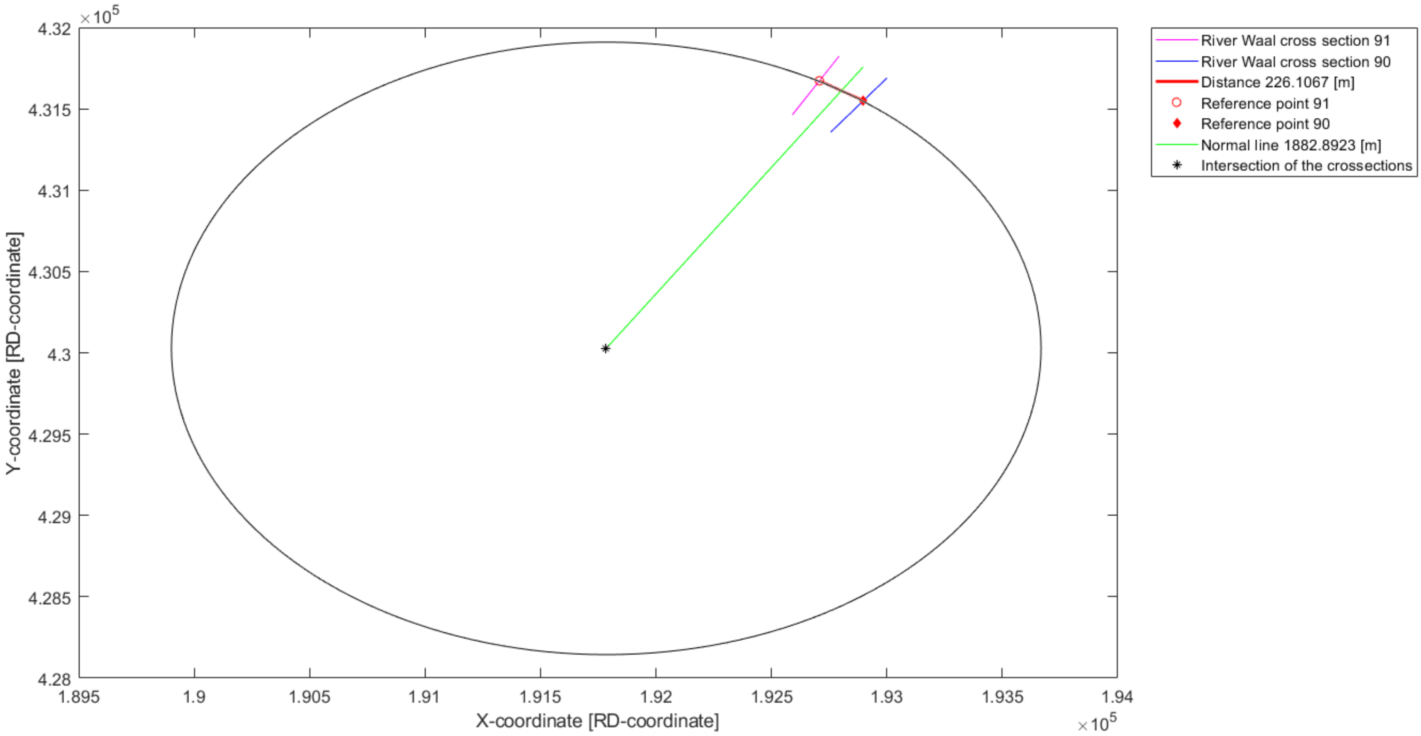

Figure 3.8: Determination of the curvature of the river Waal between two points.

3.2. Transport analysis

The fleet characteristics during extreme low discharges on the river Waal need to be determined to provide an answer to the third research sub-question. Therefore, IWT data was required and to analyse changes in the fleet, several years of data was required. So, firstly, the river Waal fleet characteristic were analysed. The river Waal fleet is part of the larger river Rhine fleet. Comparing historic fleet characteristics was not the focus of this study, however a global fleet analysis was performed. During the transport analysis the development of the river Rhine fleet was briefly analysed from the year 2000 to 2018 using the studies done by Kriedel et al. (2018) and Alewijn (2005). Even though, the total number of passages fluctuates yearly in these studies, it provides an indication of the river Waal passage numbers. The Rhine fleet was analysed from the year 2005 till 2017 by Kriedel et al. (2018). In which Kriedel et al. indicates a pronounced change in the IWT fleet characteristics between 2005 and 2010. Within the same period, the cargo volume increased while the number of IWT Rhine vessels decreased, indicating the shift from smaller inland vessels to larger vessels. Between 2016 and 2017 the number of IWT vessels stabilises again (Kriedel et al., 2018). IWT data from 2000 till 2005 was analysed by Alewijn (2005). Combining these studies the years, 2013 and 2015 were selected as the most recent years combining a representative IWT fleet composition with periods of extreme low discharge. Secondly, the source of the IWT data was determined. In the Netherlands there are two mayor IWT databases, which are managed by RWS. The first database collects IWT data at fixed measuring points, the Information and Tracking System for Inland Navigation (IVS90). There are over 2750 IVS90 measuring points in the Netherlands, collecting information about the vessel dimensions, the name, navigation route, travel time, draught and cargo specifics (Van der Burgt & Baronner, 2017). In March 2019 IVS90 was upgraded to IVS-Next, to integrate the wishes of the European and Dutch IWT sector. The second database collects Automatic Identification System (AIS) data using the Global Positioning System (GPS) of individual vessels (Van der Burgt & Baronner, 2017). Generally, AIS data is preferred, but also less easy to obtain due to privacy issues. AIS data is not restricted to specific measuring points, making it very accurate (Harati-Mokhtari et al., 2007). IWT data along the river Rhine can be obtained in both IVS90 and AIS data. AIS data for the year 2018 was not suitable for this research due to incompleteness of the data-set. Primarily, because the missing half of the data-set was the data during the low discharge period of 2018. So, IVS90 data was requested and obtained from the RWS WVL office for the years 2013, 2015 and 2018. IVS90 data has therefore been the primary source of IWT data in this research.

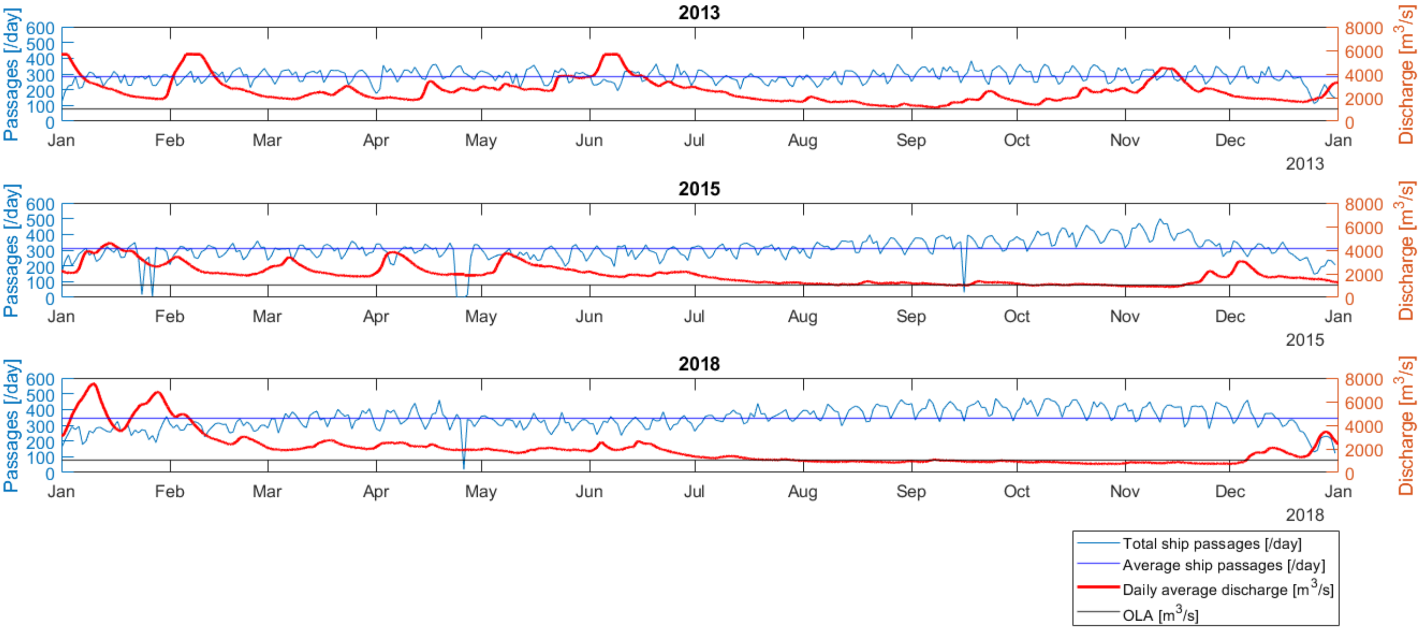

Figure 3.9: Daily averaged river discharge at Lobith and the yearly averaged number of passages per day, from IVS90 data of the years 2013, 2015 and 2018

The water depth in a river limits the navigational depth and therefore influences the fleet composition. The traffic regulations associated with extreme discharge conditions were taken into consideration during this research. For instance, when the ALR at Lobith drops below 8.5 m, pushed convoys are restricted in the number of barges they may transport. If large vessels are taken out of the service due to depth reduction, the cargo needs to be redistributed over vessels with a smaller transport capacity, causing more vessels using the fairway. This results in an increase in ship movements, which was clearly visible in the 2013, 2015 and 2018 IVS90 data and is illustrated in figure 3.9. The fleet composition during specific discharges and the total number of ship movements were analysed in detail. The analysed IWT fleet composition included both the RWS-classification and the CEMT-classification. The analysis of the IWT data resulted in a composition of the fleet which was most suited as input for the traffic simulation model at the determined river discharges of 1020, 800, 700 and 600 m^3/s.

Figure 3.9 indicates that the yearly average number of vessel movements per day increases between 2013 and 2018. In 2013 the yearly average number of vessel movements per day was 299.3, in 2015 it increased to 306.9 and reaches 342.8 in 2018. The average number of vessel movements per day increased with 2.5% between 2013-2015 and 11.7% between 2015-2018. Average fleet characteristic for the years 2013, 2015 and 2018 were compared in table 3.3 and 3.4. The compositions in 2013, 2015 and 2018 differ from each other in both percentage and in absolute value. The distribution between upstream and downstream travelling vessels, percentage wise remains the same for the years 2013 and 2015, but the absolute values deviate. Between 2013 and 2018 the number of vessels that were outside the RWS-classification system increased. The percentage, however, it remained around 5% of the yearly averaged number of passages per day. The change in the ratio loaded verses empty vessels, for all years, may be related to the increasing extremes in the discharge. However, the yearly average discharge in 2018 was higher than in 2015, but the extremes were lower in 2018. In 2015 the period of extreme low discharge was longer than in 2013, which may explain the increasing percentage of empty vessels in 2018 relative to 2015 and in 2015 relative to 2013. Combining the information provided by tables 3.3 and 3.4, it was concluded that IWT data from 2013 and 2015 had not the desired data ressemblances with the IWT data of 2018. So, the AIS data for the years 2013 and 2015 could not be a substitute for the lacking AIS data from 2018. Therefore, only a deeper investigation into the 2018 IVS90 data was required, to address the effect of extreme low discharge on the fleet composition. Hence, IVS90 data was used to addressing the third sub-question:

How does a low river discharge affect the inland waterway transport fleet characteristics?

Table 3.3: IVS90 block-data for the river Waal section between the Pannerdensche Kop and the Maas-Waal canal, for 2013-2015 and 2018 compared in yearly average values and percentages.

General characteristics			
IVS90 data	**2013**	**2015**	**2018**
Discharge [m^3/s]	2571.2	1918.5	1952.5
Number of passages	109230	112034	125121
Passages per day	299.3	306.9	342.8
Empty vessels	32%	34%	35%
Loaded vessels	68%	66%	65%
Travelling upstream	54%	54%	52%
Travelling downstream	46%	46%	48%

Table 3.4: IVS90 block-data for the river Waal section between the Pannerdensche Kop and the Maas-Waal canal, for 2013, 2015 and 2018 compared in daily average values and percentages.

Daily fleet composition						
IVS90 data	**2013**		**2015**		**2018**	
Push-tow units	15.1	5.06%	14.4	4.70%	12.4	3.63%
Coupled units	18.8	6.29%	22.9	7.48%	32.9	9.60%
M0	0.4	0.14%	0.6	0.18%	0.6	0.18%
M1	1.1	0.38%	1.0	0.32%	0.9	0.25%
M2	11.5	3.85%	10.8	3.52%	10.0	2.94%
M3	10.5	3.51%	9.5	3.08%	9.7	2.83%
M4	12.2	4.08%	10.5	3.41%	10.5	3.06%
M5	20.7	6.93%	18.9	6.17%	19.0	5.54%
M6	47.8	15.96%	44.4	14.49%	47.1	13.75%
M7	13.6	4.56%	12.5	4.09%	13.5	3.95%
M8	92.0	30.76%	98.1	31.96%	115.6	33.70%
M9	20.9	6.99%	26.0	8.46%	30.8	8.97%
M10	2.9	0.96%	3.1	1.00%	2.9	0.84%
M11	9.5	3.17%	9.6	3.14%	11.0	3.21%
M12	7.1	2.38%	9.7	3.15%	8.7	2.55%
Other	15.2	4.98%	14.9	4.85%	17.2	5.00%
Total	299.3	100%	306.9	100%	342.8	100%

Important to note is that IVS90 data is specified by the vessel's skipper and not always complete, nor correctly entered in the database (Rijkswaterstaat, Dienst Verkeer en Scheepvaart, 2009). Furthermore, IVS90 block-data is generated for the shortest possible route between the vessel's starting point and destination. The skipper, however, is not obligated to travel this route. However, the exact data coverage and correctness of IVS90 data is currently unknown. To account for the incompleteness of the 2018 IVS90 data, a data correction was performed during the analysis. The IVS90 data from 2018 counts the total number of ship movements between the Pannerdensche Kop and the Maas-Waal canal at 125,121. According to the Inland Shipping Analysis System (BIVAS) 2018 IVS data the total number of vessel movements for the Maas-Waal canal to the Pannerdensche Kop was measured at 109,812 based on transported volumes. Because BIVAS uses the transported volumes, the service vessels were filters out. The numbers suggested by Van Hal (2019) were 138,000 at Nijmegen, for the river Waal section from the German border to the Maas-Waal canal, and 132,000 for the section from Druten till the Amsterdam-Rhine canal. The found number of ship movements from the 2018 IVS90 data, namely 125,121 was assumed a correct representation of the fleet and further calculations were based on this data set.

Figure 3.10 shows the increasing number of coupled units as the discharges dropped below ALD, whereas the number of push-tow units decreased significantly. In November 2018 the daily number of push-tow units hardly reached above 5 but always stays below 10. The number of coupled units on the river Waal between the Pannerdensche Kop and the Maas-Waal canal, regularly exceeds 50 vessels per day. Comparing the numbers of push-tow and coupled units passing the river section per day from figure 3.10 with those of table 3.4, 50 instead of 12 coupled units and maximal 10 instead of 29 push-tow units used the river during extreme low discharge, which confirms the observations on the river Waal by Van t' Verlaat (2019a). These numbers also confirm a shift from the larger push-tow vessels to the smaller coupled vessels during periods of extreme low discharge.

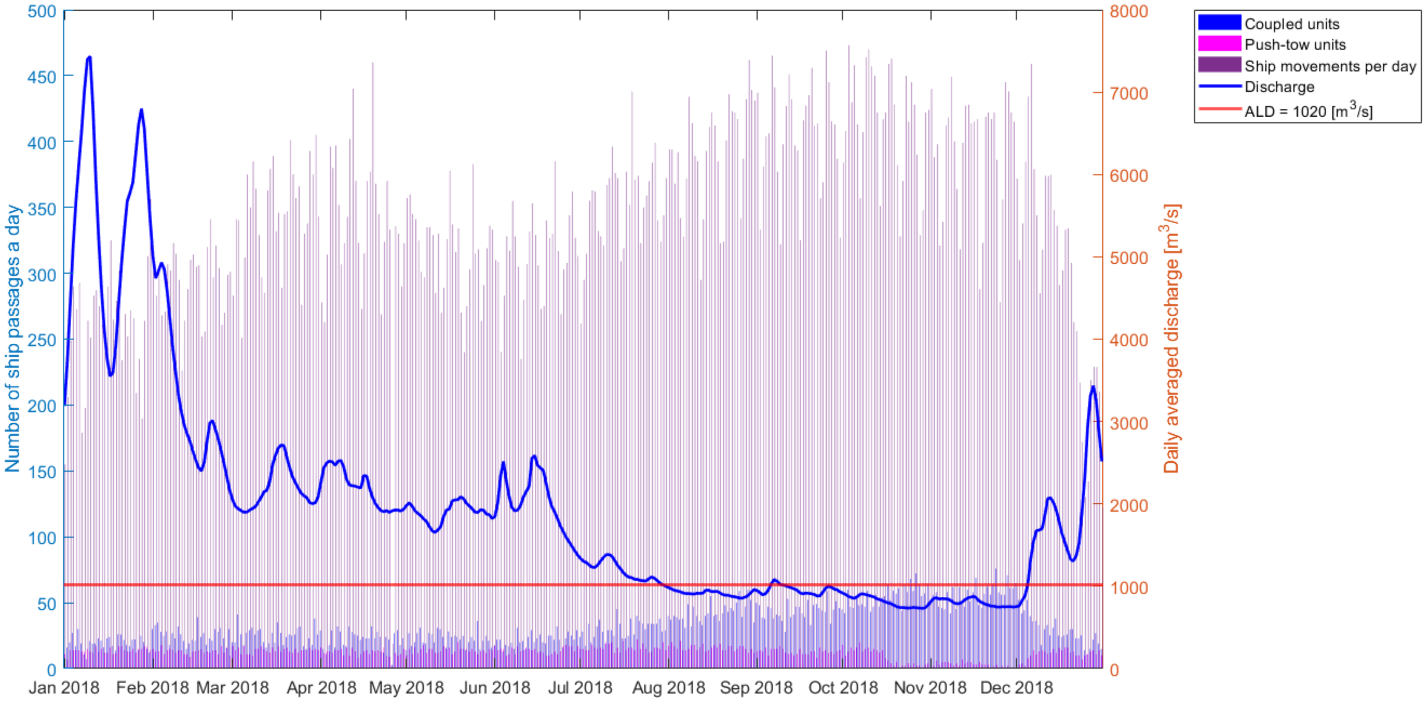

Figure 3.10: The daily averaged ship movements in 2018, distinguished in coupled units, push-tow units and the entire fleet.

Changes in the 2018 fleet composition during the extreme low discharges were analysed based on the measured, the weekly average and the daily average discharge. The lowest measured discharge in 2018 was 708.8 m^3/s at 24-Oct-2018 20:30, whereas the daily average minimal discharge was 731.5 m^3/s at 29-Oct-2018. The minimal weekly averaged discharge in 2018 was 739.6 m^3/s at 21-Oct-2018.

For an average discharge around 800 and 1020 m^3/s both the daily as the weekly average discharge were used. The daily average discharge reaches 801.2 m^3/s on 19-Nov-2018, and 799.6 m^3/s on 09-Nov-2018. A weekly average discharge of 797.9 m^3/s was measured at 14-Oct-2018, Whereas a weekly average discharge of 1020 m^3/s has not been measured at all. The weekly average discharge for 22-Jul-2018, however, was 1081.5 m^3/s, whereas for 09-Sep-2018 the discharge was 991.8 m^3/s. A daily average discharge of 1024.0 m^3/s has been measured at 09-Sep-2018. The daily averaged data from the weeks of 22-Jul, 09-Sep, 14-Oct and 21-Oct were selected and analysed in detail (see table 3.5) and represent discharges of 1020 (2x), 800, and 700 m^3/s.

Table 3.5: River Waal fleet composition between the Pannerdensche Kop and the Maas-Waal canal, during extreme low discharges in 2018.

IVS90 data	**2018 Total**		**22-Jul-2018**		**09-Sep-2018**		**14-Oct-2018**		**21-Oct-2018**	
Weekly average discharge	1969.9		1081.5		991.8		797.9		739.6	
Total passages	125121		2525		2820		2922		2826	
Average passages per day	342.8		360.7		402.9		417.4		403.7	
Weekly general characteristics										
Empty	834	34.7%	891	35.3%	990	35.1%	1095	37.5%	1040	36.8%
Loaded	1565	65.3%	1634	64.7%	1830	64.9%	1827	62.5%	1786	63.2%
East	1240	51.7%	1284	50.9%	1467	52.0%	1430	48.9%	1429	50.6%
West	1159	48.3%	1241	49.1%	1353	48.0%	1492	51.1%	1397	49.4%
Daily fleet composition										
Push-tow units	12.4	3.6%	15.2	4.2%	12.6	3.1%	7.3	1.8%	2.4	0.6%
Coupled units	32.9	9.6%	33.7	9.4%	40.6	10.1%	55.4	13.3%	60.9	15.1%
M0	0.6	0.2%	0.7	0.2%	1.0	0.2%	0.4	0.1%	0.3	0.1%
M1	0.9	0.3%	1.6	0.4%	1.0	0.2%	1.0	0.2%	1.0	0.2%
M2	10.0	2.9%	10.0	2.8%	11.4	2.8%	10.1	2.4%	9.1	2.3%
M3	9.7	2.8%	8.7	2.4%	9.0	2.2%	10.3	2.5%	9.6	2.4%
M4	10.5	3.1%	8.1	2.3%	11.0	2.7%	12.3	3.0%	9.3	2.3%
M5	19.0	5.5%	24.3	6.7%	20.9	5.2%	20.0	4.8%	18.3	4.5%
M6	47.1	13.7%	53.7	14.9%	54.4	13.5%	52.3	12.5%	46.4	11.5%
M7	13.5	4.0%	12.4	3.4%	14.0	3.5%	17.6	4.2%	18.1	4.5%
M8	115.6	33.7%	116.3	32.2%	142.9	35.5%	139.3	33.4%	138.9	34.4%
M9	30.8	9.0%	31.4	8.7%	38.1	9.5%	44.0	10.6%	46.7	11.6%
M10	2.9	0.8%	3.7	1.0%	3.9	1.0%	3.1	0.7%	2.7	0.7%
M11	11.0	3.2%	11.7	3.3%	12.0	3.0%	14.1	3.3%	16.3	4.0%
M12	8.7	2.6%	10.9	3.0%	12.1	3.0%	10.9	2.6%	9.4	2.3%
Other	17.2	5.0%	18.3	5.1%	18.0	4.5%	19.3	4.6%	14.3	3.5%
Total	342.8	100%	360.7	100%	402.9	100%	417.4	100%	403.7	100%

For the representation of the 2018 IWT traffic flow, the time dependent distribution of the number of passages was analysed. First, the data was checked for a day and night rhythm. Figure 3.11 illustrates the distribution of the daily intensity for the weekly averaged fleets, in percentages. The figure shows the general distribution of a day and night rhythm. There is a traffic peak in the early morning and a gradual decrease during the night. Second, all RWS-classes were analysed for the hourly traffic intensity during 22-Jul, 09-Sep, 14-Oct and 21-Oct. These numbers were based on the weekly average number of vessel movements per RWS-class. The distribution was highly variable between RWS-classes, as the M3 and M6 classes show in figure 3.12. In appendix C tables contain the detailed traffic intensity for the weeks 22-Jul, 09-Sep, 14-Oct and 21-Oct.

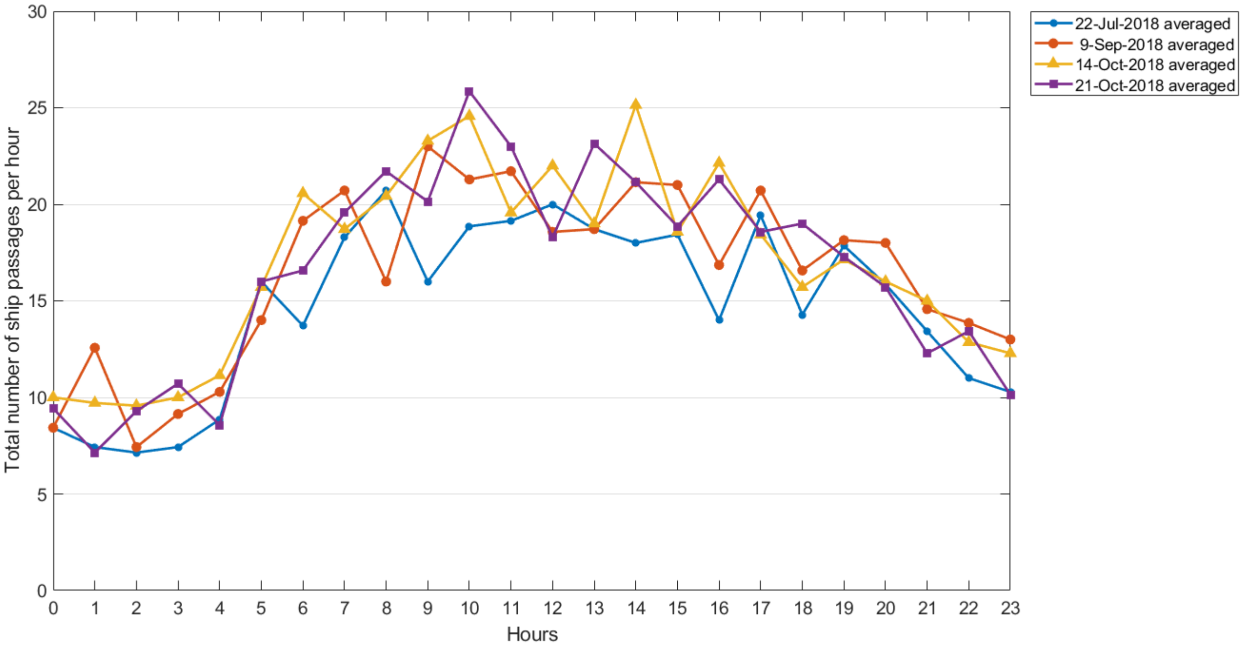

Figure 3.11: The average daily traffic intensity for the four selected weeks of extreme low discharge.

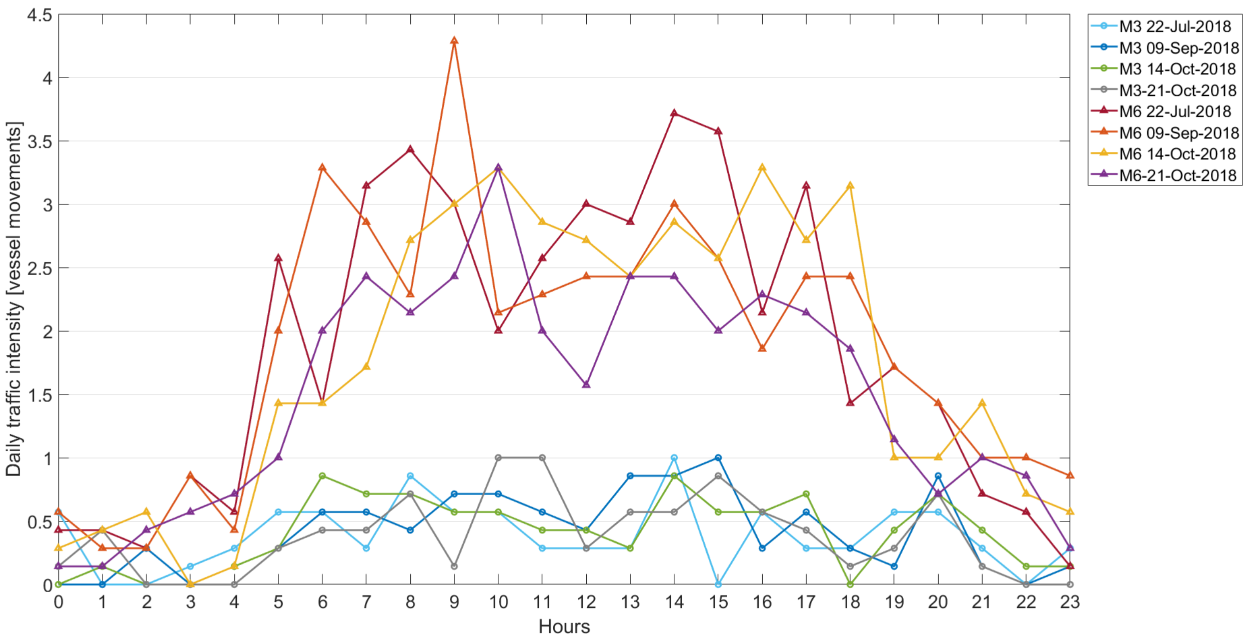

Figure 3.12: The hourly intensity in number of vessel movements for the RWS-classes M3 and M6.

3.3. Economical effects and transported cargo

The drought of 2018 had economical consequences for the IWT sector. Though the costs were high in 2018, the IWT revenues in the third quarter of 2018 were higher than in the same period in 2017 (Van Hussen et al., 2019). During the drought of 2018 the transport prices for inland vessel's increased with 30%, whereas the transportable cargo per shipment reduced to 25-30% of the vessel's cargo design capacity (Van Hussen et al., 2019). The increase in revenues can be explained as a result of the increased utilization of the IWT fleet capacity and contractual price agreements per trip but less cargo and therefore higher freight rates (Van Hussen et al., 2019). During extreme low discharges the transportable cargo per shipment reduces, reducing the total transported cargo per day. The decrease in total daily transported cargo in 2018 is illustrated in figure 3.13.

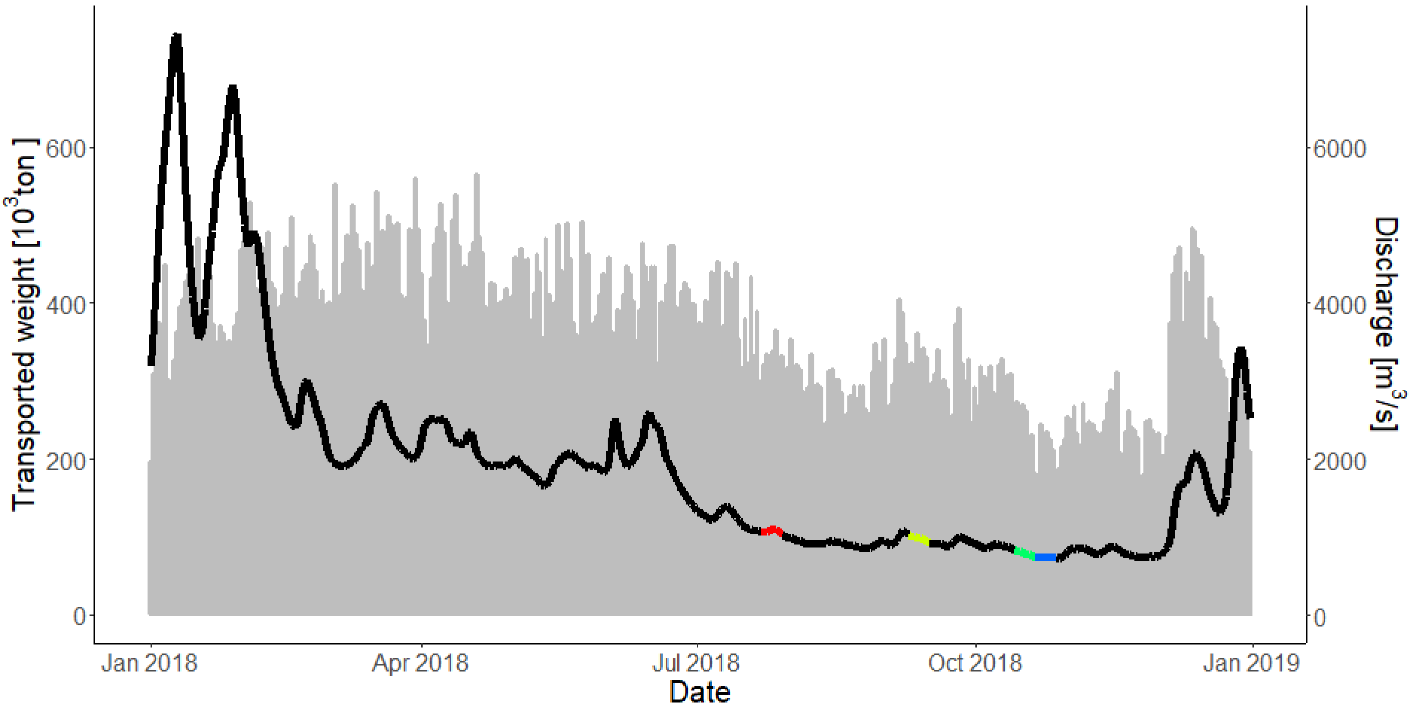

Figure 3.13: The relationship between the daily total transported weight and the discharge, obtained from 2018 IVS90 data. Highlighted are the weeks of 22-Jul-2018 (red), 09-Sept-2018 (yellow), 14-Oct-2018 (green) and 21-Oct-2018 (blue).

Figure 3.14 illustrates the relationship between the total daily transported cargo in 10^3 ton and the discharge below 1200 m^3/s. The R-square value of the relationship was only 0.661, but a decreasing trend in the total daily transported cargo and the discharge is clearly noticeable. The formula of the daily transported cargo volume = -84.65 + 0.41* the daily averaged discharge.

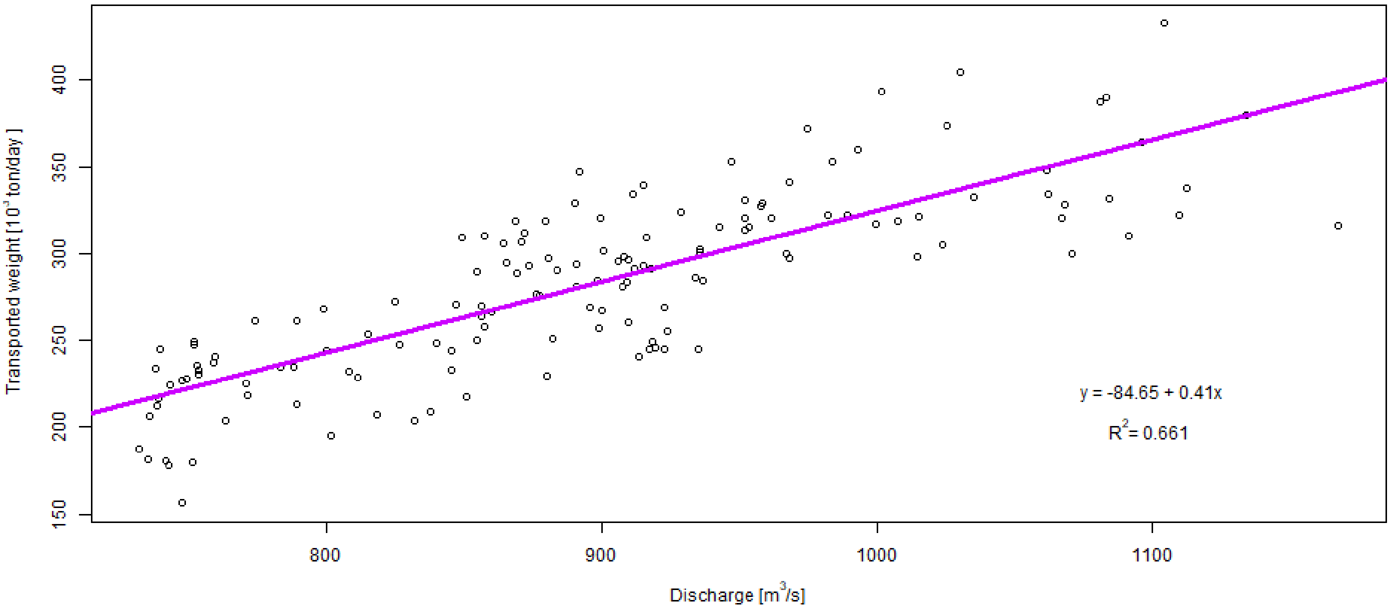

Figure 3.14: The relationship between the daily total transported weight and the discharge below 1200 m^3/s, obtained from 2018 IVS90 data.

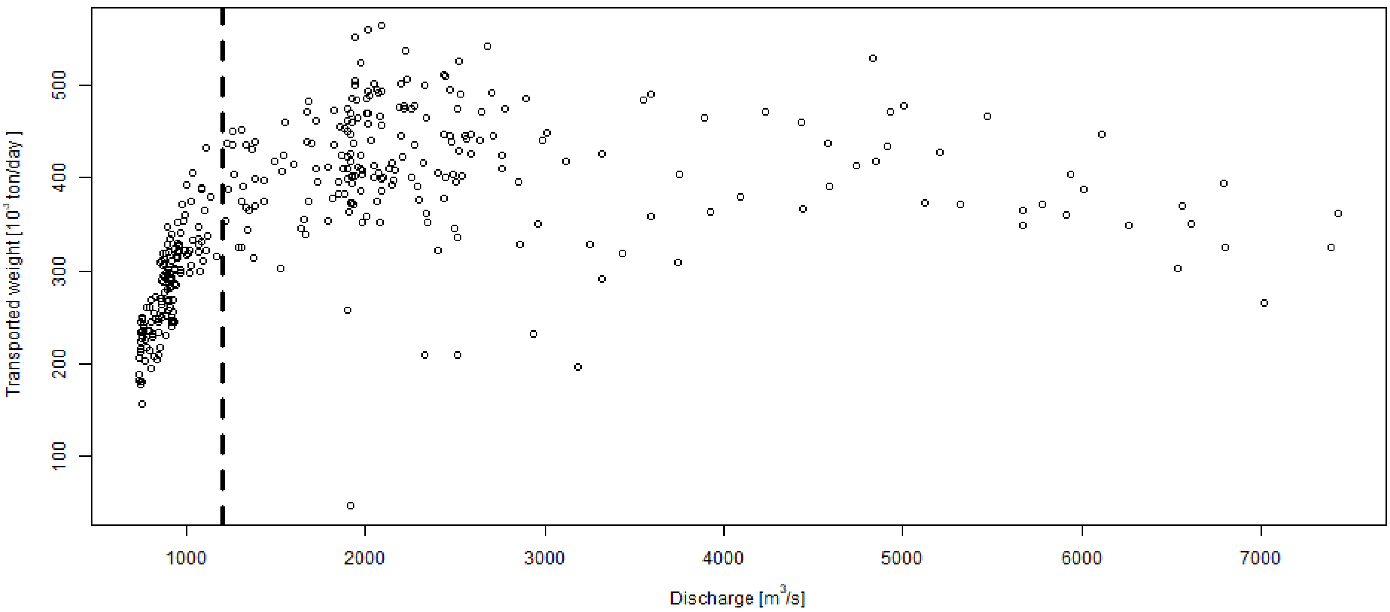

Figure 3.15: The relationship between the daily total transported weight and the discharge below and above 1200 m^3/s, obtained for 2018 IVS90 data.

The transportable cargo per shipment must remain between the 20% to 50% to remain economically viable (Van Hussen et al., 2019). The economical minimum transported cargo percentage is depending on the vessel type and transported cargo. For this reason BIVAS uses a minimum loading percentage of 33%. Figures 3.18, 3.16 and 3.17 illustrate the relationship between the transported cargo and the discharge. The colours represent data points from the weeks of 22-Jul-2018 (red), 09-Sept-2018 (yellow), 14-Oct-2018 (green) and 21-Oct-2018 (blue). With decreasing discharge the transported volume expressed in tonnage for the M8 type vessel decreases, figure 3.18. Figure 3.16 and 3.17 show the relationships between the discharge and the fraction loaded cargo for a M6 and M7 type vessel.

A statistical analysis was performed on the loaded percent unit per RWS-class vessel and the discharge associated with this loaded percent unit. The regression analysis was performed on the IVS90 data, which was coupled with the discharge data and filtered for discharges below 1200 m^3/s. A criterion of minimum 40 observations was added, to filter out the RWS-classes with to little data-points to make a reliable regression. The fraction loaded cargo represents the transported cargo volume as a fraction of the loading capacity of the vessel.

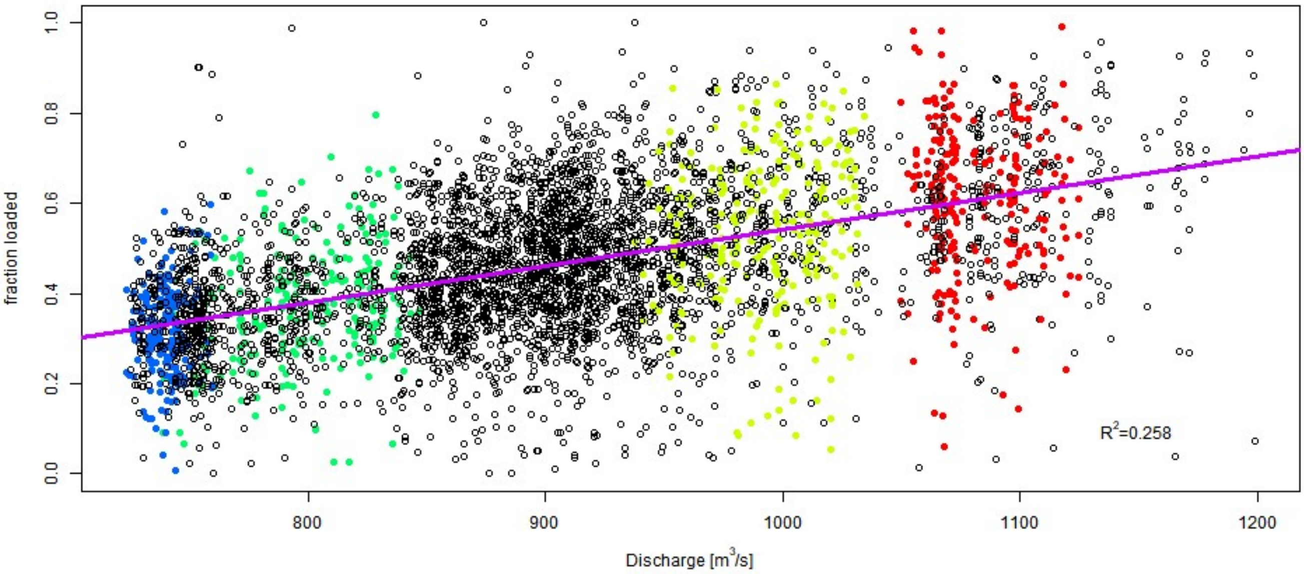

Figure 3.16: Relationship between the M6 type vessel's fraction loaded cargo and the river discharge.

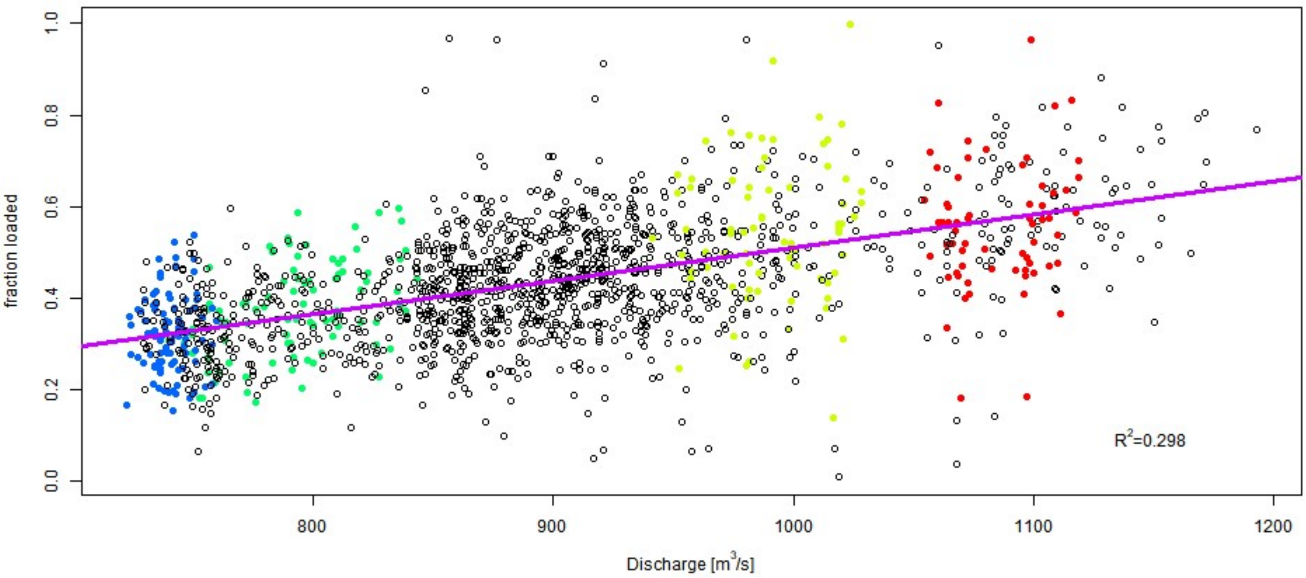

Figure 3.17: Relationship between the M7 type vessel's fraction loaded cargo and the river discharge.

The loaded percent represents the transported cargo volume as a percentage of the loading capacity of the vessel. In general, with the decrease of one discharge unit (1 m^3/s) the loaded percent unit (0-100%) of the vessel classes decreases with 0.05 to 0.1. Almost all motorised vessels had a significant relationship between the discharge and the loaded percent unit.

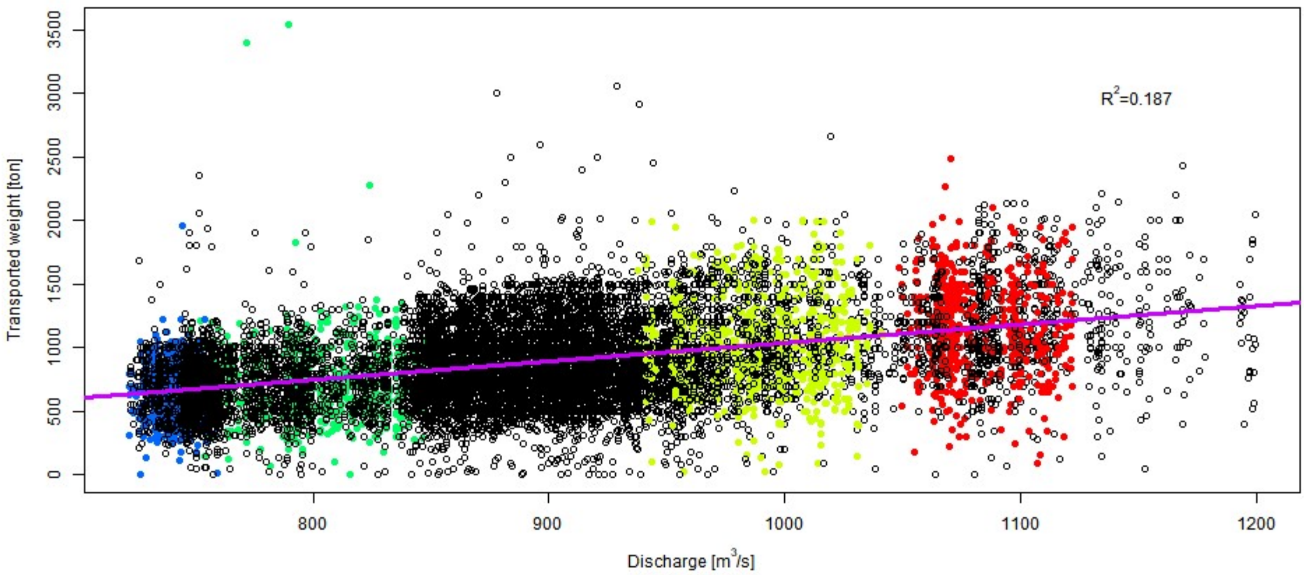

Figure 3.18: Relationship between the M8 type vessel's transported weight and the river discharge.

The RWS-class vessel's relationships of the vessel draught, transport volume and the amount of loaded vessels versus empty vessels, with the discharge, has been illustrated in figure 3.19. The Fraction loaded cargo, transported volume and vessel draught were related to the discharge as variables. A regression analyses was performed and the relationship was expressed as the R-square of the regression. The stronger the relationship of a variable with the discharge the higher the R-square value. The strongest relationships were found for the vessel draught of the push-tow units (BII-2L, BII-4 and BIIL-1), with more than 40 observations for river discharges below 1200 m^3/s. For the two barge long coupled units (C2L) the relationship between the number of loaded verses empty vessels and the discharge is relative strong. Also, the M1 type vessels seemed to have a relatively strong relationship with the discharge. However, there were only a hand full of M1 type passages observed per analysed week, making the result of the regression less reliable. The M4, M5, M6 and M7 type vessel's had a medium relationship between the vessel's draught and the discharge. The M4, M5, M6 and M7 type vessel's had all well over 50 observations per analysed week, making their relationship more solid than the M1 type vessel due to the abundance of data during extreme low discharges.

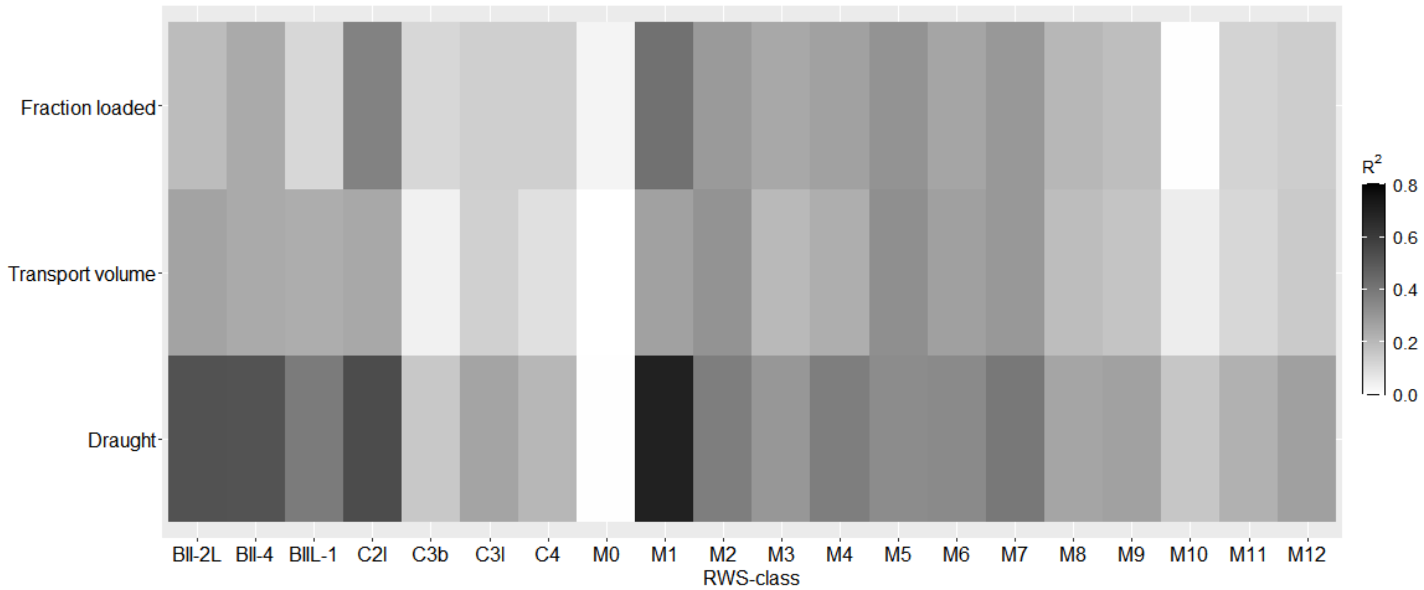

Figure 3.19: Heatmap visualising the relationship between the vessel draught, the fraction of loaded versus empty vessels and the transported volume, as a function of the discharge.

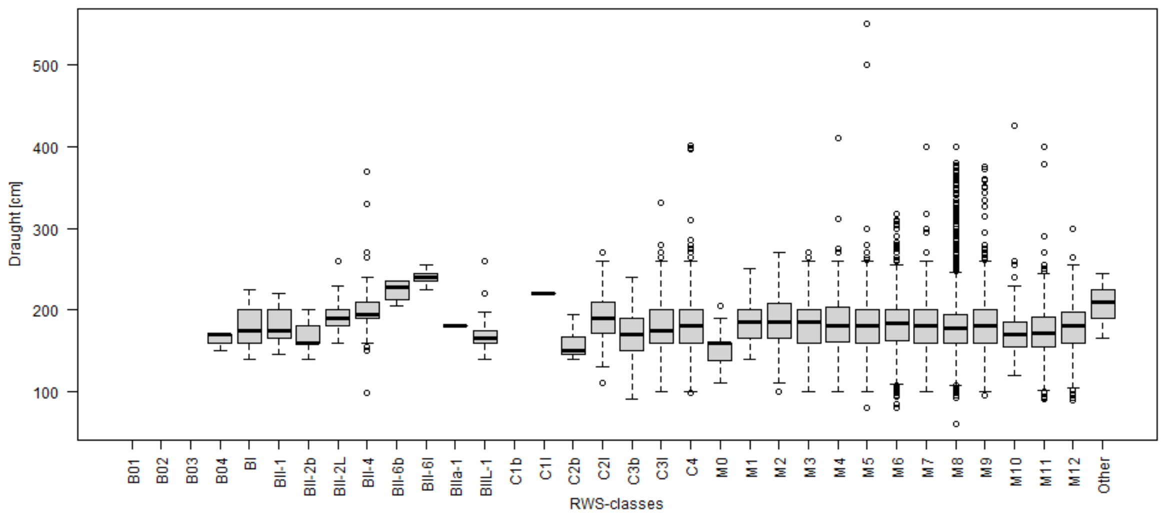

Figure 3.20: Boxplot of the loaded draught for a discharge below 1200 m^3/s per RWS-class.

Figure 3.20 shows the loaded vessel draught per RWS-class vessel for discharges below 1200 ,m^3/s. The vessel draught was investigated more thoroughly for the four weeks of drought, resulting in the average loaded draught per RWS-class per week, see table 3.6. The average loaded draught of the weeks of 22-Jul-2018 and 09-Sep-2018 were just above 2.0 m, but the other two weeks had average draught far below 2.0 m. This is consistent with the fact that for the discharge of 1020 m^3/s the cross-sectional profiles of the analysed river section had a river depth of 2.8 m at all cross-sections.

Table 3.6: Average loaded draught per RWS-class vessel and week.

RWS-class	22-Jul-2018 [cm]	09-Sep-2018 [cm]	14-Oct-2018 [cm]	21-Oct-2018 [cm]
BII-2b	-	-	165	-
BII-2L	213	208	180	164
BII-4	224	214	173	-
BIIL-1	188	172	162	151
C2L	238	213	178	159
C3b	191	191	161	159
C3L	206	196	162	155
C4	210	205	169	161
M0	-	160	-	-
M1	206	185	168	150
M2	214	202	172	152
M3	206	207	169	153
M4	211	206	168	153
M5	211	202	162	152
M6	214	200	167	156
M7	211	204	164	152
M8	207	196	163	153
M9	214	202	169	157
M10	187	187	158	153
M11	202	190	162	150
M12	205	195	159	155

Note: For the RWS-classes B01, B02, B03, B04, BII-1, BII-6b, BII-6l, BIIa-1, C1b, C1l and C2b no draught data was determined because there where less than 2 observations, which was considered unreliable.

3.4. Conclusions

The river discharges selected for further investigation with the traffic simulation model are 1020, 800, 700 and 600 m^3/s. The river section between the Pannerdensche Kop and the Maas Waal canal was selected as the river section with the most valuable contribution to this research. The selected river section contains several observed bottleneck locations during periods of extreme low discharge and numerous of the river Waal bends. The inland waterway transport fleet was affected by the low discharge in the river Waal on several aspects. When the discharge decreases the available river depth reduces, resulting in a reduced vessel draught. To compensate for the loss of transport volume, the number of shipments increases, increasing the daily intensity. The increased number of shipments is followed by a change in the general fleet composition. Therefore, the fleet composition changes for decreasing discharges. One of the most pronounced changes occurs for the number of passages by push-tow units and coupled units.

Figure 3.10, illustrates the response of the coupled units and the push-tow units to extreme low discharges. Extra trips were made by the coupled units, whereas the push-tow units were mostly taken out of service. Though the total number of vessels in the fairway increases with decreasing discharge, the total transported cargo per day reduces with decreasing discharge. For discharges below 1200 m^3/s the relationship between discharge and total transported cargo per day is strong, see figures 3.14 and 3.15. The decreasing loaded draught of the vessels for decreasing discharge explains a decrease of the total transported cargo per day. However, the intensity during extreme low discharge increases between the analysed weeks of 22-July and 09-September but remains more or less stable around 400 passages a day afterwards. Between 14-October and 21-October the average number of passages reduced, while the discharge reduced. The IWT fleet capacity is assumed to be limited during the week of 21-October, as the number of passages reduces while the discharge reduces. This limitation was probably caused by the extreme low average discharge of 739.6 m^3/s, because the maximum intensity in 2018 was 473 passages and the intensity during the week of 21-October was far below the maximum intensity. Therefore, it was concluded that as the number of passages reduced for a discharge below 800 m^3/s the traffic capacity at this discharge was reached.

From the river width analysis the average navigable width at a discharge of 1020 m^3/s was 200 m. Figure 3.6 illustrates the relation between the discharge and the minimum, maximum and average widths at a river depth of 2.0 m. During the discharge of 1020 m^3/s the maximum navigable width was 242 m, whereas the minimum width was almost 100 m less at 145 m. The minimum fairway width reduced from 145 m at a discharge of 1020 m^3/s to 89 m for a 900 m^3/s discharge and decreased even further to only 28 m for a discharges of 800 m^3/s and lower. The location of the minimum river width was in the river bend near Nijmegen. The river bend near Nijmegen was also indicated in figure 3.2 as one of the bottleneck locations in 2085 with limited river depths. Therefore, river Waal vessels may not only face limited river depths in the river bend near Nijmegen during extreme low discharge conditions but also very restricted navigable river widths.

Combining the navigable river width analysis for a river depth of 2.0 m, table 3.2 and figures 3.6 & 3.7, with the vessel draught analyses in table 3.6, the river depth of 2.0 m was very accurate for the weeks of 14-Oct-2018 and 21-Oct-2018 but less so for the weeks of 22-Jul-2018 and 09-Sept-2018. The analysed vessels of the coupled units and the push-tow units during the weeks of 22-Jul-2018 and 09-Sept-2018, had an average draught exceeding the 2.0 m. The maximum average RWS-class vessel loaded draught in the week of 22-Jul-2018 was the coupled unite C2l type vessel with a draught of 238 cm. Whereas, the maximum average RWS-class vessel loaded draught in the week of 09-Sep-2018 was 214 cm for the push-tow unit BII-4 vessel. For the other weeks all vessel classes remained below the average loaded draught of 2.0 m. However, the navigable width at a river depth of 2.0 m was assumed to represent the fairway well during the analysed weeks of the 2018 drought.

4 SIMDAS sensitivity analyses

The SIMDAS model requires some initial testing to gain sufficient model confidence. The model's sensitivity to changes in the hydraulic parameters is especially important because SIMDAS simplifies the river hydraulic characteristics. The sensitivity analysis is part of the operational model validation techniques (Leal et al., 2011). The next paragraph discusses the basic model settings, followed by the sensitivity analyses per topic.

In SIMDAS, fluctuations in traffic intensity can be represented with periods of 24 time intervals. With a time interval of 1 hour, a day and night rhythm can be simulated. Larger time intervals can be used to simulated traffic over a longer time period, but therewith the resolution of the daily fluctuations is reduced. For this research, the daily fluctuations were important and the time interval was set at 1 hour. The simulations in SIMDAS always start with an empty fairway, which does not correspond to reality. To represent reality better, it is common practice to start the traffic analysis one period later than the model simulation (De Boer & Bilinska, 2016). As a result the total simulation represents 192 hours, 8 periods, whereas the traffic analysis represents 168 hours, 7 periods.

In SIMDAS, traffic (the arrival times of the vessels) is generated by a probabilistic model. The arrival times in SIMDAS can be based on a uniform distribution or on a exponential distribution, both distributions uses the traffic intensity (the number of vessels) per hour as an input parameter (Waterloopkundig laboratorium, 1994). Afterwards a statistical test is used to check if the generated traffic is in line with the specified input regarding the fleet composition. For the statistical test a reliability parameter p is used. For SIMDAS the advised distribution type is a uniform distribution with a p value of 0.05 and a step size of 1 second (Hobo, 2019). The reliability of a simulated fleet with a p value of 0.05 is 95%. Due to the statistical model element in SIMDAS, the model output always represents the specified fleet with the specified reliability and when the model input remains unchanged the variations between model runs is very small.

The SIMDAS fleet is categorised in three categories; push-tow units, coupled-units and motorised vessels. The RWS-class vessels that were categorised as coupled-units are the C1b, C1L, C2b, C2L, C3b, C3L and C4 type vessels. The push-tow unit category includes the RWS-classes B01 till B04, BI and the RWS-classes BII till BII-6L. The motorised vessels category includes vessels from the RWS-classes M0 till M12.

4.1. River width sensitivity

The river Waal is characterised as a multi-lane river, corresponding to more than one vessel travelling in one direction using the fairway. The traffic simulation model SIMDAS, however, only recognises one lane for upstream traffic and one lane for downstream traffic as input parameters. The fairway input parameters also contain a reference line, connecting the upstream and the downstream side of the fairway. In SIMDAS the vessels using the fairway are initially positioned at a certain side and distance from the reference line but crossing the reference lane is allowed. In practise vessels use the entire fairway width if no other traffic is present, therewith the representation in SIMDAS is assumed to be accurate. However, the effect of the river width on the traffic handling in SIMDAS was investigated. From literature an advised width for the river Waal river bends was not available. The calculation of the required river width in bends is explained in the waterway guidelines ”Richtlijnen Vaarwegen” (Koedijk, 2020), resulting in the equations 4.1, 4.2 and 4.3.

Equation 4.1 is used to select the normal fairway type, which is the common fairway type for rivers (Koedijk, 2020). The six barge long push-tow unit vessel (RWS-class BII-6L) was used as the design vessel for upstream passage and the six barge wide push-tow unit vessel (RWS-class BII-6b) was used for downstream passage. These vessel types are the design vessels using the fairway in that direction. The length (L) of the BII-6L RWS-class is 270 m and the width (W) is 22.8 m, whereas the length and width of the BII-6b RWS-class are 195 m and 34.2 m. With equation 4.1 the radius (R) for the normal fairway type was calculated as 1620 m. Ships need more manoeuvring space in large river bends, therefore an extra addition for river bends was added. The bend addition was calculated based on upstream and downstream vessels using equation 4.2 as 11.2 + 14.1 = 25.3 m. Because the six barge pus-tow units account for less than 5% of the total transport, large drift factors due to wind for upstream vessel was determined at 0 m. For downstream vessels the wind factor was determined as 0.05*L = 9.8 m. Because the river Waal is an intensively used river with more than 125,000 passages in 2018 and an average transported volume of 3033 ton per ship in 2018 an intensity factor was added. An extrapolation of table 4.1 results in 85.5 m as an intensity factor. Finally, one more factor of 0.2*B was added due to large currents in rivers, resulting in 0.2*22.8 + 0.2*34.2 = 11.4 m.

$$\text{Normal bend radius} : R = 6 * L = 6 * 270 = 1620m \tag{4.1}$$

$$\begin{aligned}\text{Bend factor, upstream travelling} &= 0.25 * \frac{L^2}{R} = 0.25 * \frac{270^2}{1620} = 11.2m \\ \text{Bend factor, downstream travelling} &= 0.6 * \frac{L^2}{R} = 0.6 * \frac{195^2}{1620} = 14.1m\end{aligned} \tag{4.2}$$

Table 4.1: Fairway width addition due to intensive use in both passage numbers and average transport volumes (Koedijk, 2020)

Passages	average transport volume [ton]						
per year	1950	2150	2350	2550	2750	2950	3150
30,000	0	0	3	9	18	29	44
60,000	16	16	19	25	34	45	59
90,000	32	32	35	41	49	61	75
120,000	48	48	51	57	65	77	91
150,000	64	64	67	73	81	93	107

$$\text{Normal advised width} : 2 * 22.8 + 2 * 34.2m + 25.3 + 9.8m + 85.5m + 11.4m = 246m \tag{4.3}$$

The calculated advised river width of 246 m relates to an intensity profile of the river that incorporates high intensity traffic and room for vessels to overtake (multi-lane traffic) and additional width for sailing bends. To study the sensitivity of the SIMDAS results for the river width five different scenario’s were simulated:

- A fairway width of 150 m, which is the fairway maintenance width for the straight sections of the river Waal as agreed by the CCNR (Sloff et al., 2014).
- A fairway width of 170 m as advised by Ten Hove & Bilinska (2017) for straight river sections.
- A fairway width of 196 m, which is the advised fairway width for straight sections of the river Waal in line with the waterway guidelines (Koedijk, 2020), but based on 138,000 passages and an average transported volume of 2350 ton per ship.

- A fairway width of 246 m, which is the advised fairway width for sections of the river Waal with bends in line with the waterway guidelines (Koedijk, 2020), but based on more than 125,000 passages in 2018 and an average transported volume of 3033 ton per ship.
- The calculated river width of equation 4.3 enlarged with 10% and rounded of to even numbers resulting in a river width of 272 m.

For all the sensitivity simulations in SIMDAS the reference line was set in the middle of the river. The enlarged advised fairway width of 272 m was set as the reference profile for all sensitivity analyses except for the width sensitivity analyses. This was done to reduce width induced effects during the other sensitivity analyses. The depth was set at 5.50 m to avoid depth induced problems.

Table 4.2 summarises the simulation results for a reducing fairway width, all other parameters were kept constant over the simulations. When the river width reduces to 170 m, the delay time increases tremendously, indicating that congestions start to occur, without changing the traffic intensity. The increase in aborted ship manoeuvres and interactions, with reducing channel width, also indicate the forming of congestion. The increase in delay time for a decreasing fairway width was summarised in table 4.3. The increase in delay time for the motorised vessels was dominant for almost all reduced river width simulations. The motorised vessels were also the largest vessel group, explaining there large impact.

Figure 4.1 till 4.5 illustrate the traffic flow during the simulations. The river width reduces, limiting the navigable space of the vessels and forcing them to compact or slow down in the sharp bends. The figures also show that in SIMDAS vessels use the totally available width. The delay time per passages is calculated as the delay time per passages going upstream + the delay time per passages going downstream.

Table 4.2: The effect of a change in the river width on the traffic flow, determined per travel direction.

Fairway width	272 m	246 m	196 m	170 m	150 m
Total number of passages simulated	2846	2846	2846	2846	2846
Intensity [passages/day]	407	407	407	407	407
7 day total delay time [min]	848.6	980.3	1555.7	2359.3	3877.1
Total delay time coupled units [min]	79.9	84.3	100.6	138.4	263.8
Total delay time push-tow units [min]	28.2	35.6	43.5	68.2	86.8
Total delay time motorised vessels [min]	740.4	860.4	1411.6	2152.6	3526.5
Delay time per passage [sec]	35.8	41.4	65.6	97.8	163.5
Total number of encounters	78172	78232	78389	78629	79155
Total number of overtakes	6528	6488	6373	6215	5994
Aborted manoeuvres	133	166	343	675	1161
Total number of safety margin interactions	3895	4236	5309	6479	7707
Penetration of the safety margin of a vessel in percentage of the total number of interactions	4.6%	5.0%	6.3%	7.6%	9.1%
Ships reducing speed while passing	3.3%	3.6%	4.5%	5.6%	7.7%

Table 4.3: The increase in delay time relative to the wide river system.

Fairway width	246 m	196 m	170 m	150 m
Coupled units	6%	26%	73%	230%
Push-tow units	26%	54%	142%	208%
Motorised vessels	16%	91%	191%	376%
All categories	16%	83%	178%	357%

An acceptable maximum value for the traffic fluency parameter, ships reducing speed while passing, was set at 8% based on previous SIMDAS studies (Ten Hove & Bilinska, 2017). The safety parameter concerning the penetration of the safety margin of a vessel, increases as the river width reduces but also has a limit value of 8%. Considering the above, the 150 m width simulation approaches both the acceptable speed reducing limit and the safety limit. Using these limit values the rivers traffic capacity is almost reached at a 170 m wide fairway. In the 272 m river width simulation, for every simulated hour 23 ships had trouble adjusting there speed or position on time to remain within the safety margins. In the 150 m width simulation, this number increases up to 46 vessels per hour. These results are in line with what could be expected when a wide river is narrowed. The advised river width for straight sections of the Waal was 170 m (ten Hove, 2017) and this was the river width for which the simulated river bends reaches its limit capacity limit in terms of safety and fluency. Therefore, a significant impact of a further reduction of the river width to 150 m was expected. Therewith, it is concluded that the simulation model represents the impact of a narrow river, well.

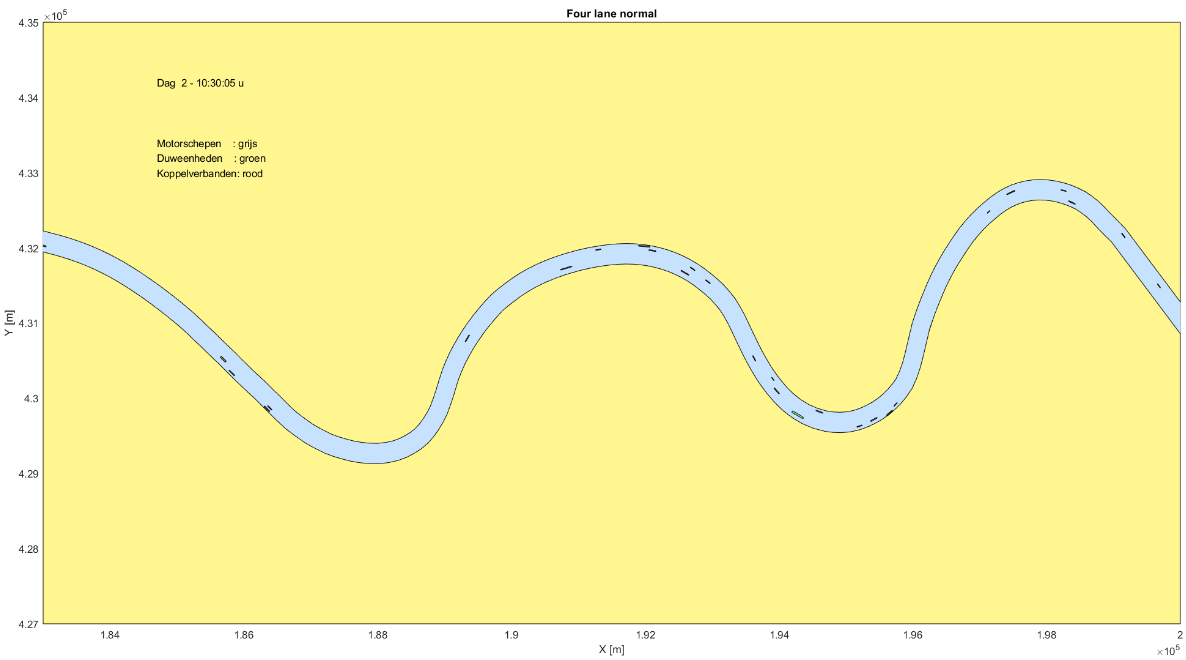

Figure 4.1: Time stamp (day 2 - 10.30) of the traffic simulation in a river with homogeneous cross-sectional dimensions. The width is 272 m and the depth is 5.50 m. The simulated intensity is the 09-Sep-2018 intensity profile.

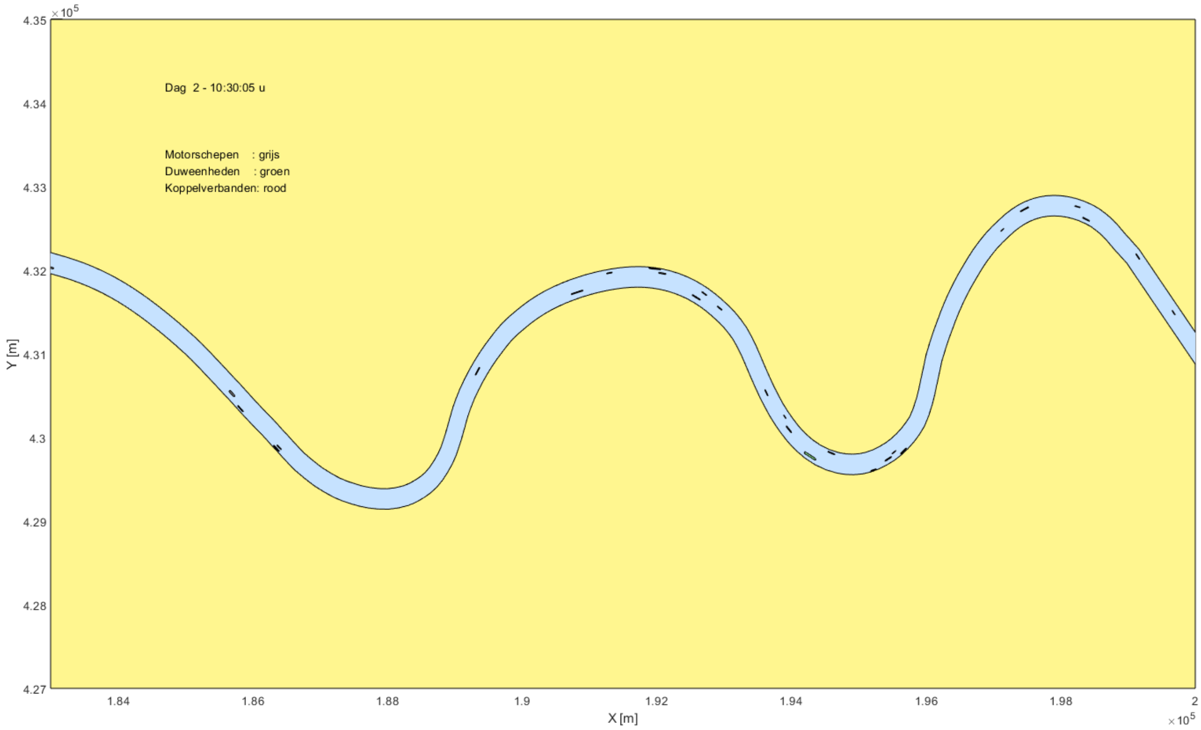

Figure 4.2: Time stamp (day 2 - 10.30) of the traffic simulation in a river with homogeneous cross-sectional dimensions. The width is 246 m and the depth is 5.50 m. The simulated intensity is the 09-Sep-2018 intensity profile.

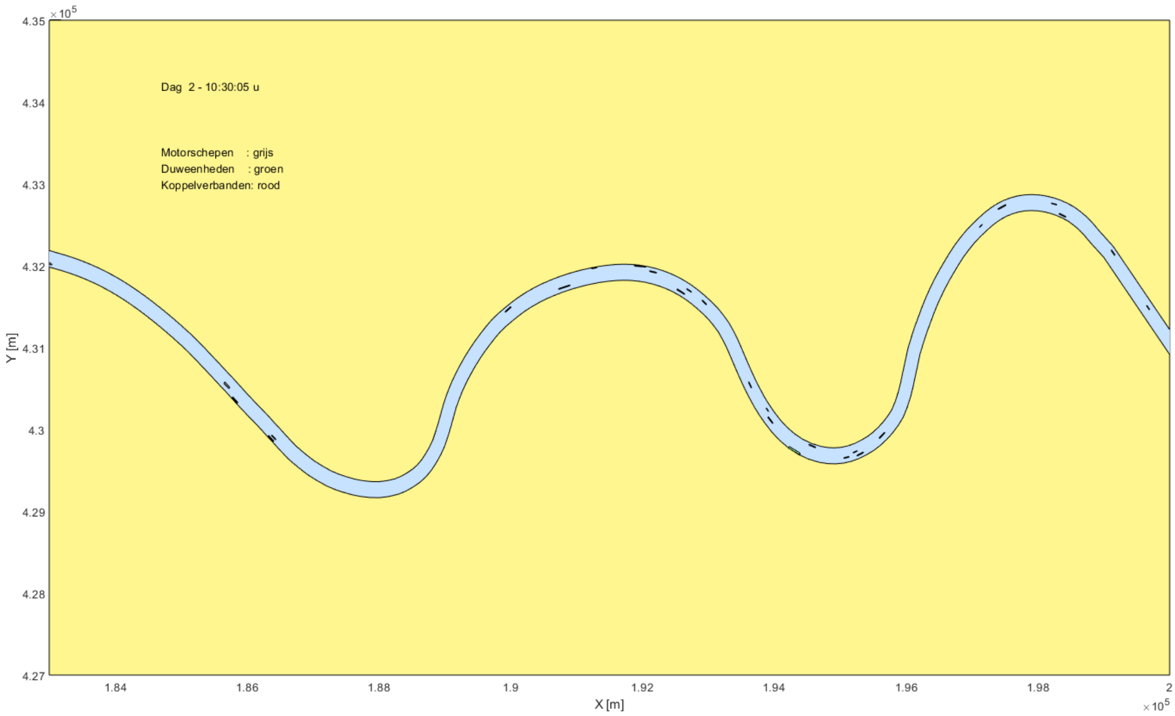

Figure 4.3: Time stamp (day 2 - 10.30) of the traffic simulation in a river with homogeneous cross-sectional dimensions. The width is 196 m and the depth is 5.50 m. The simulated intensity is the 09-Sep-2018 intensity profile.

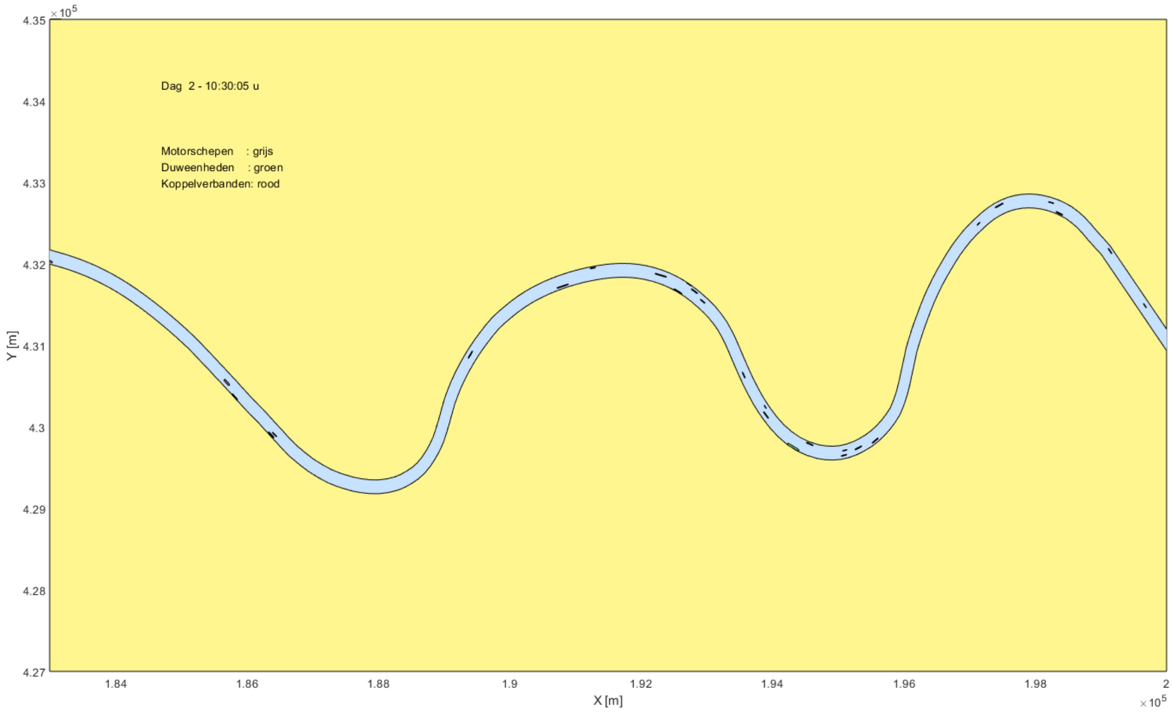

Figure 4.4: Time stamp (day 2 - 10.30) of the traffic simulation in a river with homogeneous cross-sectional dimensions. The width is 170 m and the depth is 5.50 m. The simulated intensity is the 09-Sep-2018 intensity profile.

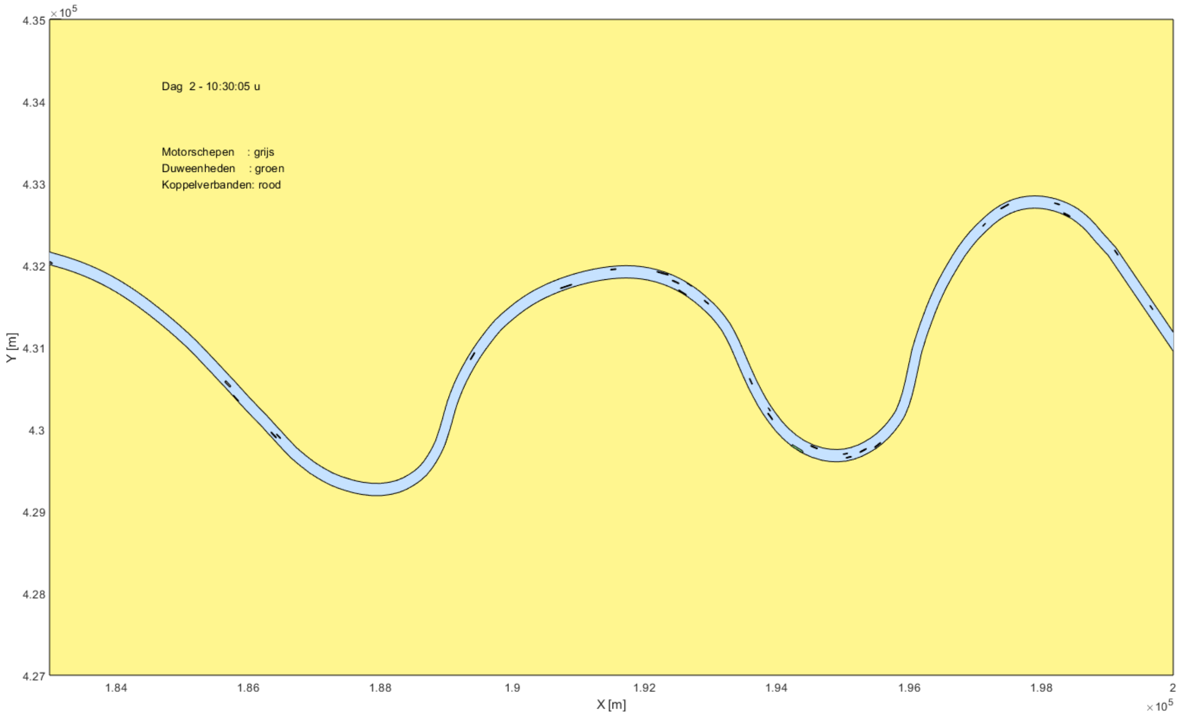

Figure 4.5: Time stamp (day 2 - 10.30) of the traffic simulation in a river with homogeneous cross-sectional dimensions. The width is 150 m and the depth is 5.50 m. The simulated intensity is the 09-Sep-2018 intensity profile.

4.2. Traffic intensity sensitivity

The number of vessel movements in the data set that was not characterised as a RWS-class vessel was around 5%. This number was considered a first step in the increased intensity simulations. The maximum number of passages in one day in 2018 was 473. When adding the assumed lack of data-coverage of about 20%, the total maximum daily number of passages is 568. Comparing the maximum value of 568 to the reference scenario used, the increase in vessel movements is around 40%. Therefore, an increase in vessel movements up to 45% was considered as an absolute maximum on the river Waal. Table 4.4 summarises the simulation results, showing an increasing number of encounters and overtakes. The delay times for all categories increases significantly but the delay time per passages remains below 1 min. From table 4.5 it can be concluded that significant impact of the intensity on the delay time is present for an increase of 30% and higher. The traffic safety remains within considerable limits, only the percentages of ships that need to slow down increases. The first hindering due to the excessive number of vessels on the 272 m wide fairway, starts at an intensity above the 500 passages per day. This was higher than expected, however, the river was modeled wider than the calculated river width of the bending parts of the river Waal, which could explain this high threshold value.

Table 4.4: The effect of a change in the number of vessel movements on the traffic flow. The 272 m river system was used as a reference system.

Parameters	Reference	+5%	+15%	+30%	+45%
Total number of passages simulated	2846	2863	3114	3535	3927
Intensity [passages/day]	407	409	445	505	561
7 day total delay time [min]	848.6	864.0	1122.7	1596.2	1952.7
Total delay time coupled units [min]	79.9	99.1	103.7	170.0	173.6
Total delay time push-tow units [min]	28.2	43.4	34.6	73.2	62.5
Total delay time motorised vessels [min]	740.4	721.5	984.4	1353.0	1716.5
Delay time per passage [sec]	35.8	36.4	43.3	54.2	54.6
Total number of encounters	78172	79828	93527	120989	149246
Total number of overtakes	6528	6690	7940	10143	12434
Aborted manoeuvres	133	134	164	213	239
Total number of safety margin interactions	3895	3957	4709	6070	7467
Penetration of the safety margin of a vessel in percentage of the total number of interactions	4.6%	4.6%	4.6%	4.6%	4.6%
Ships reducing speed while passing	3.3%	3.5%	4.2%	5.0%	5.3%

Table 4.5: The increase in delay time due to an increase in vessel movements relative to the intensity of 09-Sep-2018 in a 272 m wide river system.

Parameters	+5%	+15%	+30%	+45%
Coupled units	24%	30%	113%	117%
Push-tow units	54%	23%	159%	122%
Motorised vessels	-3%	33%	83%	132%
All categories	2%	32%	88%	130%

4.3. Draught sensitivity

To obtain a high degree of confidence in the simulation results, comparisons of the model behaviour for several parameters and simulation conditions were required (Sargent et al., 2016). A sensitivity analysis can also be called an analysis of parameter variability, and represents the effect of a change in the input on the model results (Sargent, 1979). The model parameters should represent the real systems relationships. Due to model spin-up, the schematised waterway is supplemented with a additional 2 km waterway at both ends of the schematization (Ten Hove & Bilinska, 2017 and Sargent et al., 2016). Sensitive parameters should cause significant changes in the model's behaviour. The opposite should happen to robust parameters. The parameters that were tested were the influence of a change in the maximum loaded draught of the vessels, the loaded verse empty vessel fraction, the vessel positioning and the contact range of the ships radio.

Table 4.6: Traffic simulation model sensitivity to changes in the maximum loaded draught of the vessels.

Parameters	Reference scenario	Max. draught 3.1 m	Max. draught 2.8 m	Max. draught 2.5 m	Max. draught 2.2 m
Total number of passages simulated	2846	2846	2846	2846	2846
Intensity [passages/day]	407	407	407	407	407
7 day total delay time [min]	848.6	859.4	832.9	844.2	862.5
Total delay time coupled units [min]	79.9	78.5	78.7	78.4	78.1
Total delay time push-tow units [min]	28.2	29.1	28.0	28.1	27.8
Total delay time motorised vessels [min]	740.4	751.7	726.2	737.7	755.9
Delay time per passage [sec]	35.8	36.2	35.1	35.6	36.4
Total number of encounters	78172	78173	78170	78175	78189
Total number of overtakes	6528	6520	6538	6538	6533
Aborted manoeuvres	133	121	129	129	131
Total number of safety margin interactions	3895	3867	3828	3837	3758
Penetration of the safety margin of a vessel in percentage of the total number of interactions	4.6%	4.6%	4.5%	4.5%	4.4%
Ships reducing speed while passing	3.3%	3.2%	3.3%	3.4%	3.4%

From table 4.6 it was concluded that reducing the maximum draught of the loaded vessels had a minor effect on the model results. That reducing the maximum draught of the vessel would not majorly impact the model results was expected. The vessels in SIMDAS are assigned a maximum and minimum vessel speed. The impact of the draught of the vessel's speed is therefore limited. However the effect was even smaller than expected.

4.4. Sensitivity for the factor loaded vessels

Table 4.7: Traffic simulation model sensitivity to changes in the fraction of loaded vessels.

Parameters	Reference scenario	Loaded fraction 0	Loaded fraction 0.5	Loaded fraction 1
Total number of passages simulated	2846	2824	2843	2845
Intensity [passages/day]	407	403	406	406
7 day total delay time [min]	848.6	587.1	845.1	1138.5
Total delay time coupled units [min]	79.9	22.4	67.4	112.6
Total delay time push-tow units [min]	28.2	18.8	31.0	82.7
Total delay time motorised vessels [min]	740.4	545.9	746.7	943.2
Delay time per passage [sec]	35.8	25.0	35.6	47.9
Total number of encounters	78172	71430	76645	81948
Total number of overtakes	6528	6058	6815	5953
Aborted manoeuvres	133	110	125	127
Total number of safety margin interactions	3895	3684	3904	3946
Penetration of the safety margin of a vessel in percentage of the total number of interactions	4.6%	4.8%	4.7%	4.5%
Ships reducing speed while passing	3.3%	2.4%	3.2%	4.1%

Table 4.7 shows that for a higher loaded vessel fraction the number of aborted manoeuvres hardly changes. Especially, because also the interactions per passage hardly changes. Only the percentage of vessels that needed to reduce speed during their passage increased from 2.4% for only empty vessels to 4.1% for only loaded vessels. As expected the fraction of loaded verses empty vessels had a large effect on the delay time, because loaded vessel's travel slower. From table 4.7 it was concluded that the model correctly represented the effect of an increase in the fraction of loaded verses empty vessels and the impact on the total delay time.

4.5. Sensitivity for the factor radio range

In order to examine the effect of the radio range of a vessel on the traffic flow, the standard range was compared to an increase and an decrease in the radio range, in table 4.8. Increasing the range of the ships radio, has no effect on the model results. Reducing the ships radio range increases the number of manoeuvres and the number of vessel interactions per passages. The vessel interactions increase from 5% in the reference scenario to 7% when the radio ranges was set at 1,000 m instead of 10,000 m. Therefore, the standard radio range was assumed to be the optimal radio range and maintained for all other simulations.

Table 4.8: Traffic simulation model sensitivity to changes in the radio range. In the reference scenario the radio range was 10,000 m.

Parameters	Reference scenario	Radio range 100,000 m	Radio range 1,000 m
Total number of passages simulated	2846	2846	2848
Intensity [passages/day]	407	407	407
7 day total delay time [min]	848.6	848.6	843.6
Total delay time coupled units [min]	79.9	79.9	78.7
Total delay time push-tow units [min]	28.2	28.2	29.1
Total delay time motorised vessels [min]	740.4	740.4	735.8
Delay time per passage [sec]	35.8	35.8	35.5
Total number of encounters	78172	78172	78172
Total number of overtakes	6528	6528	6500
Aborted manoeuvres	133	133	323
Total number of safety margin interactions	3895	3895	5566
Penetration of the safety margin of a vessel in percentage of the total number of interactions	4.6%	4.6%	6.6%
Ships reducing speed while passing	3.3%	3.3%	3.7%

4.6. Initial vessel position sensitivity

The last parameter that was checked on sensitivity was the initial position of a vessel in the fairway and the model results were summarised in table 4.9. By changing the initial vessel position relative to the reference line to a large fraction, the number of aborted manoeuvres reduces as well as the number of vessel interactions. The total number of penetrations of the safety margins increased with 43%. However, the delay time of the motorised vessels increases with 35% and the total number of penetrations of the safety margins reduced with 13%. Reducing the position fraction had the opposite effect and improved the travel delay time by 1%. It was concluded that SIMDAS represents the effects of changing the initial vessel position well, because putting vessels more in the middle of the fairway will result in more manoeuvres and interactions between vessels. But, positioning vessels more to the riverbanks will make the distance to overcome, while overtaking an other vessel, larger. Vessels can not move towards the riverbank to allow other vessels to overtake more easy. However, the trade-off between safety and delay times was not beneficial in either of the corrections, and the standard vessel positioning of 0.65 will be maintained for all other simulations.

Table 4.9: Traffic simulation model sensitivity to changes in the ships initial position. The initial position of a vessel was determined as a fraction of the distance from the riverside to the reference line. The reference scenario had a position factor of 0.65 of the width.

Parameters	Reference scenario	Position 0.5 width	Position 0.85 width
Total number of passages simulated	2846	2848	2845
Intensity [passages/day]	407	407	407
7 day total delay time [min]	848.6	843.6	1146.8
Total delay time coupled units [min]	79.9	78.7	54.7
Total delay time push-tow units [min]	28.2	29.1	14.4
Total delay time motorised vessels [min]	740.4	735.8	1077.7
Delay time per passage [sec]	35.8	35.5	48.4
Total number of encounters	78172	78285	78160
Total number of overtakes	6528	6500	6492
Aborted manoeuvres	133	323	10
Total number of safety margin interactions	3895	5566	3380
Penetration of the safety margin of a vessel in percentage of the total number of interactions	4.6%	6.6%	4.0 %
Ships reducing speed while passing	3.3%	3.7%	4.3%

4.7. Conclusion

With the parameter sensitivity analyses the model response of SIMDAS was examined. The models response to the increased intensity was less strong than expected, but this could be explained by the large river width that was used, compared to the advised width of 170 m by Ten Hove & Bilinska (2017). Also, the models sensitivity to vessel draught was less than expected. Although, some effects were noticeable, the effect was relatively small. Maybe a larger effect could have been achieved with smaller loaded draughts and larger step sizes, but a maximum loaded draught of 2.2 m was considered a good representation of the average draught during a discharge of 1020 m^3/s.

The model response to changes in the loaded fraction and the initial vessel position was strong for certain parameters. The effect of the radio range was mostly present in certain parameters, which was unexpected. Changes in the radio range led to small changes in the delay time, the number of overtakes and the percentage of ships reducing speed while passing. But, the effect on the number of aborted manoeuvres was large as well as the number and percentage of safety margin penetrations. A short radio range does not change the models overtaking decision behaviour but it does impact the number of times an overtaking manoeuvre has to be aborted, which was unexpected. However, the model responded to the change in parameters with reasonable results and the required model confidence was obtained. SIMDAS can be used with confidence in the output results.

5 Traffic simulations

To answer the remaining sub-questions a scenario analysis approach was used. The simulations were grouped in themes with multiple scenarios, focussing on one aspect of IWT. The three themes that were focused on were the representation of the 2018 drought, the simulation of an increased intensity and the simulation of a reduced river width with constant number of passages. The base scenario's were build upon one week of extreme low discharge values in 2018 and the associated fleet characteristics. The scenarios with decreasing navigable width and the scenarios with increasing intensities were based upon the Base 2 scenario. Table 5.1 summarises the three themes and the scenario's within these themes. The river profiles in table 5.1 were based on the river dimensions during a certain river discharge. The highly irregular river profiles were named P followed by the river discharge associated with the profile dimensions. The river profiles based on the navigable width at a river depth of 2.0 m (see table 3.2) were named W followed by the associated river discharge. All simulations were carried out with the same simulation duration of 8 periods of 24 time steps, but the results were based on 7 periods. At the beginning of a simulation SIMDAS starts with an empty fairway, which is not representing reality. Therefore, a spin-up time of 1 period was used to make the simulation results more in line with reality.

AIS data is preferred as it contains in general a larger data coverage than IVS90 data does. To compensate for the lacking data coverage additional fleet simulations were carried out to estimate the effect of a general increase in ship movements. A comparison between data coverage of AIS and IVS90 data of the same year, has not been carried out recently. Therefore the exact IVS90 data coverage was unknown during this research, however the data coverage of the IVS90 data is assumed to be around 80% based on expert experience at MARIN and RWS (personal communication).

Table 5.1: The simulation parameters summarised per simulation theme, scenario, average discharge associated with the week of the transport data, the first day of that week and the river profiles.

General theme	**Scenario description**	**Average discharge** [m^3/s]	**IWT data, first day of the week** [date]	**Average number of passages** [/day]	**River profile**
Simulation of four weeks in 2018 representing phases of the 2018 drought	Base 1	1081.5	22-Jul-2018	342	P1020
	Base 2	991.8	09-Sep-2018	385	P1020
	Base 3	797.9	14-Oct-2018	398	P800
	Base 4	739.6	21-Oct-2018	389	P700
Simulation of increased intensity on a river profile around ALD	Base 2 + 5%	991.8	09-Sep-2018 + 5%	404	P1020
	Base 2 + 15%	991.8	09-Sep-2018 + 15%	443	P1020
	Base 2 + 30%	991.8	09-Sep-2018 + 30%	501	P1020
Simulation of reduced discharge and river width but maintaining the number of passages	Base 2 - 1020 m^3/s	1020	09-Sep-2018	385	W1020
	Base 2 - 900 m^3/s	900	09-Sep-2018	385	W900
	Base 2 - 800 m^3/s	800	09-Sep-2018	385	W800
	Base 2 - 700 m^3/s	700	09-Sep-2018	385	W700

Note: The average number of passages is without the number of non RWS-class movements. The river profiles were categorised based on the discharge associated with the river profile. The river profiles starting with a P, uses the highly irregular river dimensions whereas the W profiles uses the river profiles based on a navigable river width at a river depth of 2.0 m.

5.1. Simulating the 2018 drought.

The simulations of the scenarios representing the four weeks of extreme low discharges were used to investigate whether the observed congestions in the river Waal in 2018, could be recognised and simulated with SIMDAS. Table 5.2 summarises the simulation results of Base 1 to 4. As expected the total delay time increases from scenario Base 1 till Base 4. The traffic safety remains within the 8% boundary value, for all scenarios. The delay time per passage increases to over 1 minute for the Base 4 scenario.

The average daily intensity used for the Base 2 scenario was 385 passages per day, which is entered in SIMDAS as a hourly intensity per RWS-class. SIMDAS uses a statistical module to simulated the fleet. With values rounded of on three decimals for the hourly intensity, the intensity of the SIMDAS simulations deviates slightly from the daily average intensity. From the four simulated weeks two simulations had a relative large difference between the input intensity and the simulated intensity in SIMDAS. Due to the rounding off in the input intensity and the statistical module of SIMDAS, the intensity of the Base 2 simulation was 22 passages per day higher than the input intensity, whereas the simulated intensity of the Base 3 scenario was 13 passages per day lower than the input intensity.

Table 5.2: Base scenario simulation results per direction. The discharge from the associated river profiles was used to indicate the river profile per simulation.

Discharge [m^3/ s]	1081.5	991.8	797.9	739.6
River profile	P1020	P1020	P800	P700
Intensity [passages/day]	342	385	398	389
Parameters	**Base 1**	**Base 2**	**Base 3**	**Base 4**
Total number of passages simulated	2408	2846	2700	2723
Intensity [passages/day]	344	407	386	389
7 day total delay time [min]	510.2	679.9	709.1	1736.6
Total delay time coupled units [min]	38.0	75.6	77.0	252.2
Total delay time push-tow units [min]	20.7	19.8	3.3	42.8
Total delay time motorised vessels [min]	451.6	584.5	628.8	1441.6
Delay time per passage [sec]	25.4	28.6	31.8	76.8
Total number of encounters	56946	77716	70408	73385
Total number of overtakes	4748	6547	6073	6491
Aborted manoeuvres	67	93	33	51
Total number of safety margin interactions	3305	4388	3181	3521
Penetration of the safety margin of a vessel in percentage of the total number of interactions	5.4%	5.2%	4.1%	4.4%
Ships reducing speed while passing	2.2%	2.4%	2.7%	3.3%

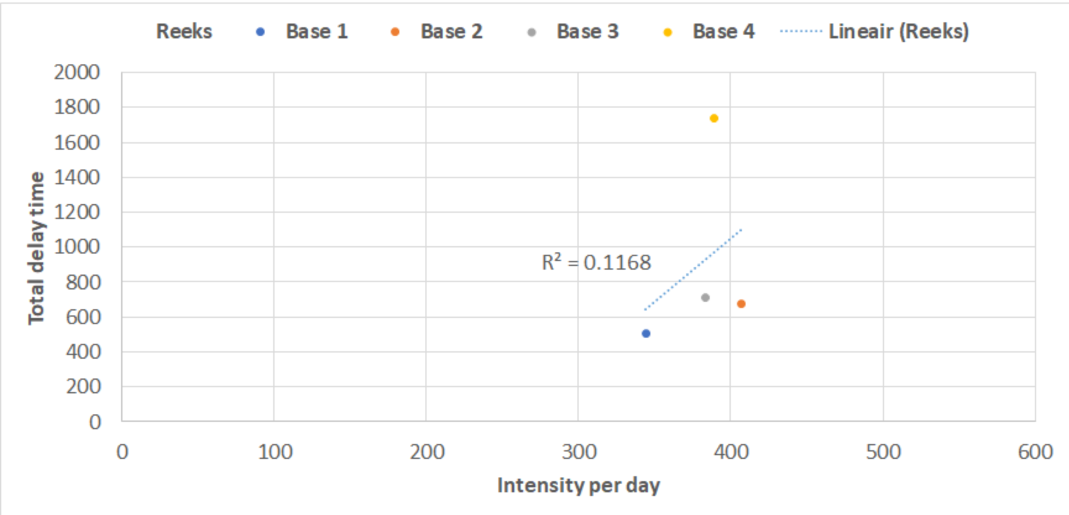

Figure 5.1: The relationship between delay times in minutes and the simulated intensity per day, for the Base scenario's.

Figure 5.1 shows that a direct relationship between the simulated intensity and the total delay time can not be found. The Base 4 scenario delay time strongly deviates from the other data points. Figure 5.2 shows the penetration of the safety margins, but a direct relationship could not be found. For R-square values below 0.8 the correlation between the parameters is considered low.

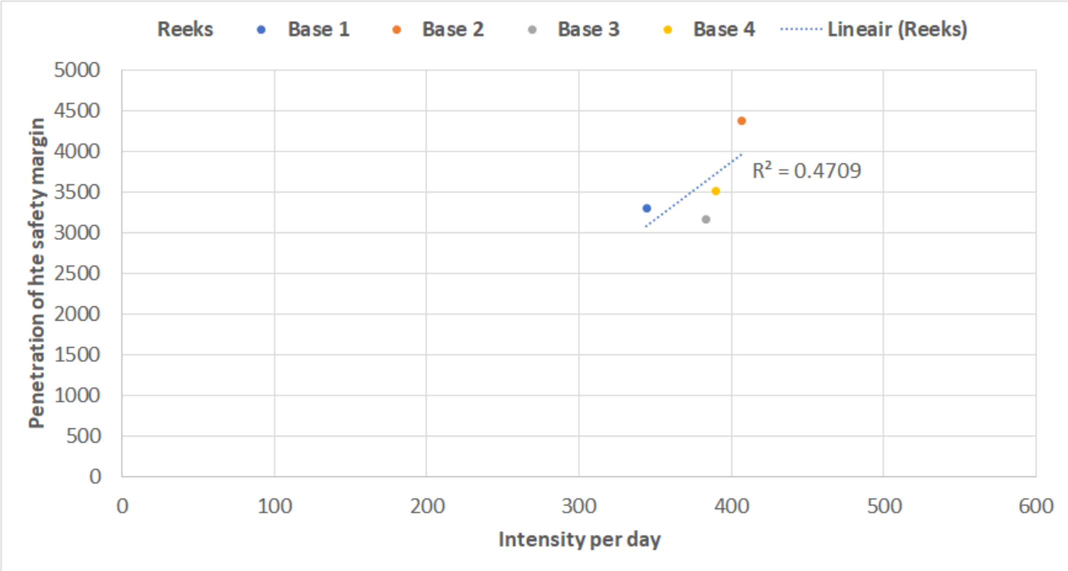

Figure 5.2: The relationship between the number of penetrations of the safety margins and the intensity per day, for the Base scenario's.

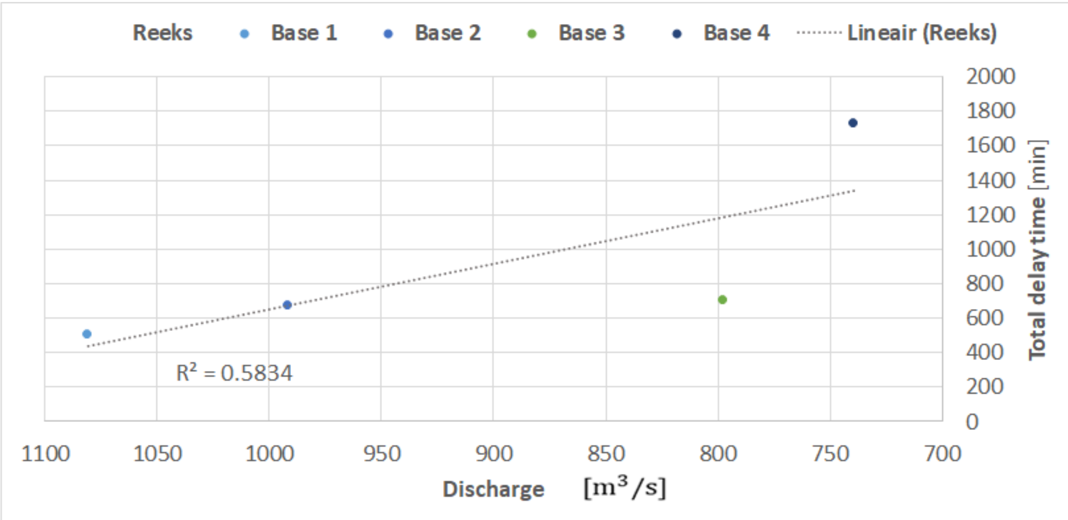

Figure 5.3: The relationship between the discharge of the simulated Base scenarios and the delay time. The Base scenarios represent four weeks of extreme drought in 2018.

Figure 5.3 shows the increase in delay time but could not directly be related to the increase in discharge. The correlation between the parameters is too week. However, the response of the delay time to the decrease in discharge is stronger than that of the delay time to the increased intensity. Clearly, figure 5.3 shows the strong increase in delay time for discharges below 800 m^3/s. The simulations correctly represent the effect of increased intensity and reduced navigability during the four weeks of extreme drought in 2018.

5.2. Simulations with increased intensity.

The simulation of the scenarios representing an increasing intensity on an constant river profile, were used to investigate the impact of increased intensity on the traffic flow and safety. Table 5.3 summarises the simulation results of increased intensity when all other parameters remained unaltered. The river profile of the Base 2 scenario was used to build these scenario simulations. Also, the traffic intensity of the Base 2 scenario was used, but altered by increasing the intensity per vessel, per hour with a percentage. The Base 2 +5% scenario was based on increasing the intensity so that the number of vessel movements of non RWS-class vessels would be included, which was approximately 5% in 2018. The Base 2 + 15% and Base 2 + 30% scenarios were based on the data coverage percentage of the expert experience of 80%, resulting in data lack of 20% and taking an under and overestimation of this number.

Table 5.3: Base 2 + extra intensity scenario simulation results.

Discharge [m^3/s]	991.8	991.8	991.8	991.8
River profile	P1020	P1020	P1020	P1020
Intensity [passages/day]	385	404	443	501
Parameters	**Base 2**	**+5%**	**+15%**	**+30%**
Total number of passages simulated	2846	2863	3114	3535
Intensity [passages/day]	407	409	445	505
7 day total delay time [min]	679.9	784.9	902.3	1287.6
Total delay time coupled units [min]	75.6	87.1	89.7	131.4
Total delay time push-tow units [min]	19.8	36.0	28.1	58.3
Total delay time motorised vessels [min]	584.5	661.8	784.4	1098.0
Delay time per passage [sec]	28.6	33.0	34.8	43.8
Total number of encounters	77716	79389	93013	120285
Total number of overtakes	6547	6661	7946	10235
Aborted manoeuvres	93	100	126	172
Total number of safety margin interactions	4388	4677	5317	6963
Penetration of the safety margin of a vessel in percentage of the total number of interactions	5.2%	5.4%	5.3%	5.3%
Ships reducing speed while passing	2.4%	2.7%	3.2%	3.7%

Table 5.3 shows that with increasing intensity the delay time, the number of encounters, number of overtakes, aborted manoeuvres and the number of penetrations of the safety margins increase as well. However, the percentages of the penetration of the safety margins of a vessel relative to the total number of vessel interactions, does not change significantly. Neither, the percentages of vessels that need to slow down maximally during their passages. Illustrating that, even though more vessels use the fairway at the same time, traffic flow and traffic safety can be maintained.

Figure 5.4 shows the relationship of the increase in intensity and the total delay time. Figure 5.5 illustrates the relationship between the simulated intensity per day and the total number of penetrations of the safety margin. The data points in figures 5.4 and 5.5 are situated more or less on one line. With increasing intensity the number of penetrations of ship's safety margins increases. From the R-square it can be concluded that the relationship between the parameters is strong because the R-square was 0.99. The relationship between the total delay time and the simulated daily intensity, was also strong as the R-square value was 0.97. Table 5.4 summarises the change in the parameters relative to the Base 2 scenario. The increase of the traffic intensity by 15% results in an increase in the traffic delay time of 33% and increases the number of ships that can not maintain their safety margins of 21%. The increase of the traffic intensity by 30% results in an increase in the traffic delay time of 89% and increases the number of ships that can not maintain their safety margins by almost 60%. The response of the delay time parameter and the number of aborted manoeuvres, are stronger than the response of the other parameters.

Table 5.4: The change of the total delay time and safety parameters in percentage, relative to the Base 2 scenario. The only difference between the scenarios was the intensity.

Parameter	Base 2 + 5%	Base 2 + 15%	Base 2 + 30%
Total delay time	+15%	+33%	+89%
Total encounters	+2%	+20%	+55%
Total overtakes	+2%	+21%	+56%
Aborted manoeuvres	+8%	+35%	+85%
Penetration of the safety margins	+7%	+21%	+59%

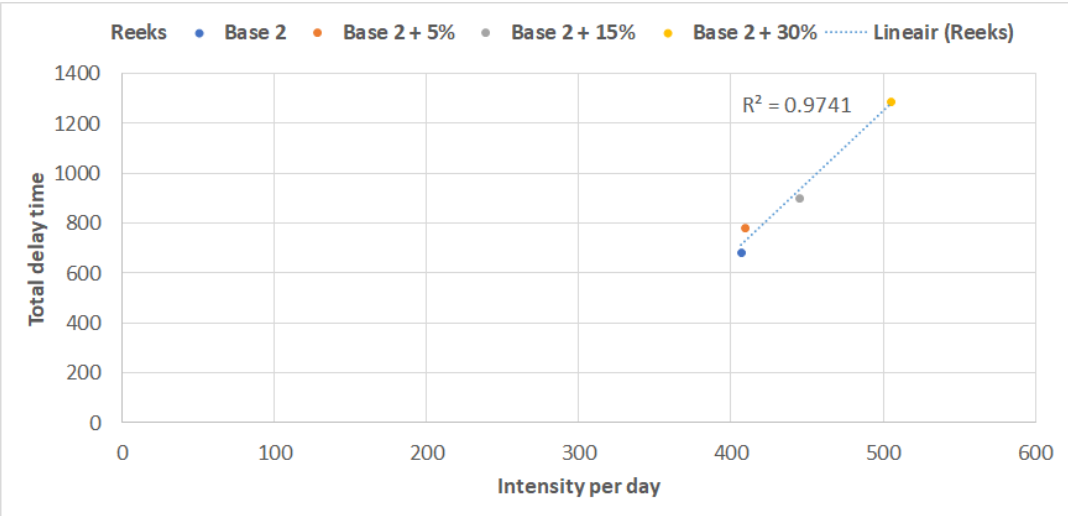

Figure 5.4: The relationship between delay times in minutes and the simulated intensity per day.

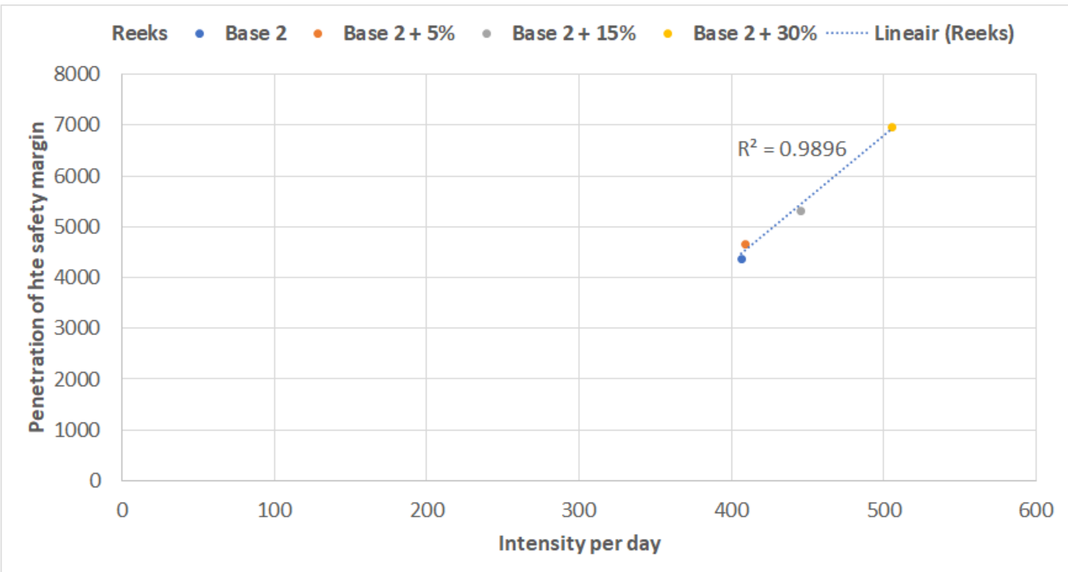

Figure 5.5: The relationship between the number of penetrations of the safety margins and the intensity per day.

The R-square of the relationship of the Base scenario's between the discharge and the delay time had a value of 0.58 (figure 5.3). It was concluded that there is a relationship between traffic flow and traffic intensity, but only if other parameters remain unaltered. From the Base scenario's it was concluded that for decreasing discharge and increasing intensity, the response to decreasing discharge is more important than the response to increasing intensity. With both conclusions an answer is provide to the sub-question: *What is the impact of the traffic intensity on the river Waal traffic flow during extreme low river discharges?* The impact of the traffic intensity on the traffic flow during extreme low discharges is less strong than the impact of the discharge on the traffic flow. However, when the discharge remains constant there is a relationship between increased intensity and reduced traffic flow. Using the highly irregular river profile at a discharge of 1020 m^3/s an intensity of 501 passages per day does not result in traffic flow or traffic safety problems.

5.3. Decreasing navigable width simulation results

The impact of the river width on the traffic flow was examined with the river profiles based on the navigable river width at a river depth of 2.0 m. The traffic intensity of the Base 2 scenario was used for all discharge scenarios, of which the results were summarised in table 5.5. Using safety limits of 8% from (Ten Hove & Bilinska, 2017), the traffic safety becomes a problem for discharges of 800 m^3/s and lower. The delay time per passage doubles from a discharge of 1020 m^3/s to a discharge of 900 m^3/s. However, the delay time per passage for the 800 and 700 m^3/s discharges remains below the 4 minutes. In table 5.5 it is clearly visible that the motorised vessels contribute the most to the total delay time.

Table 5.5: Simulations representing the river profile by the width at 2.0 m depth, for the discharge 1020, 900, 800, and 700 m^3/s. The intensity of the Base 2 scenario was used.

Discharge [m^3/s]	991.8	991.8	991.8	991.8
River profile	W1020	W900	W800	W700
Average navigable width at 2.0 m depth [m]	200	170	152	151
Intensity [passages/day]	385	385	385	385
Parameters	**1020 m^3/s**	**900 m^3/s**	**800 m^3/s**	**700 m^3/s**
Total number of passages simulated	2846	2846	2846	2846
Intensity [passages/day]	407	407	407	407
7 day total delay time [min]	1433.5	3056.4	4782.5	4595.9
Total delay time coupled units [min]	128.5	246.8	313.5	279.5
Total delay time push-tow units [min]	47.3	82.4	113.3	99.0
Total delay time motorised vessels [min]	1257.7	2727.2	4355.7	4217.4
Delay time per passage [sec]	60.4	129.0	202.1	194.1
Total number of encounters	78366	78292	79476	79418
Total number of overtakes	6418	6189	5972	5995
Aborted manoeuvres	290	984	1463	1404
Total number of safety margin interactions	4232	5917	7238	7161
Penetration of the safety margin of a vessel in percentage of the total number of interactions	5.0%	7.0%	8.5%	8.4%
Ships reducing speed while passing	4.2%	6.5%	9.2%	8.9%

The navigable river width at a river depth of 2.0 m for a discharge of 600 m^3/s could not be simulated. The navigable river width was not sufficient at several cross-sections to enable the passages of the RWS-class vessels. Especially in the river Waal bend near Nijmegen the navigable width at a river depth of 2.0 m was only 28 m at several cross-sections. The calculated width at each cross-section between the Pannerdensche Kop and the Maas-Waal canal was used to build the river profile for the simulation. This resulted in what SIMDAS called a static bottleneck, a place were vessels can not pass each other, but await till passages is possible is neither an option. The river width along the whole simulated river section was too small to provide traffic flow in both directions. With an average width in table 3.2 of only 123 m, a standard deviation of 46 m and a minimum of 28 m, the occurrence of simulation problems was expected.

A comparison between the Base 2 - 1020 m^3/s scenario and the Base 2 - 900, 800 and 700 m^3/s scenarios was provided in table 5.6. The only difference between the scenarios is the navigable width at a river depth of 2.0 m. The minimum river width for both the 800 and 700 m^3/s scenarios was also 28 m, however the average width was over 150 m. With this difference, apparently, there is enough room in the simulation model for vessels to pass or await passage. From this table it is clear that the delay time and the number of aborted manoeuvres were effected most by the decrease in navigable river width. Also, the small decrease in the number of overtakes was remarkable. The decrease in overtakes can be explained by the reduced width and therefore the room to overtake a vessel that travels slower.

Table 5.6: The change of the total delay time and safety parameters in percentage, relative to the 1020 m^3/s scenario.

Parameter	**900 m^3/s**	**800 m^3/s**	**700 m^3/s**
Total delay time	+113%	+234%	+221%
Total encounters	+0%	+2%	+1%
Total overtakes	-4%	-7%	-7%
Aborted manoeuvres	+239%	+404%	+384%
Penetration of the safety margins	+40%	+71%	+69%

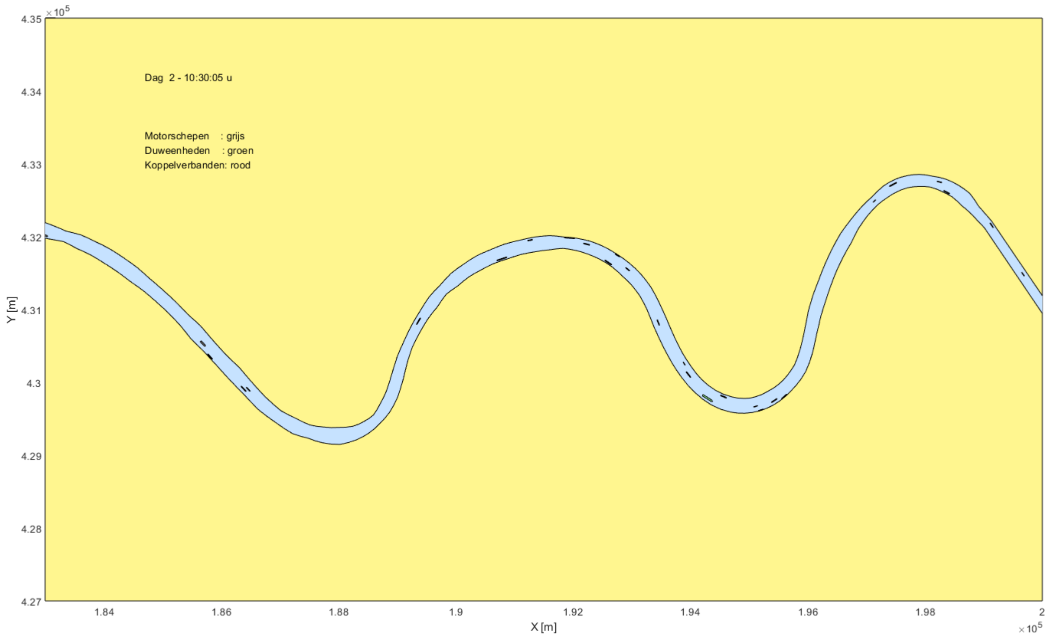

Figure 5.6: Time stamp (day 2 - 10.30) of the traffic simulation of a navigable river Waal profile at a discharge of 1020 m^3/s.

The simulation in SIMDAS showed that congestion already occurred during the 1020 m^3/s scenario, see figure 5.6. The simulation frequently showed 4 vessels sailing behind a slower vessel. Occasionally 7 vessels travelled behind one of the larger vessels, awaiting a river section were passages of the slower vessel was possible. The passage then occurred at the least sharp bend, or at the relatively straight crossing between a right and left turning river bend. Four lane traffic is no longer possible, but three vessels encountering each other was seen frequently. Considering that the definition of congestions in the Cambridge dictionary (2020) is:*"a situation in which a place is too blocked or crowded, causing difficulties"*, congestion already occurs at a discharge of 1020 m^3/s.

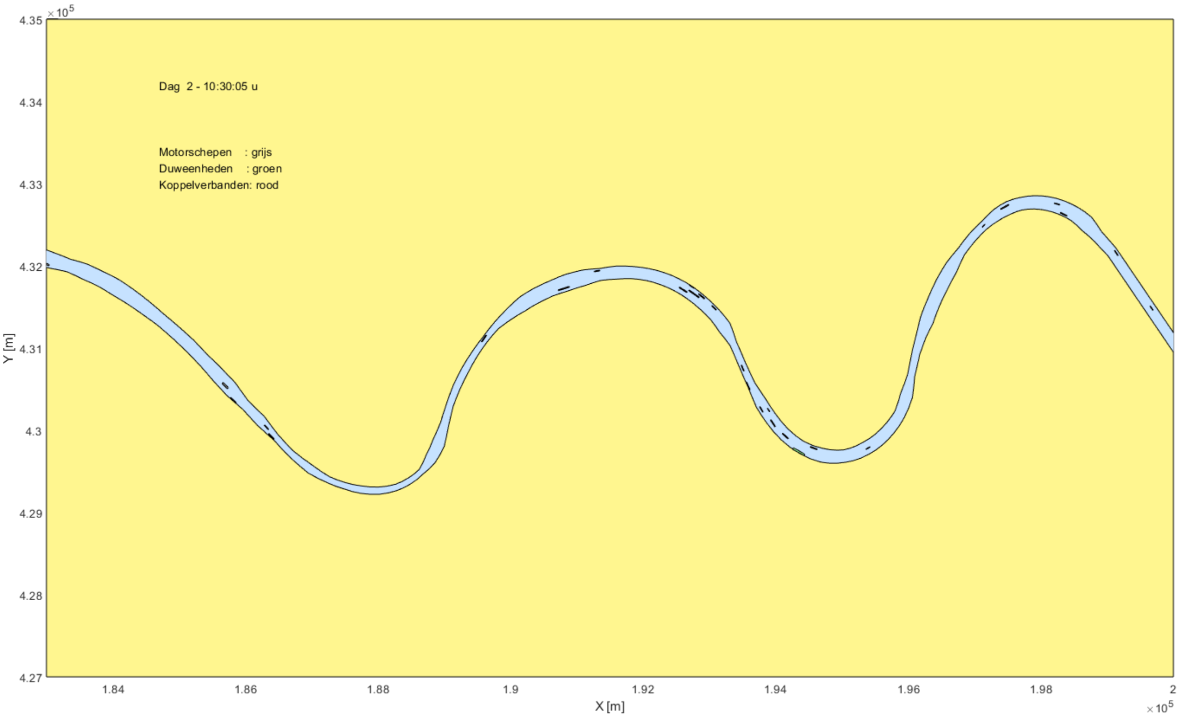

Figure 5.7: Time stamp (day 2 - 10.30) of the traffic simulation of a navigable river Waal profile at a discharge of 700 m^3/s.

During the 900 m^3/s scenario simulation groups of 4 vessels are still the most common type of congestion, however larger groups appear more frequently. Large groups of 7 or 8 vessels also occur, but remain exceptional. Two lane traffic is the standard but at some locations three vessels can encounter each other. The river profile for the 800 m^3/s scenario hardly allows for safe encountering in the river bend near Nijmegen. Overtaking a vessel requires timing and vessel groups of 5 or more are common. The passing of 3 vessels at one location only occurs for the smaller type vessels. Large groups of vessels travel along the simulated section, the smaller and faster vessels overtaking the larger and slower vessels, one by one. Generally groups larger than 8 vessels tend to spread out while moving along the river section. In the SIMDAS simulation of the 700 m^3/s scenario, see figure 5.7, the shape of the narrow river bend becomes even more capricious. Large groups of vessels travel along the Waal and when a large upstream travelling group meets a large downstream travelling group, conflicts arise. The vessels need to regroup into a one-by-one chain, travelling in both directions, to overcome the obstacle. Groups as large as 10 vessels occur.

First, the relationship between the parameters of the simulations and the river discharge were analysed in figures 5.8, 5.9 and 5.10. From these figures it is concluded that there is a clear relationship between the discharge and these SIMDAS parameters. A decreasing discharge results in an increase in the SIMDAS results. The effect seems to be strong because the R-square values were all above 0.8.

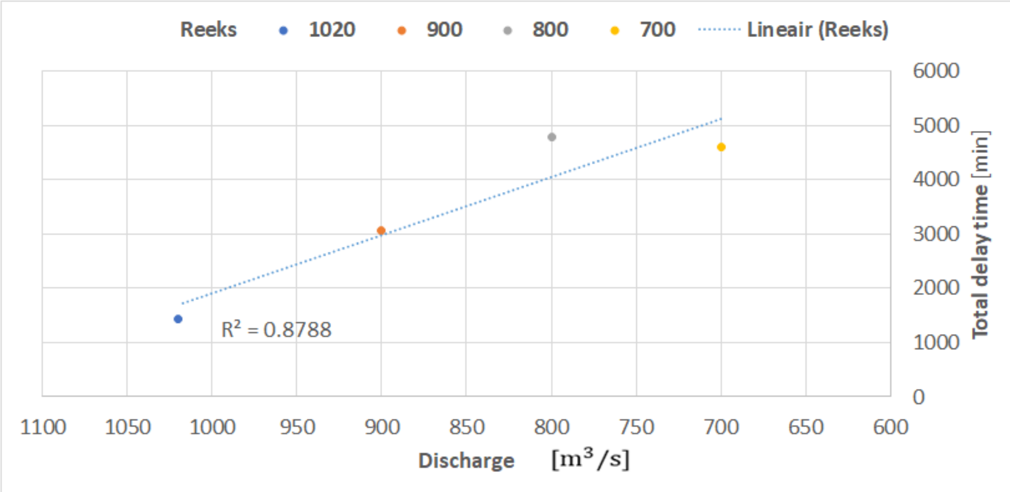

Figure 5.8: The relationship between the discharges of the scenarios and the delay times.

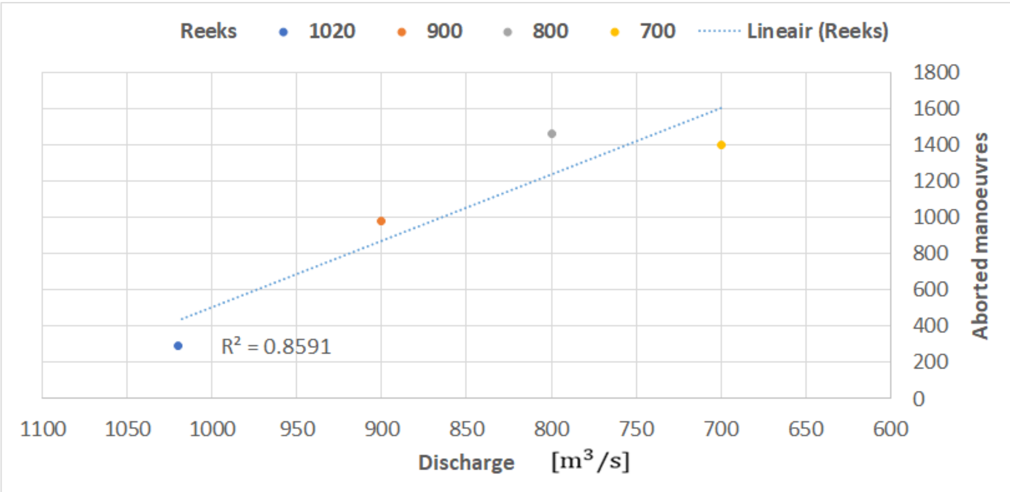

Figure 5.9: The relationship between the discharges of the scenarios and the number of aborted manoeuvres.

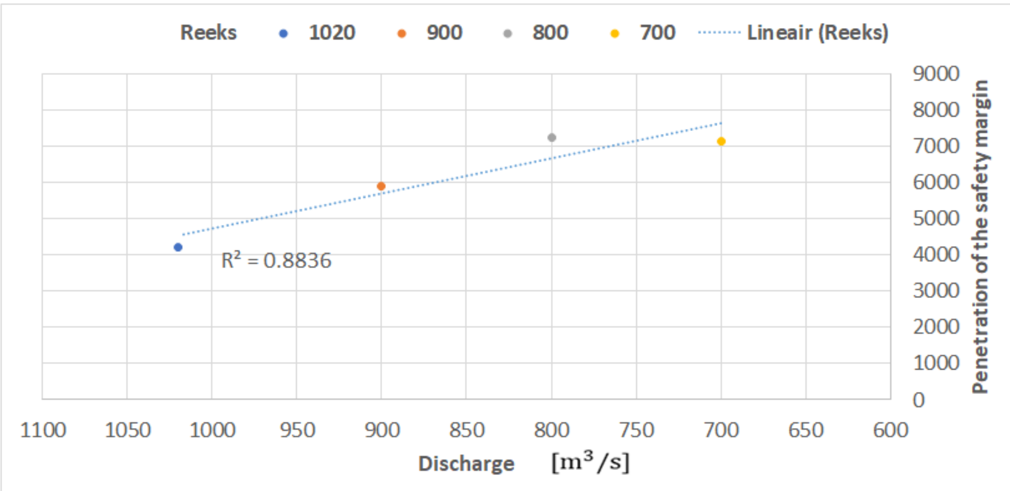

Figure 5.10: The relationship between the discharges of the scenarios and the number of penetrations of the safety margin.

Second, the relationship between the delay time and the average navigable river width at a river depth of 2.0 m was analysed in figure 5.11. Also, the relationship between the number of penetrations of the safety margin and the average navigable river width at a river depth of 2.0 m were analysed in figure 5.12. From these figures it was concluded that there is a strong relationship between the navigable width and delay time and safety. A decreasing navigable width results in an increase in the delay time. Also, with a decreasing navigable width the number of penetrations of the safety margin increases strongly. Therewith, an answer is provided to the research question: *What was the relationship between fairway traffic flow and fairway width in the river Waal during the drought of 2018?*

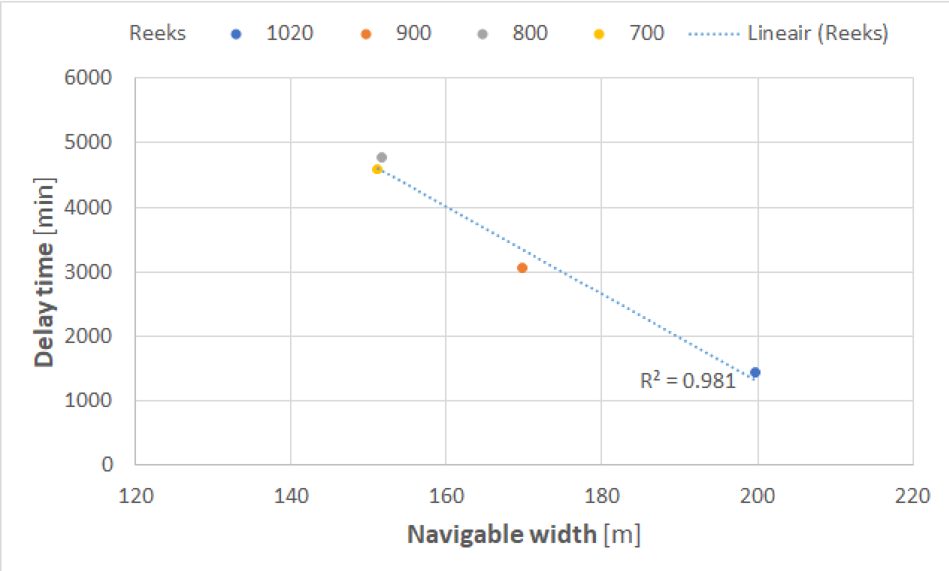

Figure 5.11: The relationship between the average navigable width at a river depth of 2.0 m and the total delay time.

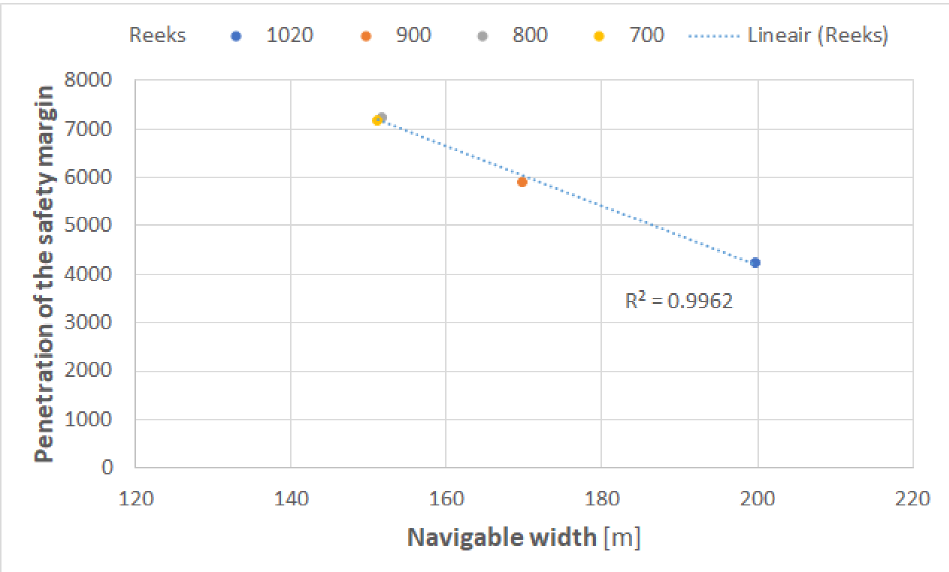

Figure 5.12: The relationship between the navigable width at a river depth of 2.0 m and the number of penetrations of the safety margin.

The effect of the river width profile, the W1020 till W700 profiles, and the decreasing discharge profile, the P1020 till P700 profiles, were investigated separately. The effect of increased intensity was investigated using a constant discharge profile (the P1020 profile). However, from the intensity simulations it was concluded that the decreasing discharge profile (the P profiles) was more imported for the traffic flow and traffic safety than the increasing traffic intensity. From the above figures and tables, it was also concluded that the navigable river width profile (the W profiles) has a stronger effect on the delay time and the traffic safety, than the discharge profile (the P profiles). Concluding that the traffic flow is effected stronger by the river width than by the traffic intensity, and therefore an answer was provided to the research question: *Are congestions during low discharges in the river Waal, triggered by the traffic intensity, the dimensions of the fairway or both?*

5.4. Economical impact

As indicated by the IWT simulation results low river discharges result in larger delay times, although the simulated delay time per vessel, on the river Waal between the Pannerdensche Kop and the Maas-Waal canal of the drought of 2018 was less than 2 minutes. The traffic simulation results were used to answer the remaining sub-question about the economical impact of congestion. For an extreme low discharge congestion cost assessment, it was not sufficient to distinguish only a few different ship types as the prices differ amongst RWS-classes (Hekkenberg et al., 2017). Table 5.7 summarises the transport tariffs per RWS-class, averaging the cost per cargo type found by Rijkswaterstaat (2018a). Actual IWT prices are depending on multiple parameters, such as fuel costs, water depth and cargo volume. Hekkenberg et al. (2017) approximated the cost of a M7 type vessel at € 90 per hour, €1.5 per minute. Comparing the cost found by Hekkenberg et al. (2017) with the average cost of an M7 type vessel of €1.5 per minute with the values calculated in table 5.7, the higher value was used.

Table 5.7: Transport cost per RWS-class during ALD discharge, distinguished in delay time tariffs.

RWS-class		**Delay time tariff**	**Number of vessels**	**Delay time**	**Cost**
		[€/minute]	simulated	[min]	[€]
Coupled units	C1b	0.91	0	0	0
	C1L	0.90	0	0	0
	C2L	2.37	27	7.6	18.1
	C2b	2.27	0	0	0
	C3L	2.97	21	5.9	17.6
	C3b	2.85	174	49.1	139.9
	C4	3.60	96	27.1	97.4
Total Coupled units			318	89.7	€273
Push-tow units	B01	1.03	0	0	0
	B02	1.11	0	0	0
	B03	1.15	0	0	0
	B04	1.20	1	0.3	0.3
	BI	1.79	2	0.5	0.9
	BII	2.11	0	0	0
	BIIa-1	2.20	0	0	0
	BIIL-1	2.37	7	1.8	4.4
	BII-2L	3.49	2	0.5	1.8
	BII-2b	3.40	5	1.3	4.5
	BII-4	6.04	90	23.6	142.8
	BII-6b	7.58	0	0	0
	BII-6L	7.35	0	0	0
Total Push-tow units			107	28.1	€155
Motorised vessels	M0	-	8	2.3	-
	M1	0.62	10	2.9	1.8
	M2	0.75	96	28.0	21.0
	M3	0.84	70	20.4	17.2
	M4	0.92	93	27.1	25.0
	M5	1.10	171	49.9	54.9
	M6	1.43	456	133.0	190.2
	M7	2.02	103	30.0	60.7
	M8	2.35	1164	339.5	797.9
	M9	2.74	298	86.9	238.2
	M10	2.94	26	7.6	22.3
	M11	3.31	98	28.6	94.6
	M12	3.68	96	28.0	103.1
Total Motorised vessels			2689	784.4	€1,627

Note: The delay time was assumed to be evenly distributed between vessels within the category, the number of vessels in the Base 2 + 15% scenario and the total cost.

When multiplying the delay time with the calculated cost per minute for the Base 2 scenario, the cost per 7 days of drought were calculated in detail in table 5.7. The cost of 7 days of extreme low discharges result in traffic induced cost of €273 for coupled units, €155 for push-tow units and €1,627 for the motorised vessels. In total this is €2,055 additional cost due to traffic delays. For a more robust and general approach, the maximum hourly tariff was used to calculate the traffic induced maximum economic impact of the river Waal between the Pannerdensche Kop and the Maas-Waal canal, for all Base scenario's. The maximum hourly tariff was €7.58 per minute and the total cost of table 5.8 varied from €3,866 up to €13,167. Table 5.7 shows that from all RWS-classes the C3b, BII-4, M6, M8 and M9 are economically important classes for the delay time costs. The five RWS-classes, C3b, BII-4, M6, M8 and M9, together account for 73% of the delay time costs, in case the delay time per vessels is evenly distributed within the vessel's category.

Table 5.8: Traffic induced costs of the four weeks of drought in 2018.

Date	Scenario	River profile	Discharge [m^3/s]	Delay time for 7 days [min]	7 day cost
22-Jul-2018	Base 1	P1020	1081.5	510	€3,866
09-Sep-2018	Base 2	P1020	991.8	680	€5,154
09-Sep-2018	Base 2 + 5%	P1020	991.8	785	€5,950
09-Sep-2018	Base 2 +15%	P1020	991.8	902	€6,837
09-Sep-2018	Base 2 +30%	P1020	991.8	1288	€9,763
14-Oct-2018	Base 3	P800	797.9	709	€5,374
21-Oct-2018	Base 4	P700	739.6	1737	€13,167
09-Sep-2018	Base 2, 1020	W1020	1020	1434	€10,870
09-Sep-2018	Base 2, 900	W900	900	3056	€23,165
09-Sep-2018	Base 2, 800	W800	800	4783	€36,255
09-Sep-2018	Base 2, 700	W700	700	4596	€34,838

The following paragraphs will provide an answer to the question: *What is the economical impact of congestion?*. The Base 2 +30% scenario is €4,609 more costly than the Base 2 scenario. Considering that, the data coverage is about 80% the traffic induced cost of the Base 2 + 15% scenario is a more representative value of the traffic induced cost for a discharge below ALD. The traffic induced cost per day that the discharge is below ALD would be maximal €977 (€977 = €6,837 / 7 days). Performing the same calculation for the scenario of the navigable width at a river depth of 2.0 m at a discharge of 1020, the cost would be €1,553 per day (€1,553 = €10,870 / 7 days). The traffic intensity of the Base 2 +15% is higher, which could result in even higher delay time cost per day. However, the traffic flow at the navigable river width was assumed to be more representative than the simulations using the highly varying cross-sectional dimensions, resulting in a delay time cost of €1,553 per day.

In 2018 the daily average discharge was 124 days below 1020 m^3/s, so below ALD. Due to the extreme low discharge in 2018 this would result in delay time cost of maximum €192,554 on the river Waal from the Pannerdensche Kop till the Maas-Waal canal. In addition to the delay time, secondary costs should also be taken into account when evaluating the economic impact of the 2018 drought. Secondary effects of the 2018 drought are amongst others, the cost due to a delay in industrial raw materials resulting in reduced industrial production, increased transportation time due to groundings and increased cost due to modal split (Briene et al., 2018). Briene et al. (2018), estimated a 65 to 155 million euro total economical effect in the Netherlands associated with the drought of 2018. Whereas, Streng et al. (2020) calculated that the economical impact of the 2018 drought for the Netherlands was 295 million euro. Due to the complexity of the calculations of the total economical impact of the 2018 drought, this study focuses on the delay time cost of a reduced navigable width on the river Waal only.

The river Waal from the Pannerdensche Kop till the Maas-Waal canal is about 21 km long and the whole river Waal is about 82 km (Binnenvaart, 2020b). Although the simulated river section of the river Waal was the section with many river bends and the bottleneck locations Nijmegen and Erlecom, more locations in the river Waal were bottlenecks during the drought of 2018. The known bottleneck locations in the river Waal were; Lobith, Erlecom, Nijmegen, Dodewaard, Dreumel and st. Andries (Roex, 2018). When extrapolating the cost of the river Waal between the Pannerdensche Kop till the Maas-Waal canal over the whole river, the delay time cost of 2018 would be €751,878. Therewith, the economical impact of congestion, in terms of delay time on the river Waal in 2018, was €751,878.

Increasing knowledge on the available river depth and width on the river Waal, IWT vessels can optimise their sailing speed, reduce fuel consumption and optimise the transportable cargo per shipment. CoVadem (2020) uses the sensors on board of the vessel to gather depth data and ship performance data. With the gathered depth data of the CoVadem fleet, members can be provided with up-to-date water depths on the river Waal. With the gathered data depth charts are generated. For an accurate depth charts, data up to 250 vessel is required and cost an investment of 1.5 million Euro (Van Wirdum, 2018). The up-scaling of the CoVadem fleet was promoted by providing the CoVadem equipment and membership free to data gathering vessels (Van Huizen, 2019a). RWS vessels are also part of the CoVadem fleet and RWS uses CoVadem data to optimise river maintenance (Aaftink, 2020). Increasing the CoVadem fleet can therefore lead to better navigable conditions during extreme low discharges due to optimised river maintenance, possibly leading to a reduction in the delay time. Also, the number of groundings during extreme low discharges can be reduced due to better depth data and the reduction of obstacles due to better maintenance (Van Huizen, 2019b). If CoVadem leads to complete absence of increased delay times, the investment in CoVadem will be payed back when there are two years of extreme low discharges on the river Waal.

5.5. Conclusion

With all the information gathered in this chapter a final answer to the main research question: *What are the effects of extreme low river discharges on the traffic flow and traffic capacity of the river Waal fairway?*, can be provided.

The traffic flow and traffic capacity in the traffic simulation model was examined using the daily intensity, the four weeks representing the drought of 2018 and the navigable river width. From the traffic simulations it was clear that there is a relationship between traffic flow and traffic intensity but only if other parameters remain unaltered. For decreasing discharge and increasing intensity, the response to decreasing discharge is more important than the response to increasing intensity. The effect of the navigable river width is stronger than the effect of the discharge. The reduced navigable river width had the strongest effect on the traffic flow and traffic intensity therefore, the occurrence of congestion was investigated using the simulations with reduced navigable width. With decreasing navigable width the traffic flow reduces strongly. The reduced traffic flow was most visible in the form of aborted vessel manoeuvres. Also, the number of overtakes reduces while navigable width reduces, which is a sign of congestion, as there is not sufficient room for vessels to overtake.

From the simulations of the river Waal it was concluded that at a discharge of 1020 m^3/s, harmonically moving congestions occur. Harmonically moving congestions were caused by groups of vessels travelling behind a slower vessel while awaiting room for overtake manoeuvres. During the drought of 2018 the discharge reduces far below 1020 m^3/s. The SIMDAS traffic flow simulation showed that groups of 7 or 8 vessels travelling behind one slower vessel, were not uncommon during extreme low discharges. The fluency parameter used in SIMDAS is the percentage of ships that need to fully reduce speed while passing the simulated river section. For the fluency parameter a threshold value was considered of 8%. The safety parameter, the penetrations of the safety margins of a vessel in percentage of the total number of vessel interactions, also has a limit value of 8%. Using both limit values and the simulation results of table 5.5, it was clear that for discharges below 800 m^3/s the traffic flow and traffic capacity of the river Waal was reached.

The economical impact of the reduced navigable width on the delay time on the river Waal between the Pannerdensche Kop and the Maas-Waal canal in 2018 was calculated with a averaged cost value of €7.58 per minute for all RWS-class vessels and all cargo types. With a total of 124 days with a discharge below 1020 m^3/s in 2018, the cost due to delay time was €192,554. When extrapolating the simulated delay time cost of 2018 for a river discharge below 1020 m^3/s to the 82 km of the whole river Waal, the total delay time cost would be €751,878.

6 Discussion

The aim of this research was to investigate the traffic flow and traffic capacity on the river Waal during extreme low discharges. With the data analyses and traffic simulations it is found that for discharges below 800 m^3/s the limits of an acceptable traffic capacity is reached, as large congestions occurred. This chapter puts the results of this study into perspective and discusses the limitations, the inaccuracy and uncertainty of the data and their effect on the results. Also, the abilities of the traffic simulation model to represent the fairway and traffic flow correctly, is addressed.

6.1. Data and their effect on the results

During periods of drought the river discharge in the river Waal reduces and as a consequence the water depth reduces. With reducing water depth the river depth and width reduces and, consequently, the vessel draught decreases. Inland waterway transport vessels anticipate on the reduced river depth by choosing the most optimal cargo loading percentage and traffic route (Schasfoort et al., 2019). The relationship between a change in the loading percentage per RWS-class vessel and the discharge was investigated during this research. It was found that for almost all RWS-class vessels, as expected, there was a strong relationship between the loading percentage and the discharge. The strong relationship between the loading percentage and the discharge explains the decrease in the total transported weight per day during extreme low discharges, even though the number of passages increases.

IVS90 data was used for all transport related data analyses during this research, however IVS90 data is manually entered by the vessel's skipper and not always correct nor complete. The correctness of the dataset is accounted for by filtering out the outliers in the dataset. Multiple analyses were performed, each accounting for different type of outliers. During the regression analyses on passages at discharges below 1200 m^3/s, the minimal number of observations per RWS-class was set on 40. This number was selected because it represents 0.1% of the total number of passages during a discharge below 1200 m^3/s in 2018. For the vessel draught analyses, a draught larger than 600 cm was considered an outlier. Most of the 437 draught outliers in the 2018 IVS90 dataset, contained draught values of 9900 cm. The 9900 cm draught value could be an IVS90 default value, but was considered an outlier during this study. During the data analysis on the loading percentage per RWS-class vessel and the discharge, the maximum and minimum loading percentages were set as 100 and 0% of the vessel's maximum transport capacity. Resulting in an exclusion of 493 observations, representing 0.39% of the 125,121 total number of vessel movements in 2018. The highest of these 493 outliers contained a loading percentage of 131% of the vessel's maximum transport capacity. Also, the exact data coverage of IVS90 data is currently unknown, but it is estimated to be around 80%. The combination of AIS and IVS90 data would have covered the data coverage knowledge gap so that a data correction could be performed with more certainty and the IVS90 could be validated on input correctness. Also, with AIS data the vessel trajectories are known, which could be used to validate the representation of the traffic flow in SIMDAS. However the AIS data of 2018 did not contain the data during the period of drought and therefore could not resolve the knowledge gap. As a result, the data analyses done in this research uses only IVS90 data and always underestimates the number of vessel movements. The data filtering was needed to achieve reliable results but increases the difference between the analysed number of observations and the actual number of passages. The underestimation of the number of passages was accounted for by the increased intensity scenario simulations. With the underestimation of the number of vessel movements, the daily intensity is underestimated as well. Therefore, the found river Waal traffic capacity limit could potentially be at a higher discharge than 800 m^3/s.

Kievits (2019) developed a simulation model to asses the impact of extreme low discharges on the river Rhine's IWT network performance. The model developed by Kievits (2019) was based on the assumption that the smaller push-tow units had to stop operations when the navigable water depth in the river falls below 2.25 m. The 2.25 m depth criterion was based on the assumption that the economical loading limit is 35% of the maximum cargo volume of the vessel. Using this depth criterion means that at the end of October 2018 no push-tow units were operating. The analysed IVS90 data of the weeks of 22-July, 09-September, 14 October and 21 October 2018 and the article by Van t' Verlaat (2019a) suggest differently. In the week of 21-October, indeed, the lowest number of small push-tow units were registered, but there were on average still 2.4 push-tow units operating per day, while the weekly average discharge reduced to 739.6 m^3/s and the average vessel draught reduced to under 1.6 m. The large six-barge push-tow units were not observed transporting cargo in any of the four weeks of extreme low discharge. The 2018 IVS90 data showed that the RWS-classes remained operational for a longer time period than the model by Kievits (2019) assumes. Moreover, the research by Kievits (2019) focuses on the coal and iron ore transport only, whereas the current research does not distinguish between cargo types. Furthermore, the current research focuses on a small section of the river Waal, whereas the study by Kievits (2019) focuses on the river Rhine from Rotterdam till Duisburg. Though Kievits (2019) looks at a larger part of the river Rhine, the selection of the economical loading percentage of 35% and the associated minimum depth, should not be different when focussing on only a part of the river Rhine. By using the strict criterion of a water depth of 2.25 m for push-tow units, the model of Kievits (2019) does not represent the traffic flow on the river Waal correctly and underestimates the transport capacity during extreme low discharges.

Relating the river discharge to the river depth is complex, because river bed profiles are highly variable in cross-sectional direction. Bed forms in the river can also change over time and multi-beam measurements capture the river bed at a certain moment in time. The annual multi-beam measurements of 2017 were used being the most recent bed level data, but contains a collection of measurements over a period of months. As there are continuous dredging operations in the river, it is also uncertain whether some bed forms have been removed already before the measurement. The gathered multi-beam and water level data had to be transformed into water depths in order to fulfil the SIMDAS input requirements. During these transformations the data was not corrected for bed forms. Bed forms appeared to be one of the obstacles in 2018 for navigation (Van de Plicht, 2018), and vessels grounded (Lengkeek, 2018). Most relevant bed forms are the moving subaqueous dunes that develop on the river bed due to sediment transport, but also static bed forms generated by irregular bank lines or groynes contribute to shallowness. Bed forms (dunes) have lengths of 50 to 100 m. Bed forms in the lower part of the river Waal can be 1 to 1.5 m high, and in the more upstream part of the river Waal 0.5 to 1 m. The bed forms in the upper reaches are slightly lower due to a higher gravel content in the bed (Jans et al., 2018). But due to their irregularity some bed forms can be much higher. In general bed forms grow during high flows and decay after the flow decreases. However, their attenuation is slow, and often after fall of a flood the bed forms can still be more significant than after a few months of low flow. The timing of the multi-beam measurements is very relevant for making a proper analysis because when the measurements are quite old the bed forms may have attenuated already or moved to other locations. Up till now every two weeks a multi-beam measurement of the navigation channel was carried out, but in the new contract for dredging this obligation will disappear and the multi-beam measurements will no longer be available for RWS. During the extreme low discharges of 2018 bed forms played a role in IWT navigation and correcting for bed forms would mean neglecting the navigation obstacles and reduce the delay time of the SIMDAS simulations. Van Dorsser and Buitendijk (2018), analysed the 2018 river Waal data on least available depth (LAD in Dutch: minst gepeilde diepte MGD) and found that the depth in the river Waal did not meet the required depth of 2.80 meter for 89 days (from January till September 2018).

The LAD value is literally the lowest point in the river and during the drought of 2018 the lowest LAD was 1.80 m. Van Dorsser and Buitendijk (2018), state that at ALD the required depth in the river Waal was structurally not available for navigation. In practise, the ALD had a LAD value of at least 2.10 m and maximum 2.50 m. Skippers use the LAD to calculate the maximum draught of their vessel (Van Huizen, 2018). Combining the study of Van Dorsser and Buitendijk (2018) with the draught analysis in this report, the use of a navigable river width at a river depth of 2.0 m was found to be reasonable, because the LAD and the analysed vessel draught were in the same order of magnitude as the river depth. Without a correction for river bed forms, the obtained river profiles had high variations in depth over the cross-section. These high variations sometimes resulted in a split of the fairway lanes at a depth of 2.0 m as often the most critical depths were found in the center of the river rather than on the sides. For the consistency of the study only the widest fairway sections were selected and represented in SIMDAS. The exclusion of splitted fairway lanes resulted in a strong reduction of the river width. Therefore, the fact that this study does not correct the river profile for river bed forms so that the river profile includes navigation obstacles during extreme low discharges, must be taken into consideration when interpreting the navigable width analyses.

During the current research it was found that the occurrence of congestion was highly correlated with the navigable width. However, a relationship between traffic intensity and the occurrence of congestion was less evident. During the drought of 2018 congestion occurred in the winding parts of the river Waal due to a reduced navigable width (Van t' Verlaat, 2019a). Congestions with a length of several kilometres were observed (Van t' Verlaat, 2019a). Research by Zhang et al. (2014) indicates that the occurrence of congestions in rivers correlates to the occurrence of groundings rather than to high transport volumes. Groundings were found to increase the risk of congestion the most. Also width-limited channels and weather conditions that reduce visibility and navigability, would significantly increase the congestion risk. Other factors could also contribute to the occurrence of congestion, for example vessel dimensions (Zhang et al., 2014). Zhang et al. (2014), also found that there was an increasing risk for congestions when considering skipper owned private vessels. The increased number of accidents during the drought of 2018, of which several groundings (Rijkswaterstaat, 2019b), confirmed the theory by Zhang et al. (2014). The current research described in this report may only account for a small part of the drought induced delay times and is related to the river width. Therefore, the calculated delay times on the river Waal between the Pannerdensche Kop and the Maas-Waal canal during the 2018 drought of 1 to maximum 3 min per passages, can be considered as a minimum. Considering the followed approach taking into account all schematisations and limitations it is concluded that the study gives reliable results.

In the current research, the navigable width in the river Waal was found to be an important factor for both traffic flow and traffic safety. In the river Waal there is a river training pilot project going on to examine the effect of longitudinal training dams on various river functions. Longitudinal training dams reduce the navigable width during low river discharges due to sedimentation (Mosselman et al., 2020). The width reduction at the pilot location due to the longitudinal training dams, for a discharge of 800 m^3/s is 30 m and the width reduction is 40 m at ALD (Mosselman et al., 2020). Considering the very limited navigable width in the bending parts of the Waal, an extra reduction due to longitudinal dams would be very unfavourable for navigation. During the pilot project various skippers expressed their fear for a negative impact of longitudinal training dams on inland navigation (Verbrugge et al., 2018), which was also adressed by Mosselman et al. (2020). The resistance from the IWT community against longitudinal training dams in the river Waal is therefore strong and consistent throughout the pilot project (Mosselman et al., 2020). Though the effect of longitudinal training dams was not taken into account, longitudinal dams in the river Waal will most likely increase the traffic problems during extreme low discharges.

6.2. Simulations results

Traffic simulations were executed with SIMDAS. The model has some limitations, and although there were also data limitations, it was useful to continue the study. First, SIMDAS does not account for the delay time due to risk averse navigation. During the 2018 drought, not only more vessels caused delay times but also the risk averse navigation strategy of the skipper resulting in a speed reduction (Lengkeek, 2018), increasing the travel time. In SIMDAS also, the river profile and water level were modeled as constant parameters. The effect of small changes in the river discharge and associated navigable width and depth on the traffic flow and intensity, were therefore, neglected. Still, the effect of an average discharge on a discharge average IWT intensity is represented well by SIMDAS, as the programme was developed as such. Ten Hove & Bilinska (2017), investigated the required navigable width on the river Waal for the new waterway guidelines ”Richtlijnen Vaarwegen”, using SIMDAS. They concluded that in a 2094 m long, 170 m wide bend with a 1700 m radius, the maximum traffic capacity was reached at an intensity of 589 simulated vessels per day. The simulated river Waal profile of the present research contained bends with similar radius and length, but the navigable width of the river Waal strongly reduces during extreme low discharge. The prescribed fairway width of 170 m by Ten Hove & Bilinska (2017) was only available at a river depth of 2.0 m, for discharges of 900 m^3/s and higher. Though the simulated intensity in the study by Ten Hove & Bilinska (2017) was higher and the simulated river section much shorter, the trends were relatively similar. The intensity distribution over the day and the effect of extreme low discharge on the daily transported weight were also comparable.

For the simulation in SIMDAS all vessels within a RWS-class were assigned the same sailing speeds. A maximum and a minimum vessel speed were defined. In reality the sailing speed of a vessel not only depends on the traffic flow and loading conditions but also, amongst others, on the availible engine power and the shape of the hull (Kievits, 2019 and Hekkenberg et al., 2017). Making it more difficult to assign a general vessel speed to all vessels within the same RWS-class. Also, the fairway in SIMDAS uses one lane for the positioning of upstream travelling vessels and one lane for the positioning of downstream travelling vessels. With this principle vessels are able to use the available width of the fairway, as there are no lane boundaries involved. As a result the four lane system on the river Waal can not be forced upon the vessels other than by changing the width of the fairway. The representation of multiple lane traffic in SIMDAS, have not been investigated jet. However, in reality vessels use the entire width of the fairway when possible and alter their position if need, which is represented well in SIMDAS. Therefore, it was concluded that SIMDAS can represent the traffic flow during the extreme low discharges of 2018.

During the Base scenario simulations in SIMDAS the river profiles with highly varying cross-sectional dimensions were used. However, common practise in SIMDAS was schematising the river profile to an angular profile rather than a profile close to reality. During the simulations it was noticed that local shallow zones in the riverbed caused irregularities in the vessels trajectory. These irregularities could impact the smoothness of the traffic flow during the simulations, potentially impacting the delay times. The highly varying cross-sectional dimensions were not used during the scenario simulations with the navigable width at a river depth of 2.0 m. Though, both the senario simulation representing the drought of 2018 and the river width at a 1020 m^3/s river discharge scenario simulation were based on the 09-Sep-2018 intensity, the total delay time differs significantly. This difference in delay time can be explained by the interaction between the vessel draught and the river bed in SIMDAS not being optimal. The vessel draught is an input value in SIMDAS and was kept constant for both simulations, which explains the relative small impact of changes in vessel draught. Therefore, the bed profile was the only parameter that was changed, causing the difference between both scenario results. The difference between the scenario’s delay times was 753.6 min. The impact of the highly varying cross-sectional dimension is therefore large and should be investigated more thoroughly. Also, in reality RWS changes the position of the beacon line during extreme drought to enable the 2.80 m river depth for as long as possible. Changing the position of the beacon lines during extreme drought was not considered in the Base scenario simulations. However, the simulations containing the navigable width at a river depth of 2.0 m could also represent the effect of altering the beacon line of the fairway. Taking into account this discrepancy in SIMDAS, and all of the above mentioned factors impacting the traffic flow, the calculated effects are underestimates of the real impact of extreme low discharge on the traffic flow on the river Waal. Considering the above it was concluded that SIMDAS can be used in the context of this study.

6.3. Economical impact

The SIMDAS scenario containing the river Waal navigable width at a river depth of 2.0 m for a discharge of 1020 m^3/s, resulted in a 2018 total delay times cost on the river Waal between the Pannerdensche Kop and the Maas-Waal canal of €192,554. These cost were based on the 124 days in 2018 that the river discharge was below 1020 m^3/s and the delay time tariff of €7.58 per minute. Extrapolation of the delay time cost on the river section between the Pannerdensche Kop and the Maas-Waal canal, to the entire river Waal resulted in delay time cost of the 2018 drought of over 750,000 euro.

The economical consequences of drought were most pronounce on the river Waal (Schasfoort et al., 2019). Schasfoort et al. (2019) also state that more than half of the national inland waterway transport costs were made on the Rotterdam-Lobith corridor. Therefore, the cost due to increased delay times on the river Waal are very relevant for the total economic effects of drought. The calculated cost due to delay time were calculated based on the cost per hour per RWS-class vessel. The cost per RWS-class vessel was averaged over all cargo types. This simplification neglects the effect of the cargo sector's market forces. To put the economical impact of congestion in terms of delay time cost, into perspective the up-scaling investment in CoVadem up to 250 vessels, was 1.5 million euro (Van Wirdum, 2018). CoVadem uses the measuring equipment on board of the member vessels to gather depth data and vessel performance data. With the up-scaling of the CoVadem fleet, reliable depth data charts can be provided so that skippers can optimise their cargo loading percentage. The real time depth charts of CoVadem provide skippers more up-to-date knowledge of the fairway depths on their route (Van Huizen, 2019b), which could potentially reduce the delay time during extreme low discharges. Especially, when the delay time due to groundings is taken into consideration.

Overall, the economical impact of extreme low discharge is difficult to examine. The economical impact of the drought of 2018 on the Dutch economy was investigated by Streng et al. (2020) and Briene et al. (2018). Their calculations varied from 295 million euro (Streng et al., 2020) to an economical lower and upper value of 65 and 155 million euro (Briene et al., 2018). The economical impact of the drought of 2018 goes much further than only the traffic related costs and the reduced transport volumes, because the long duration of the 2018 drought also reduced the reliability of IWT as a mode of transportation. The economical impact also involves the impact of the drought on the investment strategy of companies (Streng et al., 2020). Therefore, the calculated delay time cost of the drought of 2018 were only small, but still significant and should be taken into consideration when calculating the economical impact of drought.

7 Conclusion

The goal of this research was to investigate the impact of extreme low discharges in the river Waal on the IWT traffic flow and traffic capacity. The study consisted of two parts: a data analysis followed by a traffic simulation study. Both parts of the research showed that the traffic capacity of the river Waal is at its limit at 800 m^3/s. With the traffic simulations the occurrence of congestion and a reduced traffic flow in the river Waal in 2018 was confirmed. Therewith an answer is given on the main research question regarding the effects of extreme low discharges on the traffic flow and traffic capacity. During the traffic simulations large congestions with more than 10 vessels continuously travelling behind one larger vessel occurred for discharges of 800 m^3/s, but harmonically moving congestions with about 7 vessels temporary travelling behind one larger vessel were already observed for discharges of 1020 m^3/s. In the following text more detailed conclusions are provided giving answer to the sub-questions such as the relevant low discharges and their effects on the fleet composition, the river width and the economical impact.

The river section between the Pannerdensche Kop and the Maas-Waal canal was the most important bottleneck for inland navigation during extreme drought and therefore this river section was investigated more thoroughly. The selection of the river section to simulate, was based on previous river studies during low discharges and observations during the drought of 2018. For the drought of 2018, the only IWT data source available was IVS90 data. In the hydraulic analyses the discharges 1020, 800 and 700 m^3/s were selected as the most relevant discharges for the traffic simulations. To assess the effect of extreme low discharges on the fleet composition on the river Waal the IVS90 data of 2018 was analysed based on four weeks of extreme low discharge, representing discharges of 1020 (2x), 800 and 700 m^3/s. Comparing the IVS90 data of 2018 with the IVS90 data of 2013 and 2015, the total and daily intensity in 2018 was higher. The intensity was determined as the number of passages between the Pannerdensche Kop and the Maas-Waal canal. In the transport analyses the RWS-classes were subdivided into three categories, the push-tow units (all RWS-classes starting with index B), the coupled-units (all RWS-classes starting with index C) and the motorised vessels (all RWS-classes starting with index M). Looking at the average fleet composition in 2018, the daily number of passages by coupled units increased for lower average discharges (for 1500 m^3/s and lower), whereas the daily average number of passages by push-tow units decreased. The increase of the number of coupled units was most pronounced during the period with discharges below the agreed minimal discharge at Lobith of 1020 m^3/s, the ALD level. A steep decline in the number of push-tow units was noticed at the end of October 2018 and persisted for over one month, until the discharge level exceeded the ALD value again in December 2018. These general trends were also present within the four weeks selected for analysis, representing the drought of 2018.

Due to low discharges the maximum draught of the vessels reduced, reducing the amount of cargo per vessel. In 2018 the effects of extreme low discharges on the fleet composition and transported cargo were extremely noticeable at the end of October. The daily average transported freight reduced even though the number of passages increased. The transported freight per day for a discharge below 1200 m^3/s was highly dependent on the discharge. Also the loaded cargo percentage for the RWS-classes with sufficient data were highly dependent on the discharge. Push-tow units remained in operation for the examined weeks of the 2018 drought, even though the study by Kievits (2019) would suggest that push-tow units stop operating during these extreme low discharges. The M8 RWS-class vessel remained the most common type of vessel on the river Waal during all examined river discharges, accounting for over 30% of the daily number of passages. A required minimal river depth of 2.80 m was agreed by the CCNR for discharges of 1020 m^3/s at Lobith. Based on the multi-beam measurements and the water level data the required minimal river depth of 2.80 m for the entire river section was no longer possible from a 900 m^3/s discharge and lower. Therefore, a navigable width at a river depth of 2.0 m was determined for the river width analyses and the traffic simulations. The 2.0 m was based on the averaged vessel draught during the four examined weeks of 2018 and the maximum depth available in the river profile during a discharge of 600 m^3/s. The average vessel draught during the first week representing the discharge of 1020 m^3/s was maximum 238 cm for the RWS coupled unit class C2L. In the second week representing the discharge of 1020 m^3/s the maximum draught was 214 cm for the RWS push-tow unit class BII-4. The average vessel draught for the week representing the discharge of 800 m^3/s was maximum 180 cm for the RWS push-tow unit class BII-2L. In the week representing the discharge of 700 m^3/s the maximum averaged vessel draught was 164 cm for the RWS push-tow unit class BII-2L.

The navigable width at a river depth of 2.0 m was determined for all cross-sections between the Pannerdensche Kop and the Maas-Waal canal, for a discharge of 1020, 900, 800, 700 and 600 m^3/s. The average navigable width at a depth of 2.0 m decreased from 200 m for a discharge of 1020 m^3/s to 123 m for a discharge of 600 m^3/s. Based on the navigable river width simulations for a discharge of 1020 m^3/s the economical impact of delay time cost in 2018 were significant. The delay time cost for the simulated river section was €1,553 per day for a discharge below ALD. With 124 days of extreme low discharges in 2018, the total delay time cost for the simulated river section between the Pannerdensche Kop and the Maas-Waal canal in 2018 was €192,554. When assuming that the selected river section represents the traffic flow and traffic capacity of the whole river Waal the delay time cost due to extreme low discharges could potentially be over 750,000 euro when extrapolated. However, the total economical impact of the extreme low discharge in 2018 was in the order of tens of millions and higher, as the total economical impact of drought also include the change in modal split, the reduced productivity of industries, the grounding of ships and more indirect consequences of a reduced river discharge.

Based on observations during the extreme drought in 2018 and the IVS90 data of 2018, the traffic flow and traffic capacity was limited over the whole period with discharges below ALD. The traffic flow and capacity were limited as the traffic intensity decreased while the transportable cargo per shipment reduced and traffic problems were observed. In October 2018 congestions on the river Waal were observed while the discharge was about 800 m^3/s. The fluency parameter and the traffic safety parameter were used as congestion indicators during the SIMDAS simulations. The percentage of the number of ships that need to reduced their speed to a minimum while passing the simulated river section was used as the fluency parameter with an acceptable limit value of 8%. The safety parameter was set at a limit value of 8% and involved the penetration of the safety margins of a vessel in percentage of the total number of vessel interactions during the simulation. Simulations of the traffic flow showed harmonically moving congestions consisting of 7 or more vessels travelling behind one larger or slower vessel while awaiting room to overtake. From the simulations it was found that the decreasing navigable river width impacted the traffic flow in 2018 more than the decreasing discharge. This conclusion was based on the river width simulations and the simulations with a highly varying river profile. The highly varying river profiles were based on the multi-beam measurements of 2017 and the water levels at certain discharges, which did not incorporate changes in the beacon line. For a correct representation of the traffic flow during extreme low discharges changes in the beacon line position should be incorporated. The navigable river width simulations incorporate changes in the beacon line in a certain way and was therefore considered more reliable than the simulations with highly varying river profiles. Also, the impact of increased intensity on the traffic safety and fluency was less than the impact of a reduced river width, while both phenomena were analysed separately and showed significant effects on the traffic safety and fluency. Therefore, congestions in the river Waal during extreme low discharges are mostly related to a reduction of the fairway dimensions, though the effect of increased intensity are significant. Based on the simulations of the navigable river width at a river depth of 2.0 m and the limit values, congestion in the river Waal occurred at a discharge of 800 m^3/s. However, traffic problems were already noticeable in the form of harmonically moving congestions, at a discharge of 1020 m^3/s.

With both the traffic simulations and the analysed data it was found that the maximum traffic capacity of the river Waal was reached at discharges of 800 m^3/s and below.

8 Recommendations

The recommendations in this chapter followed from the performed research and were based on the purpose of this study. The recommendations that followed from the data analyses were discussed first. After that, this chapter addresses the recommendations based on the traffic simulations and as last some recommendations for authorities were provided.

8.1. Need for correct data

Data corrections were performed during the data analyses in order to make reliable results. These data corrections were mostly needed because the 2018 IVS90 data coverage showed omissions and the correctness was unknown. The lack of knowledge on IVS90 data coverage in general impacts the results of this research by means of a fundamental underestimation of the traffic intensity. The underestimation of the traffic intensity impacts the traffic flow and therefore the calculated delay time and economical effects. Also during exceptional conditions like extreme discharges the availability is necessary and the knowledge on data coverage becomes even more important. Therefore, further research on IVS90 data coverage and correctness is recommended, especially during extreme low discharge conditions.

The limited available data during extreme low discharge conditions in 2018 during the data analyses resulted in the exclusion of several RWS-classes due to insufficient data. In this research a detailed IWT analysis was performed on the IVS90 data of 2018. However, more data points per RWS-class are needed. Combining the data of multiple years with extreme low discharges could resolve the need for more IWT data points to analyse all RWS-classes. With more drought data, RWS-classes with only limited number of passages can be analysed and a more detailed fleet composition during extreme low discharge can be composed. When combining multiple years of IWT data, the general change in fleet composition due to vessel renewal must also be taken into account. The general ship renewal trend assumed today, is that smaller vessels are replaced by larger vessels, increasing their individual transport capacity but reducing the number of vessels that can remain operational during extreme low discharges. With the investigation of the RWS-class fleet in more detail and the analysis of the fleet compositions changes over time, traffic simulations for future fleet compositions could be performed. With future fleet composition traffic simulations the effect of changes in the fleet composition on the traffic flow, during extreme low discharge can be determined. With these results, insight can be provided on the impact of general ship renewal trends on the traffic flow and traffic capacity during extreme low discharges.

One factor impacting traffic flow during extreme low discharges on the river Waal is the occurrence of groundings. During this research the effect of groundings was not taken into account. However, from literature it is known that more accidents and groundings occurred during the drought of 2018. It will give more insight to know more about these accidents and groundings. How did they occur, and how long did it take to resolve the issue? Knowing the nature of accidents and groundings during extreme low discharges can help to take action to prevent future accidents and groundings. Also, the time span can provide insight into the impact of accidents and groundings on the traffic flow in the river during extreme low discharges. Also, other relevant questions could be investigated like: what were the locations where groundings occurred and were there multiple groundings on one specific location? Investigation into these questions could help waterway management authorities to take action and prevent groundings in the future.

8.2. SIMDAS improvements

In this research traffic simulations were carried out with SIMDAS. With SIMDAS multiple scenarios were simulated. Three main themes were the basis of the performed scenario simulations, the four weeks representing the drought of 2018, an increasing intensity and a reduction of the navigable river width. The difference between the themes about the four weeks representing the drought of 2018 and the reduction of the navigable river width, was the input intensity and the entered river profile. When remaining the intensity constant between models but changing the river profile from highly variable as in reality, to a more abstract profile representing the navigable river width, it was found that there was a large difference in the model output. The SIMDAS simulations with a highly variable river profile showed irregularities in the vessels trajectory but had relatively lower output values than the simulations representing the navigable river width. Therefore, it is recommended to investigate the vessel trajectory response to highly varying cross-sections in SIMDAS.

Currently the representation of fairways with multiple traffic lanes in SIMDAS can not be guided. SIMDAS uses only one lane for upstream travelling vessels and one lane for downstream travelling vessels, which are separated by the reference line. It is assumed that SIMDAS represents reality well as traffic lanes are not visible in the fairway and vessels use the available fairway width. However, the representation of the traffic lanes in SIMDAS has not been validated and should be investigated when addressing fairways with multiple lanes during high intensities. In order to investigate multiple lane traffic, AIS data is required to follow the vessel's trajectories and determine the number of traffic lanes used in practise.

8.3. Advice for waterway management authorities

In this research it was found that the delay time cost due to the extreme low discharge conditions in 2018 was potentially significant. Therefore, it is recommended to take the effect of increased delay time cost due to discharges below the agreed low discharge level at Lobith of 1020 m^3/s (the ALD level) into account in future economical impact assessments. In the navigable river width analysis it was found that during discharges of 900 m^3/s and lower, the river depth of 2.80 m could not be found for all cross-sections. The very limited available water depth during extreme low discharges was further confirmed by the least available depth values of 2018. Monitoring the river bed should be a high priority for RWS as the river depth agreements of the CCNR were frequently not met in 2018. However, the disappearance of the obligation to monitor the river bed every couple of weeks in the new RWS dredging contract seems contradicting the observations in 2018 which involve very limited available river depths and the consequence of large bed forms during low discharges for navigation. With the very limited fairway depth in the river Waal during extreme low discharges, also the navigable river width is limited. It was found that at several cross-sections the river width was less than the maintenance width of 150 m. The minimum navigable width at a river depth of 2.0 m was only 28 m.

In the river Waal there is a pilot project on longitudinal training dams. Longitudinal training dams are placed more inwards to the centre-line of the fairway in order to increase the flow rate and increase the local depth in the river. The spatial efficiency on the river Waal reduced at the pilot project location. It was found that the skippers on the river Waal kept more distance from the longitudinal training dams than was necessary due to a psychological impact. During the evaluation of the pilot project it was found that at extreme low discharges the river width reduction at the longitudinal training dams was 30 to 40 m extra compared to the river at traditional training works. However, the debate on replacing existing training works in the river Waal with nature enhancing longitudinal training dams continues. Obviously, if existing training works in the river Waal will be replaced by longitudinal training dams, the effect on the navigable width during extreme low discharges must be minimised.

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A

Traffic simulation model equations

First of all, the represented subject vessel speed and distance from the reference line are determined with:

$$d_{max} \leq d_g \leq d_{min} \tag{A.1}$$

$$ug \leq u_{max} \tag{A.2}$$

in which:

d_{ref}	=	Reference distance.	[m]
d_{max}	=	Maximal distance from the reference line.	[m]
d_g	=	Desired distance.	[m]
d_{min}	=	Minimal distance from the reference line.	[m]
u_{ref}	=	Reference speed of the object vessel.	[m/s]
u_{max}	=	Maximal speed of the vessel.	[m/s]
u_g	=	Desired speed of the object vessel.	[m/s]

The desired distance is thereby determined with:

$$u_g \leq u_{max}$$

if	$d_{min} \leq d_{ref} \leq d_{max}$	then $d_g = d_{ref}$
if	$d_{ref} < d_{min}$	then $d_g = d_{min}$
if	$d_{ref} > d_{max}$	then $d_g = d_{max}$

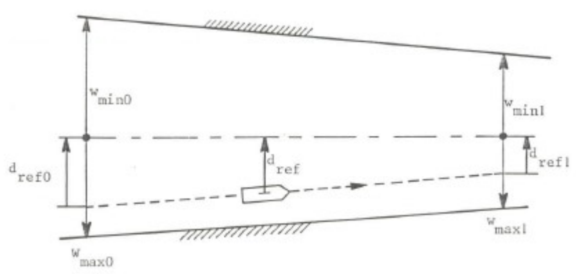

Figure A.1: The subject ship position relative to the reference line and fairway boundaries (Bekendam et al., 1988)

The order of processing is set with the priority scheme:

$$P = [s_1, s_2, \ldots s_n] \tag{A.3}$$

in which:

s_1 = The situation with the highest priority.

s_n = The situation requiring the lowest priority.

After handling a situation, a new path is defined with the following equations:

$$d_1 = \frac{(w_{max1} - w_{min1})}{(w_{max} - w_{min})} \cdot (d - w_{min} + w_{min1}) \tag{A.4}$$

$$tan\left(\alpha_{ref}\right) = \frac{\left(d_{ref0} - d_{ref1}\right)}{1 - x'} \tag{A.5}$$

in which:

w_{min}, w_{max}	=	The instantaneous fairway boundaries.	[m]
w_{min1}, w_{max1}	=	The fairway boundaries at the end of the reference line.	[m]
d	=	The instantaneous lateral distance.	[m]
$1 - x'$	=	The distance till the end of the reference line.	[m]

and

d_1 = d_{ref1}

d = d_{ref0}

The minimal spacing between ships is determined as:

$$A = f_A \cdot l_s + 0.5\left(l_s + l_j\right) \tag{A.6}$$

$$B = f_B\left(b_s + b_j + w\left(\Delta b_s + \Delta b_j\right)\right) + 0.5\left(b_s + b_j + \Delta b_s + \Delta b_j\right) \tag{A.7}$$

in which:

l	=	Ship length	[m]
b	=	Ship width	[m]
s	=	Subject ship index	
j	=	Index other ships	
f_A, f_B	=	Model parameters depending of ship class, direction and loading.	
Δb	=	Added width	
w	=	Weight factor for the added width, depending on ship class, direction and loading.	

and $0.5\left(b_s + b_j + \Delta b_s + \Delta b_j\right)$ is a midpoint correction

To determine whether another ship is coming from the front, the back or the side, C is calculated.

$$C = f_C \cdot f_{A,i} \cdot l_i + 0.5\left(l_s + l_j\right) \tag{A.8}$$

in which:

l = Ship length

i = Index for lagging ships.

f_C = Model parameter, equal to all ship classes.

f_A = Model parameter depending of ship class, direction and loading.

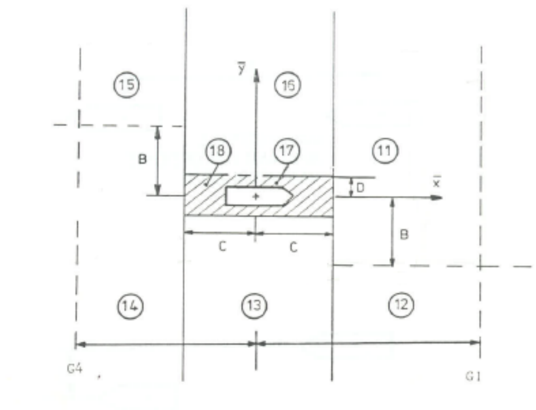

Figure A.2: The overtaking procedures for the possible manoeuvres 11 to 18 (Bekendam et al., 1988)

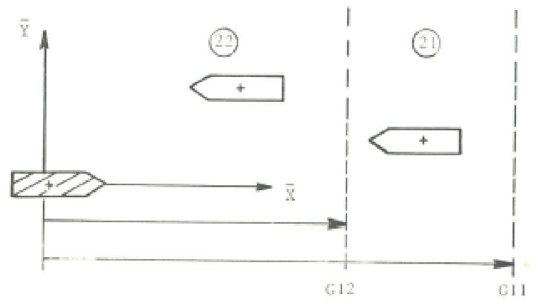

Figure A.3: Encountering procedures for the possible manoeuvres 21 and 22 (Bekendam et al., 1988).

The observed distance is determined as G1 to G4 for overtaking and G11 to G13 for encountering, see figures A.2 and A.3. The observation limits are specified with model factors per ship class, called f_{G1}, f_{G4} as well as f_{G11} and f_{G12}. During manoeuvring vessels outside these observation boundaries are not accounted for.

$$G1 = f_{G1} \cdot f_{A,s} \cdot l_s + 0.5\left(l_s + l_j\right) \tag{A.9}$$

$$G4 = f_{G4} \cdot f_{A,j} \cdot l_j + 0.5\left(l_s + l_j\right) \tag{A.10}$$

$$G11 = f_{G11} \cdot \left(l_s + l_j\right) + 0.5\left(l_s + l_j\right) \tag{A.11}$$

$$G12 = f_{G12} \cdot \left(l_s + l_j\right) + 0.5\left(l_s + l_j\right) \tag{A.12}$$

Ships from the front are therefore determined with: $x' \geq C$. Resulting in the fairway positions:

Position 11: $y' > -B$ and $x' < G1$

Position 12: $y' \leq -B$ and $x' < G1$

Position 21: $G12 \leq x' < G11$

Position 22: $0 < x' < G12$

When there is a ship aside the subject ship then $|x'| < C$:

Position 13: $y' \leq -D$

Position 16: $y' \geq D$

Position 17: $|y'| < D$ and $x' > 0$

Position 18: $|y'| \leq D$ and $x' \leq 0$

in which:

D	=	$0.5\left(b_s + b_j + \Delta bm_s + \Delta bm_j\right)$
Δbm	=	Instantaneous extra path width.

Lastly, ships coming from the back are therefore determined with: $x' \leq C$.

Position 14: $y' < B$ and $-x' < G4$

Position 15: $y' \geq B$ and $-x' < G4$

For encountering the minimal distance is defined as BT. Where f_{BT} refers to the model parameter and Δbb is the maximal path width.

$$BT = f_{BT}\left(b_s + b_j + w\left(\Delta bb_s + \Delta bb_j\right)\right) + 0.5\left(b_s + b_j + \Delta bb_s + \Delta bb_j\right) \tag{A.13}$$

The drift angle is determined as:

$$\beta = f_d \cdot \left(\left(2\frac{u_a}{u_r} - 1\right) \cdot \frac{L}{R}\right) \tag{A.14}$$

$$f_d = c_\beta \left(\frac{T}{h}\right) \tag{A.15}$$

in which:

f_d	=	Drift factor	[rad]
c_β	=	Drift coefficient	[rad]
T	=	Draught of the ship	[m]
h	=	Water depth	[m]
u_a	=	Ground speed	[m/s]
u_r	=	Speed of the ship relative to the water	[m/s]
L	=	Ship length	[m]
R	=	Bend radius	[m]

At bottleneck locations, see figure A.4, ships moving with the flow direction must give priority to vessels moving upstream. Ship x must give priority to ship y. Holding the position of ship x at the decision point, until the passage of transect B is possible. At the decision point in transect C, the procedure is repeated, figure 10-1 from (Bekendam et al., 1988).

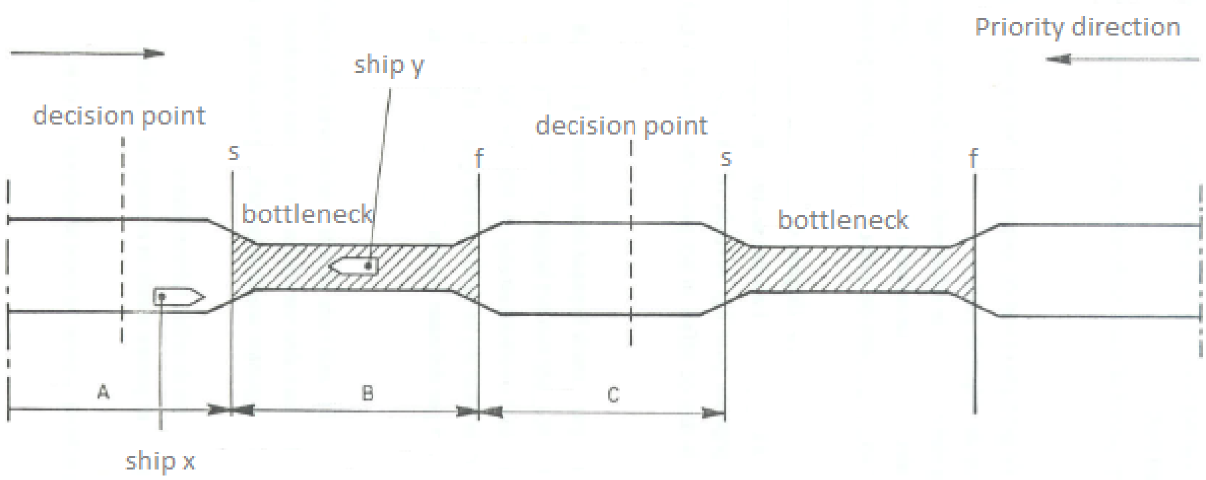

Figure A.4: SIMDAS bottleneck handling procedure. Ships moving with the flow direction give priority to vessels moving against the flow direction.

In river sections where sailing with a blue sign is permitted (see figure A.5), upstream vessels must adapt there speed/course. The program gives special attention to the blue sign lane crossing vessels, figure 11-1 from (Bekendam et al., 1988).

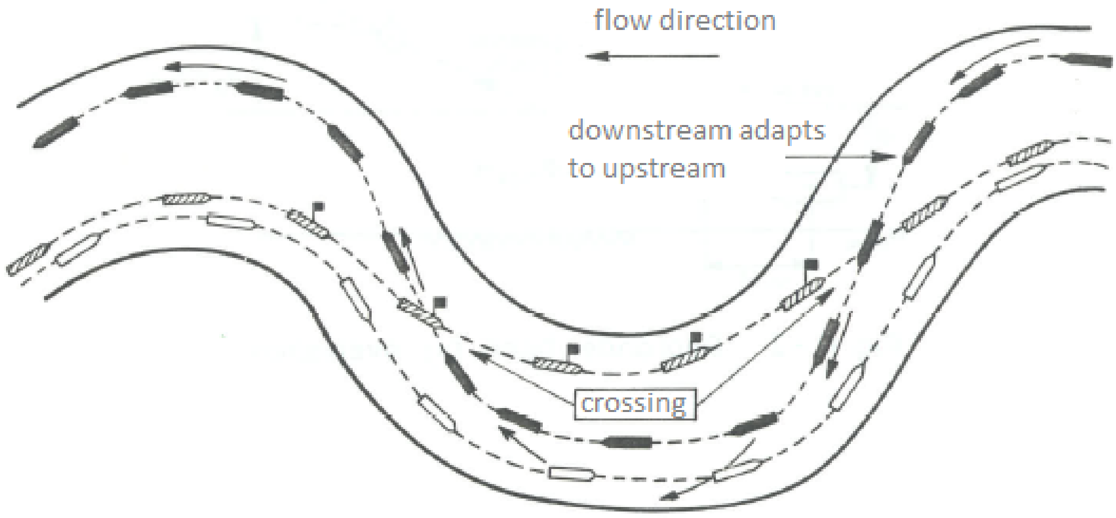

Figure A.5: SIMDAS example of a blue sign fairway section. Vessels moving with the flow direction must adapt there speed to avoid conflicts with vessels moving against the flow direction while crossing to the opposite side of the fairway.

In river bends the keep-your-lane procedure is more complicated. Furthermore, blue sign sections are making bends even more complicated. Therefore, the program adapts the procedure, illustrated in figures A.6 & A.7.

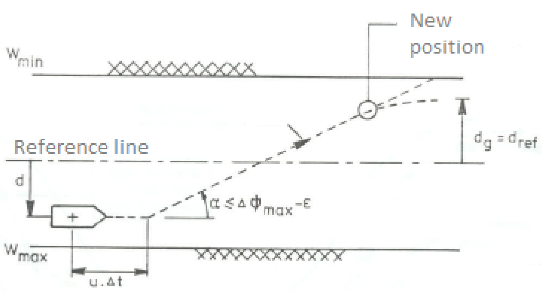

Figure A.6: Lane crossing procedure for ships simulated with SIMDAS (Bekendam et al., 1988).

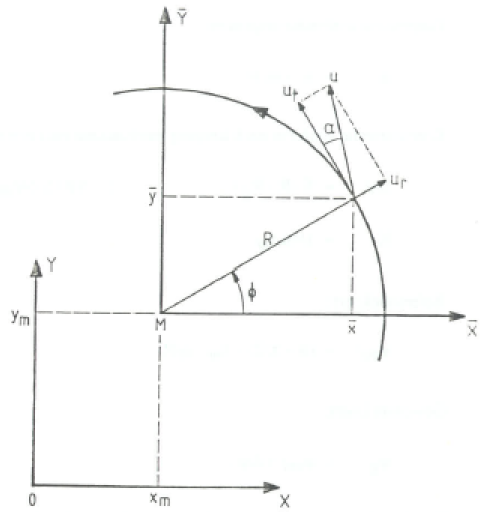

Figure A.7: Keep-your-lane principle for circular reference lines in SIMDAS (Bekendam et al., 1988).

B

Hydraulic analysis

River Rhine discharge data at Lobith is freely available from Rijkswaterstaat and can be accessed easily. Discharge data is gathered from 1901 onward. To reduce the computation time in MATLAB first the discharge in 2018 is analysed, figure B.1. Followed by the top 15 average discharge in Sep-Nov (table C.1), figure B.2.

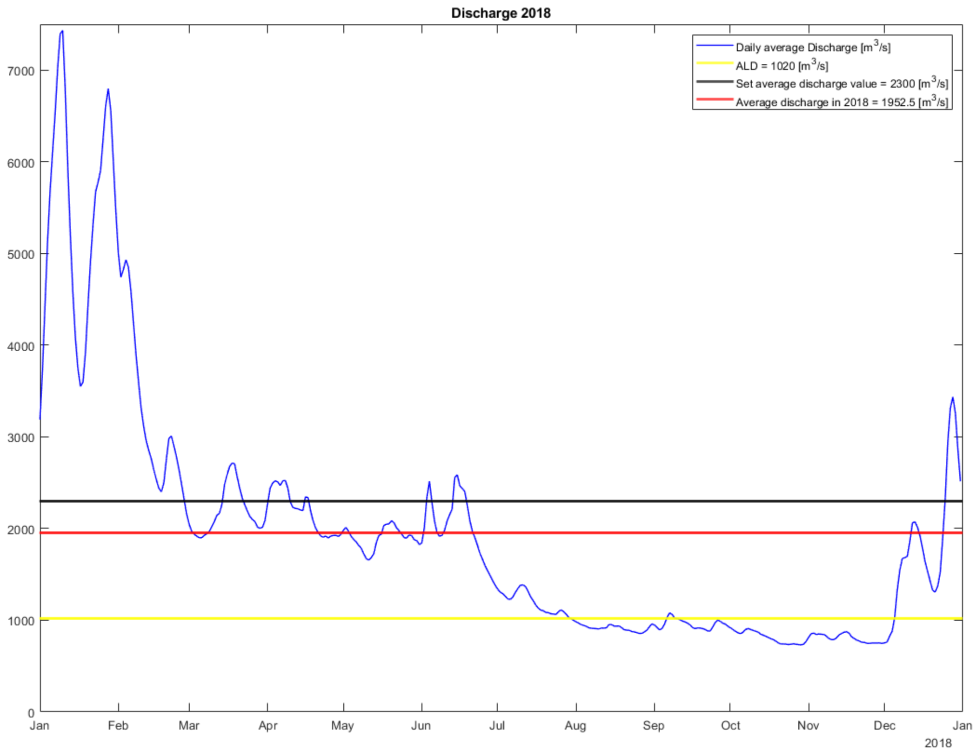

Figure B.1: Daily averaged river discharge at Lobith in 2018, including the 2018 average discharge, the agreed low discharge and the average discharge (Hermeling, 2004).

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Table B.1: Historic discharge data, containing the top 15 days with discharge below 1200 m^3/s and average low discharges (Scheijven, 2019). Furthermore, the measured lowest discharge is ranked in a top 15.

	Q < 1200 m^3/s		**Average Q, May-Aug**		**Average Q, Sep-Nov**		**Lowest Q per year**	
	Year	days	Year	Q [m^3/s]	Year	Q [m^3/s]	Year	Q [m^3/s]
1	1921	233	1921	1084	1949	746	1929	575
2	1976	198	1976	1132	1947	821	1947	620
3	1949	191	1934	1254	1959	850	1949	635
4	1964	162	1949	1260	2018	859	1963	665
5	1947	156	1947	1300	1921	902	1921	670
6	1972	142	1964	1399	1943	964	1954	680
7	2018	138	2011	1418	1953	987	1953	685
8	1943	116	2003	1420	1962	997	2018	709
9	1934	112	1943	1470	1971	1004	1959	715
10	2003	105	1952	1486	1976	1028	1971	760
11	1929	104	2018	1501	1906	1071	2003	780
12	1904	101	1998	1520	1907	1074	1943	780
13	2011	100	1959	1563	1929	1084	1976	782
14	1959	95	1950	1577	1911	1109	1972	800
15	1911	94	1929	1579	2003	1122	1962	810

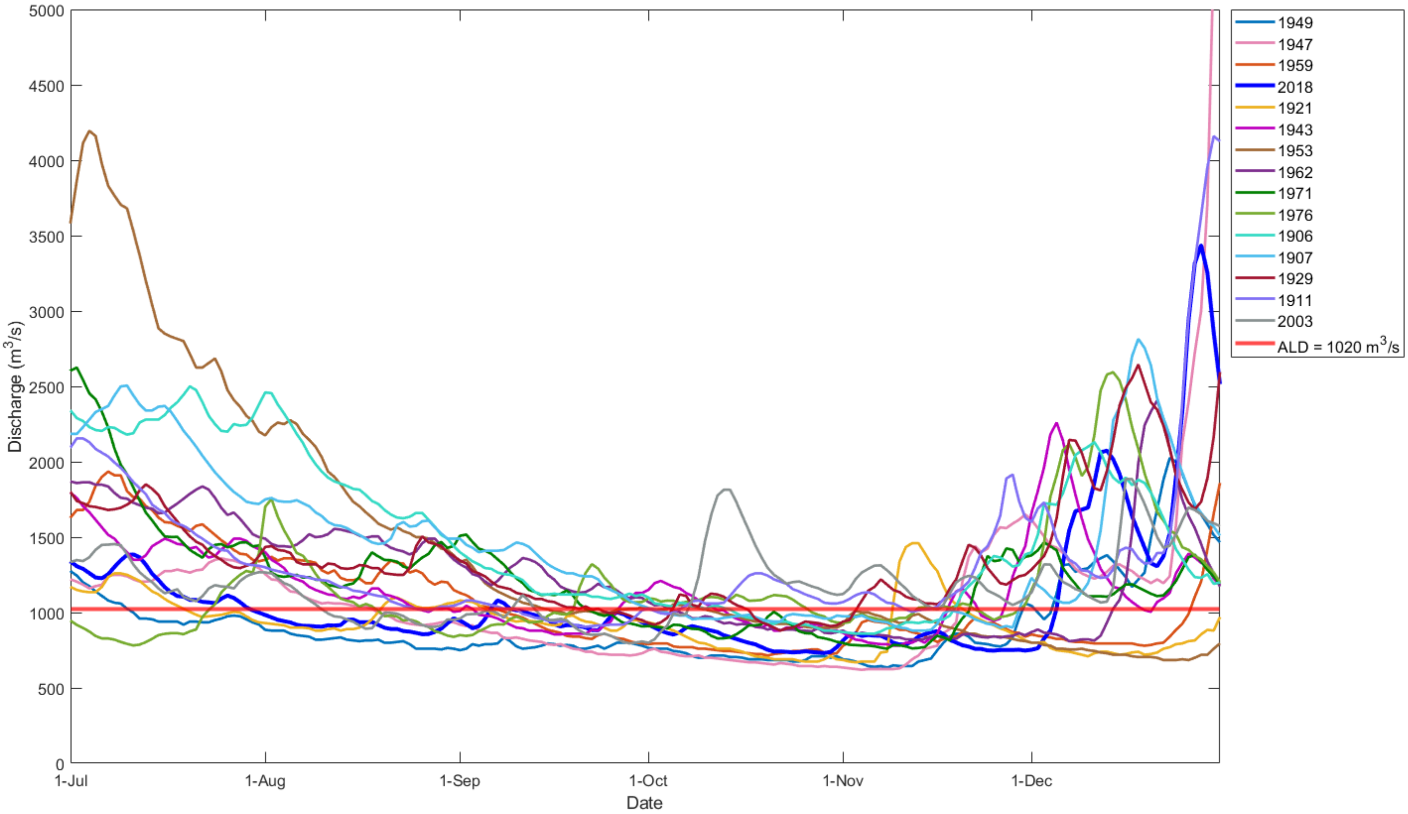

Figure B.2: Top 15 average low discharge zoomed in for July till December measured at Lobith, plotted in ranking order.

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B.1. River width

To confirm the chosen river section, the Pannerdensche Kop till the Maas-Waal canal, based on bottleneck occurrences, the depth contour-lines were analysed for the extreme low discharges. Figures B.3 and B.4 show the contour lines associated with a discharge of 800 m^3/s at Lobith. Furthermore, figures B.5 and B.6 show the same contour lines for a discharge of 700 m^3/s., while figures B.7 and B.8 consider 600 m^3/s. These figures, clearly show the limited navigational dimensions in the rivers right turning lower bends. Both bends are right turning bends, as the river flows from the right to the left side of the figure. Therefore, at the right side (upstream side) the Pannerdensche Kop is located and at the left side (downstream) the Maas-Waal canal.

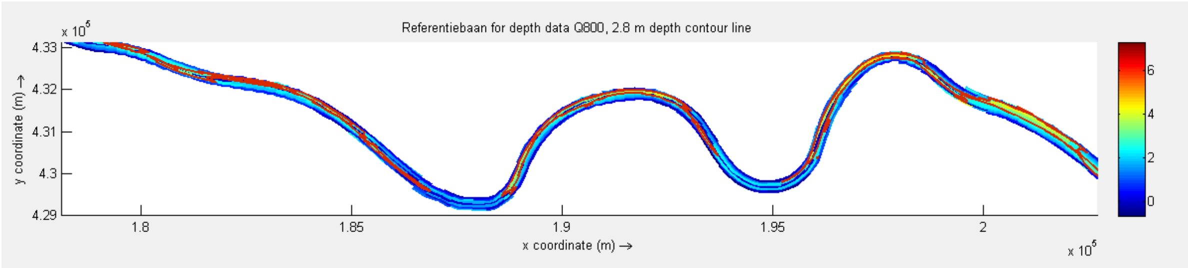

Figure B.3: Depth contour lines at 2,8 m for a discharge of 800 m^3/s at Lobith.
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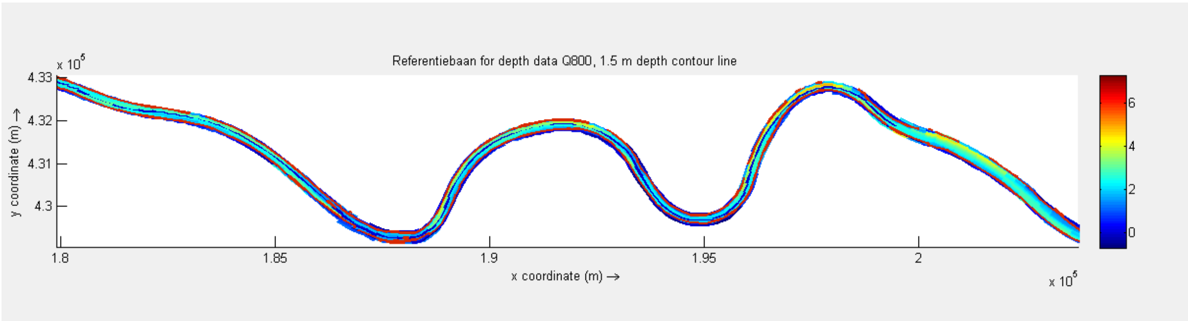

Figure B.4: Depth contour lines at 1,5 m for a discharge of 800 m^3/s at Lobith.
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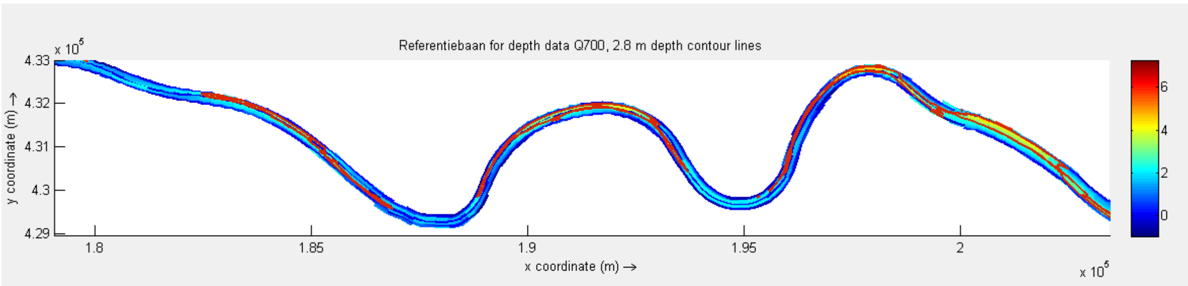

Figure B.5: Depth contour lines at 2,8 m for a discharge of 700 m^3/s at Lobith.
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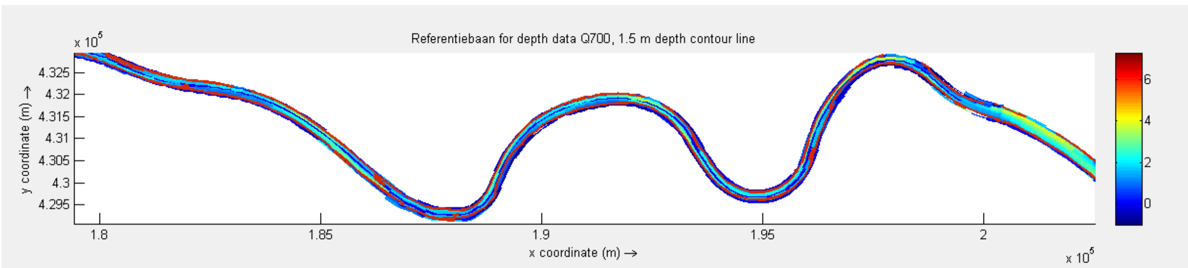

Figure B.6: Depth contour lines at 1,5 m for a discharge of 700 m^3/s at Lobith.
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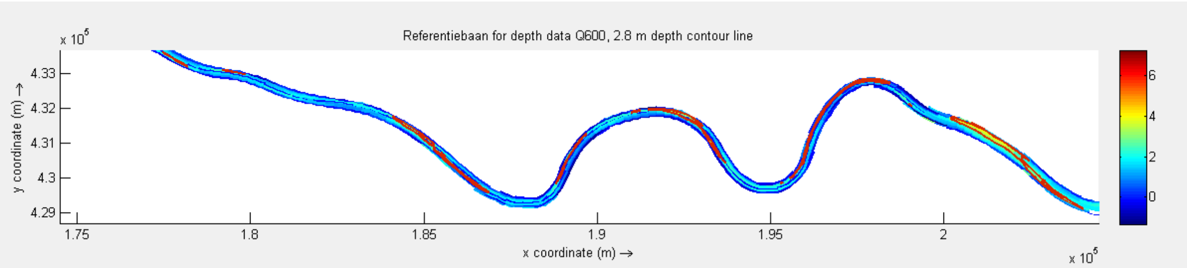

Figure B.7: Depth contour lines at 2,8 m for a discharge of 600 m^3/s at Lobith.
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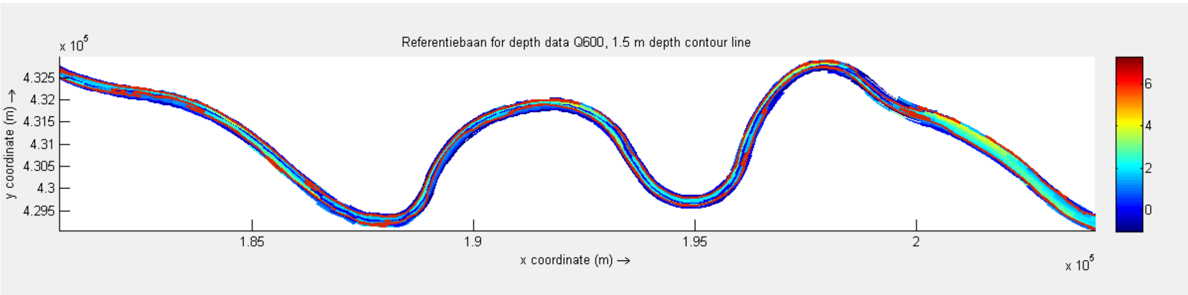

Figure B.8: Depth contour lines at 1,5 m for a discharge of 600 m^3/s at Lobith.
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Combining all cross-sectional data in MATLAB results in more data points then SIMDAS can process. The selection of 5 left and 5 right cross-sectional data points is checked based on visual characteristics. The SIMDAS model interpolates the profile to connect the individual data points. The reference line does not count for one of the 5 points, it is assigned separately. For all profiles the river width was determined at a depth of 2.0 m. The depth of 2.0 m was chosen based on the available depth for all discharges. The 2.80 m depth criteria from the ALD, was already no longer possible for all cross-sections during a discharge of 900 m^3/s.

Table B.2: Bend radius between two consecutive cross-sectional profiles with direction T for clockwise rotation and F for anti-clockwise rotation.

Position	Radius [m]	Direction [F/T]	Position	Radius [m]	Direction [F/T]	Position	Radius [m]	Direction [F/T]
55	57873.05	T	85	8435.39	T	115	1414.68	T
56	1992.23	F	86	7967.69	F	116	1628.83	T
57	1615.08	F	87	2179.87	F	117	1774.77	T
58	1520.49	F	88	1900.27	F	118	2010.29	T
59	1396.31	F	89	1896.66	F	119	3065.35	T
60	1296.21	F	90	1882.89	F	120	4043.61	T
61	1176.87	F	91	1875.85	F	121	5024.53	T
62	1132.58	F	92	1925.98	F	122	8831.30	T
63	1167.23	F	93	2042.98	F	123	8587.43	T
64	1563.82	F	94	2132.60	F	124	10832.82	T
65	2287.73	F	95	2340.63	F	125	31171.32	F
66	2781.78	F	96	3052.33	F	126	7371.91	F
67	3113.62	F	97	3841.06	F	127	8754.18	F
68	3094.97	F	98	3997.11	F	128	8108.89	F
69	3135.41	F	99	3718.17	F	129	7589.07	F
70	3303.41	F	100	2897.09	F	130	7102.64	F
71	3369.04	F	101	2437.53	F	131	5767.83	F
72	8857.51	F	102	2397.78	F	132	4662.40	F
73	18302.81	T	103	2397.75	F	133	4079.48	F
74	3057.46	T	104	2437.68	F	134	4102.25	F
75	1373.44	T	105	2609.60	F	135	4454.51	F
76	1234.48	T	106	2825.52	F	136	5192.44	F
77	1141.96	T	107	2878.30	F	137	8866.05	F
78	1113.46	T	108	3185.92	F	138	12567.25	F
79	1171.52	T	109	7568.33	F	139	15231.54	F
80	1278.68	T	110	3416.32	T	140	-	-
81	1353.49	T	111	1202.15	T			
82	1560.04	T	112	923.28	T			
83	2534.14	T	113	852.74	T			
84	5620.10	T	114	1023.11	T			

Table B.3: River width for the cross-sectional profiles 55 till 90, for the discharges 1020, 900, 800, 700 and 600 m^3/s.

Position units	1020 [m]	900 [m]	Change %	800 [m]	Change %	700 [m]	Change %	600 [m]	Change %	Total change %
55	162	155	-4	154	-1	154	0	104	-33	-36
56	153	153	0	153	0	153	0	92	-40	-40
57	161	159	-2	159	0	159	0	85	-47	-48
58	217	217	0	217	0	217	0	124	-43	-43
59	190	190	-1	190	0	190	0	105	-45	-45
60	180	179	-1	179	0	179	0	107	-40	-41
61	153	149	-3	146	-2	146	0	107	-27	-30
62	166	162	-3	162	0	162	0	92	-43	-45
63	165	155	-6	155	0	155	0	92	-41	-44
64	171	164	-4	164	0	164	0	92	-44	-46
65	171	153	-10	153	0	153	0	92	-40	-46
66	145	120	-18	120	0	120	0	83	-31	-43
67	158	122	-23	122	0	122	0	85	-30	-46
68	178	132	-26	132	0	123	-7	85	-31	-52
69	222	200	-10	199	-1	190	-5	72	-62	-67
70	219	205	-6	201	-2	201	0	92	-54	-58
71	217	200	-8	198	-1	197	-1	78	-60	-64
72	220	205	-7	203	-1	203	0	83	-59	-62
73	229	210	-8	146	-30	146	0	106	-28	-54
74	226	142	-37	121	-14	121	0	91	-25	-60
75	212	207	-2	110	-47	110	0	97	-12	-54
76	216	206	-5	185	-10	185	0	55	-70	-75
77	212	195	-8	162	-17	162	0	160	-1	-24
78	199	188	-5	169	-10	169	0	168	-1	-15
79	211	184	-13	169	-8	169	0	167	-1	-21
80	201	180	-10	153	-15	153	0	150	-2	-25
81	209	192	-8	172	-11	171	-1	171	0	-18
82	213	185	-13	160	-13	160	0	158	-1	-26
83	211	183	-14	168	-8	168	0	167	-1	-21
84	221	192	-13	173	-10	173	0	161	-7	-27
85	224	196	-13	171	-12	171	0	132	-23	-41
86	232	129	-45	115	-11	115	0	88	-23	-62
87	241	112	-53	106	-5	106	0	89	-16	-63
88	227	107	-53	106	0	106	0	78	-26	-66
89	223	190	-15	190	0	190	0	80	-58	-64
90	217	173	-20	172	0	172	0	143	-17	-34

Table B.4: River width for the cross-sectional profiles 91 till 125, for the discharges 1020, 900, 800, 700 and 600 m^3/s.

Position	1020	900	Change	800	Change	700	Change	600	Change	Total change
units	[m]	[m]	%	[m]	%	[m]	%	[m]	%	%
91	213	171	-20	171	0	170	0	134	-22	-37
92	192	168	-12	168	0	168	0	142	-15	-26
93	187	161	-14	161	0	161	0	132	-18	-29
94	182	156	-14	156	0	156	0	130	-17	-28
95	168	149	-11	149	0	149	0	113	-24	-33
96	156	148	-2	148	0	148	0	107	-28	-32
97	195	159	-19	159	0	159	0	109	-31	-44
98	201	147	-27	146	-1	146	0	102	-30	-49
99	196	192	-2	192	0	191	-1	120	-37	-39
100	208	204	-2	204	0	204	0	188	-8	-10
101	198	189	-5	189	0	189	0	160	-15	-19
102	208	191	-8	191	0	191	0	138	-28	-34
103	196	188	-4	188	0	187	-1	133	-29	-32
104	208	142	-32	141	-1	141	0	93	-34	-55
105	163	100	-39	99	-1	98	-1	86	-12	-47
106	195	89	-54	86	-3	86	0	70	-18	-64
107	172	101	-41	96	-5	95	-1	84	-12	-51
108	171	124	-27	109	-12	109	0	105	-4	-39
109	164	127	-23	111	-13	111	0	111	0	-32
110	190	124	-35	106	-15	106	0	106	0	-44
111	207	184	-11	127	-31	127	0	127	0	-39
112	209	200	-4	189	-5	188	-1	188	0	-10
113	200	183	-8	164	-10	163	-1	163	0	-18
114	159	142	-10	28	-81	28	0	28	0	-83
115	180	167	-7	33	-80	32	-3	31	-2	-83
116	196	175	-11	42	-76	42	0	42	0	-79
117	235	217	-8	88	-59	86	-2	86	0	-63
118	217	194	-11	92	-53	91	-1	90	-1	-59
119	184	167	-9	41	-75	40	-3	39	-3	-79
120	216	197	-9	59	-70	59	0	59	0	-73
121	185	123	-34	113	-8	113	0	113	0	-39
122	211	101	-52	91	-10	91	0	91	0	-57
123	215	100	-53	90	-10	90	0	90	0	-58
124	235	164	-30	150	-8	150	0	150	0	-36
125	215	145	-33	134	-8	132	-1	132	0	-39

Table B.5: River width for the cross-sectional profiles 126 till 140, for the discharges 1020, 900, 800, 700 and 600 m^3/s.

Position	1020	900	Change	800	Change	700	Change	600	Change	Total change
units	[m]	[m]	%	[m]	%	[m]	%	[m]	%	%
126	217	200	-8	200	0	200	0	200	0	-8
127	242	199	-18	196	-1	195	-1	195	0	-19
128	199	172	-14	172	0	172	0	172	0	-14
129	198	176	-11	176	0	174	-1	174	0	-12
130	197	169	-14	169	0	169	0	169	0	-14
131	199	165	-17	165	0	165	0	165	0	-17
132	225	185	-18	185	0	185	0	185	0	-18
133	219	198	-10	198	0	198	0	198	0	-10
134	218	210	-3	158	-25	158	0	158	0	-27
135	200	193	-3	193	0	193	0	193	0	-3
136	201	196	-3	196	0	196	0	196	0	-3
137	221	221	0	221	0	221	0	220	0	0
138	197	197	0	197	0	197	0	197	0	0
139	229	228	-1	228	0	228	0	223	-2	-3
140	216	216	0	216	0	216	0	216	0	0

Table B.6

Profiles	1020	900	Change	800	Change	700	Change	600	Change	Total change
units	[m]	[m]	%	[m]	%	[m]	%	[m]	%	%
Averaged width	200	170	-15%	152	-10%	151	0%	123	-17%	-38%
Standard deviation	23	33	14%	44	20%	44	1%	46	19%	21%
Maximal value	242	228	0%	228	0%	228	0%	223	0%	0%
Minimal value	145	89	-54%	28	-81%	28	-7%	28	-70%	-83%

C

Transport analysis

C.1. General ship data

In table C.1 the CEMT-class and RWS-class were combined, leading to 33 different vessel classes.

Table C.1: Vessel CEMT-class descriptions and draught data combined with the vessels RWS-class for ships navigating the river Waal (Koedijk and Steijn, 2017, Ten Hove & Bilinska, 2017 and Roelse et al., 2002).

	CEMT-class	RWS-class	Description	Beam [m]	Length [m]	Loaded draught [m]
Coupled units	I	C1b	2 Péniches wide	10.1	38.5	2.5
	I	C1L	2 Péniches long	5.05	80	2.5
	IVb	C2L	IV + Europe I long	9.5	180	3.0
	Vb	C3L	Va + Europe II long	11.4	180	3.5
	VIa	C2b	IV + Europe I wide	18.5	103	3.0
	VIa	C3b	Va + Europe II wide	22.8	105	3.5
	VIb	C4	Va + 3 Europe II	22.8	185	3.5
Push-tow units	I	B01	barge pushed convoy	5.2	55	1.9
	II	B02	barge pushed convoy	6.7	61	2.6
	-	B03	barge pushed convoy	7.5	78	2.6
	III	B04	barge pushed convoy	8.2	85	2.7
	IV	BI	Europe I convoy	9.5	94	3.0
	Va	BII	Europe II convoy	11.4	92	3.5
	Va	BIIa-1	Europe IIa convoy	11.4	110	3.5
	Va	BIIL-1	Europe IIa convoy long	11.4	136	3.5
	VIa	BII-2b	2 barge pushed convoy wide	22.8	105	4.0
	VIb	BII-4	4 barge pushed convoy	22.8	193	4.0
	Vb	BII-2L	2 barge pushed convoy long	11.4	185	4.0
	VIIa	BII-6b	6 barge pushed convoy wide	34.2	195	4.0
	VIc	BII-6L	6 barge pushed convoy long	22.8	270	4.0
Motorized vessels	0	M0	Remaining	5.0	28	1.8
	I	M1	Péniche (Spits)	5.1	39	2.5
	II	M2	Kempenaar	6.6	55	2.6
	III	M3	Hagenaar	7.2	70	2.6
	III	M4	Dortmund Eems	8.2	73	2.7
	III	M5	Ext. Dortmund (Verlengde Dortmunder)	8.2	85	2.7
	IVa	M6	Rhine Herne vessel (Rijn Herne Schip)	9.5	85	2.9
	IVa	M7	Ext. Rhine Herne (Verlengde Rijn Herne)	9.5	105	3.0
	Va	M8	Large Rhine vessel (Groot Rijnschip)	11.4	110	3.5
	Va	M9	Ext. Large Rhine vessel (Verl. Groot Rijnschip)	11.4	135	3.5
	VIa	M10	Rhinemax vessel	13.6	110	4.0
	VIa	M11	Rhinemax vessel	14.2	185	4.0
	VIa	M12	Rhinemax vessel	17.0	135	4.0

C.2. IVS90 data analysis

IVS90 data was gathered for this study because AIS data for the low discharge period in 2018 was not available. To analyse whether AIS data from other years could be an alternative, first vast changes in the Rhine fleet were analysed. Figure C.1 shows the increase in cargo volume while the number of vessels decrease. (Kriedel et al., 2018) states that the number of vessels stabilises between 2016 and 2017.

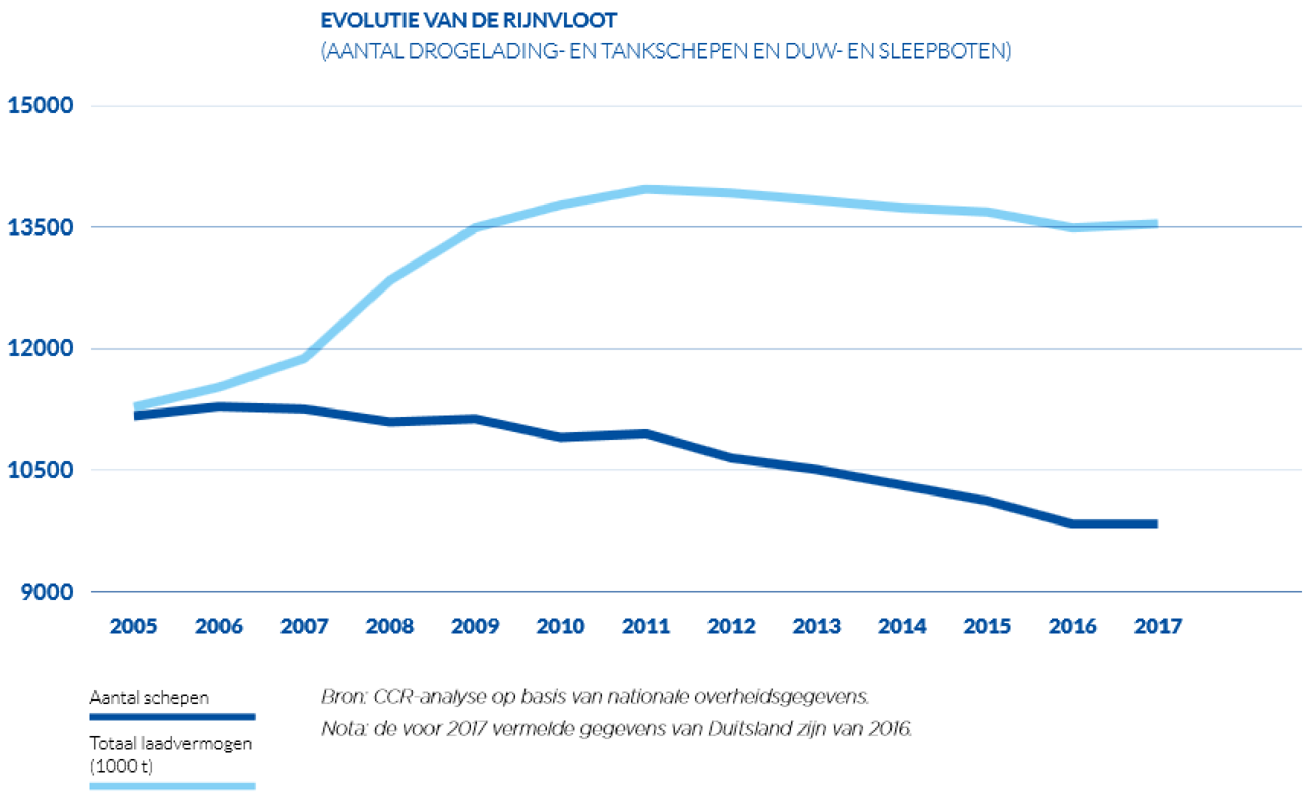

Figure C.1: Changes in number of Rhine vessels (dark-blue) and vessel cargo volume (light-blue) (Kriedel et al., 2018).

Due to the large variation in the number of Rhine vessels, a comparison of IVS90 data from recent periods of extreme drought was necessary to make a well-founded decision. Therefore, IVS90 data was collected for the years 2013, 2015 and 2018. The data sets were compared to observe a trend in IWT during low discharge, figure C.2. In this figure, a clear trend is observed in the increasing number of movements a day with decreasing discharge. For the years 2015 and 2018, a rapid decrease in vessel movements follows directly after a long period of drought. However, this phenomena could also be related to the holiday season at the end of December, which coincided in 2015 and 2018 with the end of a long period of extreme low discharge.

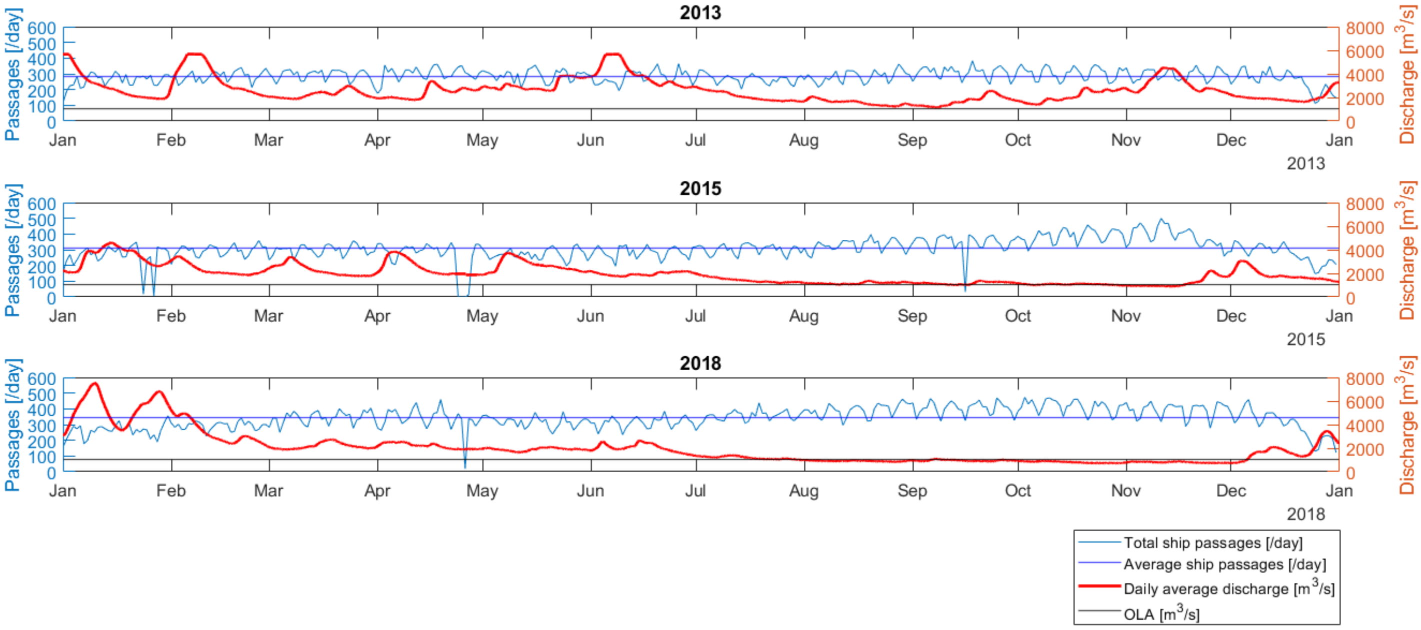

Figure C.2: The number of ship movements combined with the discharge at Lobith, for 2013,2015 and 2018.

Figure C.3: Measuring points IVS90 and river Waal sections. The river section between the Pannerdensche Kop and the Maas-Waal canal is called G12W1 and markted Bordeaux red (Reeze et al., 2017).

Figure C.3 indicates the IVS90 block-data. The block-data for the river section between the Pannerdensche Kop and the Maas-Waal canal is indicated in Bordeaux red and is called G12W1. The total number of passages in 2013, 2015 and 2018 based on the IVS90 block-data G12W1, ranges between the values in table C.2 and the values in figure C.4. Looking at the order of magnitude of the analysed data, 109230 to 122539 vessel movements, figure C.4 relates relatively well.

Table C.2: Number of passages and cargo volume transported a year between Weurt and Germany, from the year 2000 until 2005 (Alewijn, 2005).

	German border - Weurt		Pannerdensch canal	
	IWT	Cargo	IWT	cargo
Year	[Number of passages]	[ton]	[Number of passages]	[ton]
2000	130,174	7,196,732	21,263	3,646
2001	136,001	7,230,442	23,188	24,166
2002	131,235	7,230,442	21,508	24,166
2003	140,329	7,661,510	19,469	91,015
2004	135,326	9,939,282	19.344	201,743
2005	133,729	9,631,558	20,615	250,040

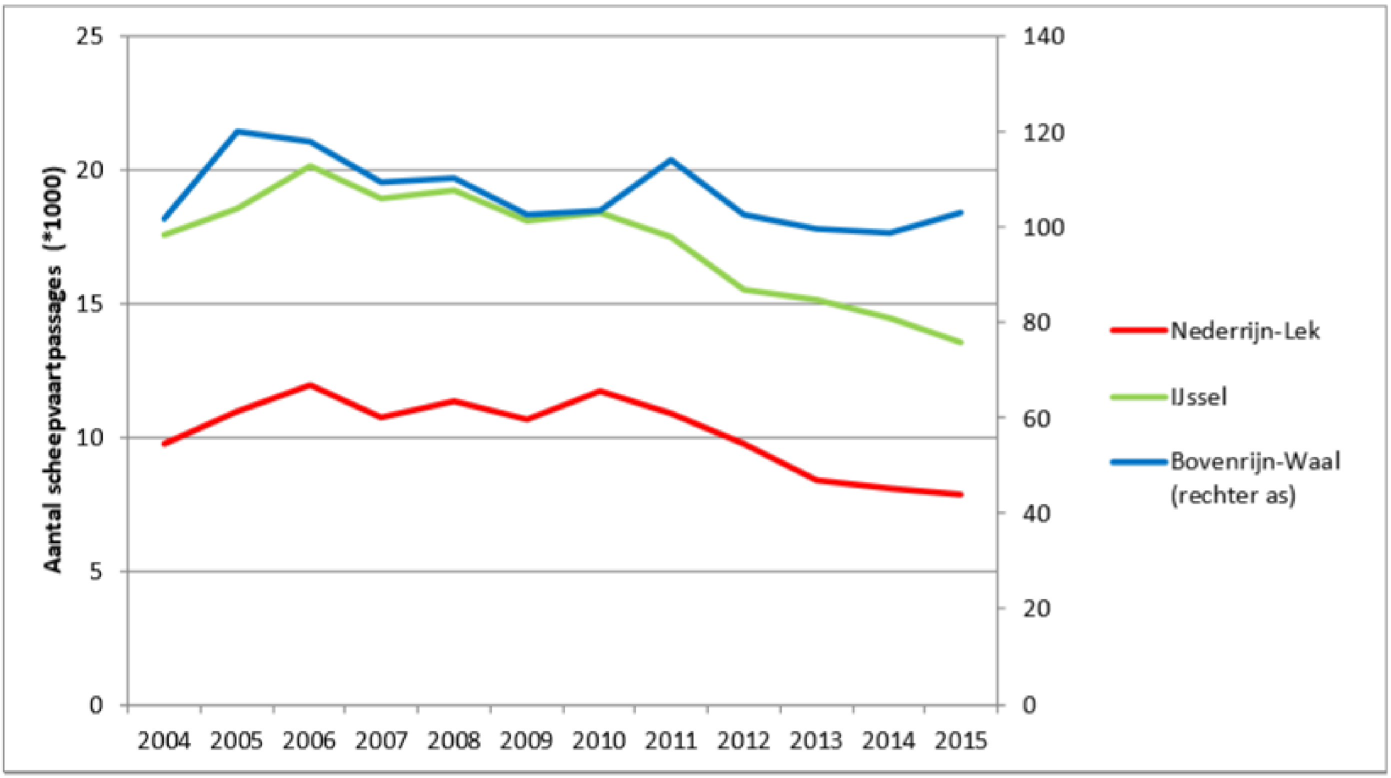

Figure C.4: In blue the total number of ship passages in the Waal counted at Nijmegen by Reeze et al. (2017) from 2004 till 2015.

In depth analysis was carried out for the 2018 IVS90 data. First the overall fleet composition, Loading status and travelling direction were analysed in figure C.5.

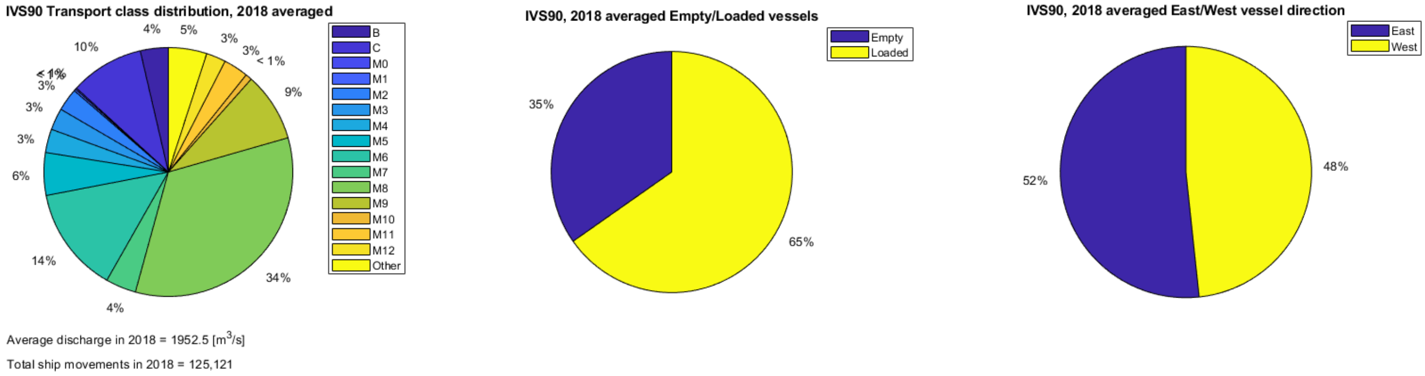

Figure C.5: Distribution of RWS-class vessels in 2018, with the 2018 average discharge, total ship movements, distribution between empty/loaded vessels and ratio between East and West going vessels.

Table C.3: Statistical inland waterway transport data parameters from 2015 by Ten Hove & Bilinska, (2017).

2015 MARIN	Water level [m]	Discharge [m^3/s]	Ships [/day]	Draught [m]	Weight [ton]
Average	8.8	1878.9	307.7	2.0	1478.9
Maximum	12.4	4624.8	496.0	5.0	21160.0
Minimum	7.0	882.8	7.0	0.5	0.0
St.deviation	1.3	828.7	64.1	0.7	1996.1

Table C.4: Statistical analysis of the 2015 inland waterway transport IVS90 data parameters.

2015 IVS90	Water level [m]	Discharge [m^3/s]	Ships [/day]	Draught [m]	Weight [ton]	Travel time [min]
Average	8.9	1918.5	306.9	1.9	2720.5	97.2
Maximum	12.4	4624.8	499.0	5.0	19723.0	18465.0
Minimum	7.0	882.8	0.0	0.5	0.0	0.0
St.deviation	1.3	823.7	70.1	0.8	2950.1	136.9

Table C.5: Statistical analysis of the 2018 inland waterway transport IVS90 data parameters

2018 IVS90	Water level [m]	Discharge [m^3/s]	Ships [/day]	Draught [m]	Weight [ton]	Travel time [min]
Average	8.7	1952.5	342.8	1.9	3033.0	142.9
Maximum	14.6	7433.4	473.0	5.1	36521.0	18064.0
Minimum	6.5	731.5	19.0	0.5	0.0	0.0
St.deviation	1.9	1366.4	67.5	0.7	2737.8	97.8

Push-tow units and couples units are investigated more thoroughly indicating that several RWS-classes were not counted in IVS90 for the investigated weeks with the weekly average discharges of 1081, 992, 798 and 740 m^3/s. The 6 barge push-tow units were not counted as expected for the analysed extreme low discharge events, with discharges far below 1600 m^3/s. While, 4 barge push-tow convoys were decreasing rapidly in numbers as the discharge decreases.

Table C.6: Push-tow units and coupled units investigated per RWS-class at weekly average discharges of 1081, 992, 798 and 740 m^3/s.

IVS90 data	22-Jul-2018		09-Sep-2018		14-Oct-2018		21-Oct-2018	
Weekly averaged discharge	1081.5		991.8		797.9		739.6	
Weekly fleet passages	2525.0		2820.0		2922.0		2826.0	
Average daily passages	360.7		402.9		417.4		403.7	
Daily averaged passages for push-tow units and coupled units								
Push-tow units	15.1	4.2%	12.6	3.1%	7.3	1.8%	2.4	0.6%
Coupled units	33.7	9.4%	40.6	10.1%	55.4	13.3%	60.9	15.1%
Daily unit passages specified in RWS-class								
B01	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
B02	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.14	0.2%
B03	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
B04	0.00	0.0%	0.14	0.3%	0.00	0.0%	0.29	0.5%
BI	0.00	0.0%	0.29	0.5%	0.57	0.9%	0.43	0.7%
BII-1	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
BII-2b	0.28	0.6%	0.57	1.1%	0.86	1.4%	0.43	0.7%
BII-2l	0.43	0.9%	0.43	0.8%	0.57	0.9%	0.29	0.5%
BII-4	13.86	28.3%	10.43	19.6%	4.57	7.3%	0.00	0.0%
BII-6b	0.00	0.0%	0.14	0.3%	0.00	0.0%	0.00	0.0%
BII-6l	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
BIIa-1	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
BIIL-1	0.57	1.2%	0.57	1.1%	0.71	1.1%	0.86	1.3%
C1b	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
C1l	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
C2b	0.14	0.3%	0.00	0.0%	0.00	0.0%	0.00	0.0%
C2l	2.43	5.0%	2.57	4.8%	2.43	3.9%	2.71	4.3%
C3b	1.14	2.3%	3.43	6.5%	2.86	4.6%	2.29	3.6%
C3l	19.43	39.8%	21.86	41.1%	26.29	41.9%	27.43	43.3%
C4	10.57	21.6%	12.71	23.9%	23.86	38.0%	28.43	44.9%

C.3. Traffic intensity

C.3.1. Week 1: 22-Jul-2018

Table C.7: Intensity for the coupled units and push-tow units per hour going East, averaged over the week of 22-Jul-2018.

	RWS-Class number of passages East 22-Jul-2018																			
Hour	C1b	C1L	C2b	C2L	C3b	C3L	C4	B01	B02	B03	B04	BI	BII-1	BII-2b	BII-2L	BII-4	BII-6b	BII-6L	BIIa-1	BIIL-1
0	0.000	0.000	0.000	0.000	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.286	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.429	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.143	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.143
5	0.000	0.000	0.000	0.000	0.000	0.429	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.143
8	0.000	0.000	0.000	0.143	0.000	0.286	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.143	0.000	0.714	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000	0.286	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.429	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.143	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	1.286	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.286	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.143
16	0.000	0.000	0.000	0.000	0.000	0.286	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.143	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.143	0.143	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.143	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.143	0.000	0.286	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.714	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.286	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.571	0.000	0.000	0.000	0.000

Table C.8: Intensity for the motorised vessels per hour going East, averaged over the week of 22-Jul-2018.

RWS-Class number of passages East 22-Jul-2018														
Hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Other
0	0.000	0.000	0.000	0.571	0.143	0.143	0.429	0.143	2.000	0.714	0.286	0.143	0.000	0.000
1	0.000	0.000	0.429	0.000	0.000	0.000	0.286	0.143	1.571	0.143	0.000	0.143	0.143	0.429
2	0.000	0.000	0.143	0.000	0.143	0.143	0.000	0.000	1.429	0.857	0.143	0.000	0.000	0.286
3	0.000	0.000	0.000	0.000	0.000	0.000	0.714	0.000	1.000	0.714	0.000	0.286	0.286	0.000
4	0.000	0.000	0.143	0.143	0.000	0.286	0.429	0.000	2.143	0.429	0.000	0.143	0.143	0.143
5	0.000	0.000	0.286	0.571	0.000	0.571	2.143	0.143	2.571	1.000	0.286	0.571	0.429	0.286
6	0.000	0.000	0.000	0.286	0.571	0.429	1.143	0.571	3.000	0.571	0.000	0.000	0.286	0.286
7	0.000	0.000	0.286	0.286	0.000	0.571	2.143	0.857	2.714	0.429	0.000	0.857	0.143	0.429
8	0.000	0.000	0.571	0.571	0.429	1.143	2.714	0.429	3.714	0.571	0.000	0.286	0.143	0.429
9	0.000	0.000	0.286	0.429	0.143	1.000	2.000	0.143	2.143	0.286	0.143	0.286	0.429	0.286
10	0.000	0.000	0.143	0.143	0.000	0.714	0.571	0.429	3.286	1.143	0.143	0.286	0.143	0.571
11	0.143	0.143	0.429	0.000	0.429	1.571	1.571	0.143	2.571	0.571	0.000	0.143	0.286	0.143
12	0.000	0.000	0.143	0.143	0.143	0.714	2.143	0.714	3.571	1.571	0.000	0.143	0.000	0.714
13	0.000	0.143	0.143	0.143	0.286	0.714	1.857	0.143	2.571	0.286	0.143	0.286	0.429	0.286
14	0.000	0.286	0.143	0.143	0.143	0.571	2.000	0.429	1.857	0.714	0.000	0.000	0.143	0.429
15	0.286	0.000	0.143	0.000	0.571	0.571	2.571	0.286	2.429	1.000	0.000	0.143	0.429	0.571
16	0.000	0.000	0.571	0.286	0.143	0.714	0.714	0.714	1.286	0.571	0.143	0.143	0.143	0.429
17	0.000	0.000	0.286	0.143	0.714	0.429	1.857	0.143	3.714	0.429	0.143	0.286	0.143	0.429
18	0.000	0.000	0.857	0.000	0.000	0.286	1.286	0.143	1.857	0.286	0.000	0.000	0.429	0.857
19	0.000	0.000	0.000	0.286	0.571	0.857	1.143	0.143	2.429	0.571	0.000	0.286	0.286	1.000
20	0.000	0.000	0.286	0.143	0.000	0.714	0.857	0.286	2.714	0.857	0.000	0.571	0.286	1.429
21	0.000	0.000	0.143	0.143	0.143	0.286	0.571	0.143	1.714	0.143	0.143	0.429	0.286	0.571
22	0.000	0.143	0.143	0.000	0.286	0.286	0.000	0.000	2.429	0.571	0.000	0.143	0.143	0.429
23	0.000	0.000	0.143	0.143	0.143	0.143	0.000	0.429	2.286	0.714	0.000	0.286	0.000	0.000

Table C.9: Intensity for the coupled units and push-tow units per hour going West, averaged over the week of 22-Jul-2018.

	RWS-Class number of passages West 22-Jul-2018																			
Hour	C1b	C1L	C2b	C2L	C3b	C3L	C4	B01	B02	B03	B04	BI	BII-1	BII-2b	BII-2L	BII-4	BII-6b	BII-6L	BIIa-1	BIIL-1
0	0.000	0.000	0.000	0.000	0.000	0.429	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.571	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.143	0.000	0.286	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143
3	0.000	0.000	0.000	0.000	0.143	0.714	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.143	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.143	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.143	0.429	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.143	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.429	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
11	0.000	0.000	0.143	0.286	0.143	0.714	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.143	0.000	0.714	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.143	0.000	0.857	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.143	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.286	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.143	0.143	0.429	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.571	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.143	0.143	0.143	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.857	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.143	1.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.286	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.571	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000

Table C.10: Intensity for the motorised vessels per hour going West, averaged over the week of 22-Jul-2018.

RWS-Class number of passages West 22-Jul-2018														
Hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Other
0	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.143	1.286	0.143	0.000	0.143	0.000	0.714
1	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.143	1.571	1.000	0.000	0.000	0.143	0.429
2	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	1.000	0.429	0.286	0.143	0.143	0.429
3	0.000	0.000	0.000	0.143	0.000	0.000	0.143	0.000	1.286	0.143	0.286	0.143	0.286	0.286
4	0.000	0.000	0.000	0.143	0.000	0.000	0.571	0.143	1.143	0.429	0.143	0.286	0.286	0.143
5	0.000	0.000	0.000	0.000	0.143	0.429	0.857	0.143	2.571	0.857	0.143	0.429	0.143	0.286
6	0.000	0.000	0.143	0.143	0.286	0.143	0.714	0.286	2.571	0.857	0.143	0.000	0.143	0.000
7	0.000	0.000	0.571	0.000	0.143	1.000	1.571	0.286	2.000	0.857	0.000	0.429	0.429	0.286
8	0.000	0.143	0.429	0.286	0.143	1.000	1.143	0.429	3.143	0.429	0.000	0.429	0.000	0.714
9	0.000	0.000	0.143	0.143	0.000	0.571	1.857	0.571	3.143	0.571	0.000	0.286	0.143	0.429
10	0.000	0.000	0.429	0.429	0.429	0.714	1.571	0.286	3.143	1.286	0.000	0.286	0.429	0.429
11	0.143	0.000	0.571	0.143	0.429	0.714	1.286	0.143	3.571	0.429	0.143	0.286	0.143	0.286
12	0.000	0.143	0.143	0.143	0.000	1.143	1.286	0.714	3.000	0.429	0.286	0.000	0.571	0.429
13	0.143	0.000	0.143	0.143	0.286	1.000	1.286	0.429	2.714	0.571	0.000	0.429	0.286	0.286
14	0.000	0.000	0.571	0.429	0.143	1.714	2.143	0.286	2.714	0.571	0.143	0.429	0.429	0.143
15	0.000	0.143	0.286	0.143	0.571	0.286	1.571	0.429	3.000	0.857	0.000	0.286	0.000	0.000
16	0.000	0.000	0.286	0.429	0.000	0.429	2.143	0.143	1.571	0.571	0.000	0.143	0.286	0.000
17	0.000	0.143	0.286	0.286	0.143	0.429	1.714	0.143	4.000	0.714	0.000	0.571	0.143	0.000
18	0.000	0.143	0.286	0.000	0.000	0.429	0.571	0.571	2.714	0.857	0.000	0.143	0.000	0.286
19	0.000	0.000	0.000	0.286	0.000	0.857	1.143	0.143	2.714	1.143	0.143	0.286	0.286	0.429
20	0.000	0.000	0.000	0.571	0.286	0.143	0.857	0.143	2.286	0.857	0.143	0.000	0.286	0.000
21	0.000	0.000	0.000	0.143	0.000	0.000	0.571	0.000	4.286	0.429	0.000	0.143	0.429	0.429
22	0.000	0.143	0.000	0.000	0.143	0.429	0.571	0.286	2.143	1.000	0.000	0.286	0.000	1.143
23	0.000	0.000	0.000	0.143	0.000	0.000	0.286	0.000	1.714	0.857	0.286	0.286	0.714	0.286

C.3.2. Week 2: 09-Sep-2018

Table C.11: Intensity for the coupled units and push-tow units per hour going East, averaged over the week of 09-Sep-2018.

	RWS-Class number of passages East 09-Sep-2018																			
Hour	C1b	C1L	C2b	C2L	C3b	C3L	C4	B01	B02	B03	B04	BI	BII-1	BII-2b	BII-2L	BII-4	BII-6b	BII-6L	BIIa-1	BIIL-1
0	0.000	0.000	0.000	0.000	0.143	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.571	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.143	0.286	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.429	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.143	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.429	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.143	0.286	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.143	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.286	0.000	0.714	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.143	0.429	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.143	0.143	0.714	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	1.143	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.286	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.143	0.000	0.714	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.143	0.000	0.286	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.286	0.000	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.571	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.143	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.286	0.143	0.714	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000

Table C.12: Intensity for the motorised vessels per hour going East, averaged over the week of 09-Sep-2018.

	RWS-Class number of passages East 09-Sep-2018													
Hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Other
0	0.000	0.000	0.143	0.000	0.000	0.000	0.571	0.000	2.429	0.857	0.286	0.143	0.000	0.000
1	0.000	0.000	0.000	0.000	0.143	0.143	0.286	0.286	2.429	1.429	0.000	0.286	0.429	0.286
2	0.000	0.000	0.000	0.286	0.000	0.286	0.143	0.286	1.714	0.143	0.000	0.000	0.286	0.286
3	0.000	0.000	0.000	0.000	0.000	0.143	0.571	0.000	2.429	0.714	0.143	0.286	0.286	0.286
4	0.000	0.000	0.286	0.143	0.000	0.286	0.286	0.000	2.143	0.429	0.286	0.286	0.143	0.429
5	0.000	0.000	0.286	0.143	0.143	0.571	1.714	0.286	2.857	0.286	0.143	0.000	0.143	0.000
6	0.000	0.000	0.286	0.286	0.429	0.429	2.286	0.429	2.571	1.143	0.000	0.429	0.571	0.429
7	0.000	0.000	0.143	0.286	0.286	1.286	2.143	0.571	3.571	1.286	0.000	0.143	0.429	0.714
8	0.000	0.000	0.286	0.143	0.286	0.857	1.571	0.571	3.143	0.143	0.000	0.429	0.286	0.000
9	0.000	0.143	0.571	0.571	0.143	0.857	2.714	0.286	4.143	0.429	0.000	0.286	0.286	0.429
10	0.286	0.143	0.429	0.429	0.286	0.571	1.429	0.429	4.143	1.143	0.286	0.000	0.429	0.000
11	0.000	0.000	0.571	0.429	0.857	0.429	1.429	0.857	3.429	1.286	0.000	0.571	0.000	0.429
12	0.000	0.000	0.286	0.286	0.571	0.571	1.571	0.429	3.429	1.286	0.143	0.286	0.429	0.571
13	0.286	0.000	0.286	0.143	0.571	1.143	1.429	0.000	3.714	0.571	0.143	0.000	0.143	0.429
14	0.000	0.000	0.429	0.429	0.571	0.714	2.000	0.714	2.857	0.857	0.000	0.429	0.143	0.571
15	0.429	0.000	0.000	0.286	0.571	0.286	1.714	0.429	3.429	0.714	0.143	0.000	0.286	0.286
16	0.000	0.000	0.286	0.143	0.000	0.286	1.286	0.143	3.000	0.714	0.000	0.429	0.429	0.429
17	0.000	0.000	0.571	0.143	0.429	0.143	1.714	0.000	3.714	0.714	0.143	0.429	0.143	0.571
18	0.000	0.143	0.143	0.286	0.286	0.714	1.429	0.429	3.143	0.286	0.000	0.286	0.143	0.571
19	0.000	0.000	0.143	0.143	0.429	0.286	1.286	0.286	3.714	0.857	0.000	0.571	0.143	1.143
20	0.000	0.000	0.286	0.571	0.286	0.714	1.000	0.714	2.429	0.714	0.143	0.000	0.571	1.000
21	0.000	0.000	0.286	0.143	0.143	0.286	0.429	0.000	2.571	0.286	0.000	0.143	0.143	0.714
22	0.000	0.143	0.429	0.000	0.286	0.286	0.571	0.000	2.571	0.857	0.000	0.571	0.286	0.143
23	0.000	0.143	0.000	0.143	0.143	0.286	0.857	0.000	3.143	1.571	0.000	0.286	0.143	0.000

Table C.13: Intensity for the coupled units and push-tow units per hour going West, averaged over the week of 09-Sep-2018.

	RWS-Class number of passages West 09-Sep-2018																			
Hour	C1b	C1L	C2b	C2L	C3b	C3L	C4	B01	B02	B03	B04	BI	BII-1	BII-2b	BII-2L	BII-4	BII-6b	BII-6L	BIIa-1	BIIL-1
0	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.286	0.143	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.143	0.000	0.000	0.000	0.143
3	0.000	0.000	0.000	0.000	0.143	0.571	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.143	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.143	0.429	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.143
6	0.000	0.000	0.000	0.000	0.143	1.143	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.857	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.143
9	0.000	0.000	0.000	0.000	0.000	0.429	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.143	0.000	0.143	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.143	0.000	0.714	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.429	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.143	0.429	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.286	0.429	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.286	0.143	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.143
15	0.000	0.000	0.000	0.000	0.000	0.571	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000
16	0.000	0.000	0.000	0.286	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.143	0.857	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.143	0.286	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.286	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.714	0.143	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.143	1.000	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.571	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.143	0.286	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.286	0.429	0.143	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.429	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000

Table C.14: Intensity for the motorised vessels per hour going West, averaged over the week of 09-Sep-2018.

	RWS-Class number of passages West 09-Sep-2018													
Hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Other
0	0.000	0.000	0.000	0.000	0.143	0.143	0.143	0.000	0.714	0.429	0.286	0.143	0.571	0.143
1	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	2.571	0.857	0.000	0.571	0.143	1.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	1.286	0.143	0.000	0.000	0.143	0.429
3	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	1.571	0.143	0.000	0.000	0.000	0.714
4	0.000	0.000	0.286	0.000	0.000	0.000	0.286	0.143	2.286	0.714	0.000	0.286	0.286	0.286
5	0.000	0.000	0.000	0.143	0.000	0.286	0.571	0.286	2.286	1.571	0.000	0.143	0.000	0.286
6	0.000	0.000	0.000	0.286	0.143	0.571	1.571	0.571	2.143	1.571	0.143	0.143	0.143	0.143
7	0.000	0.000	0.571	0.286	0.143	0.429	0.857	0.714	3.143	0.714	0.000	0.143	0.286	0.857
8	0.000	0.000	0.286	0.143	0.143	0.571	1.143	0.143	3.000	0.857	0.143	0.286	0.286	0.571
9	0.000	0.000	0.000	0.143	0.429	0.714	1.857	0.571	4.143	1.000	0.143	0.143	0.571	0.286
10	0.000	0.000	0.429	0.143	0.429	1.286	1.143	0.857	3.429	1.286	0.000	0.143	0.286	0.143
11	0.000	0.143	0.143	0.143	0.286	0.143	1.571	0.143	3.714	1.000	0.143	0.143	0.286	0.000
12	0.000	0.000	0.571	0.000	0.143	0.143	1.714	0.143	3.429	0.714	0.000	0.143	0.000	0.143
13	0.000	0.000	0.286	0.714	0.000	0.857	1.571	0.429	3.286	0.857	0.000	0.143	0.143	0.143
14	0.000	0.143	0.286	0.429	0.286	0.714	2.000	0.286	3.571	0.714	0.000	0.857	0.286	0.000
15	0.000	0.000	1.143	0.286	0.286	0.571	1.286	0.714	3.714	0.857	0.286	0.286	0.143	0.286
16	0.000	0.000	0.000	0.286	0.571	0.714	1.714	0.286	2.714	0.286	0.143	0.143	0.571	0.000
17	0.000	0.000	0.714	0.143	0.143	1.000	0.571	0.286	4.000	1.286	0.000	0.571	0.429	0.000
18	0.000	0.000	0.000	0.000	0.286	0.714	1.000	0.286	3.143	0.571	0.000	0.000	0.429	0.571
19	0.000	0.000	0.143	0.143	0.143	0.143	1.000	0.143	3.429	0.429	0.143	0.429	0.143	0.143
20	0.000	0.000	0.143	0.286	0.286	0.143	0.714	0.286	3.000	0.857	0.143	0.429	0.286	0.286
21	0.000	0.000	0.143	0.000	0.143	0.143	1.286	0.143	4.286	1.000	0.286	0.286	0.143	0.000
22	0.000	0.000	0.143	0.000	0.143	0.000	1.000	0.429	2.571	1.143	0.143	0.143	0.000	1.000
23	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	2.714	0.429	0.000	0.143	0.286	0.857

C.3.3. Week 3: 14-Oct-2018

Table C.15: Intensity for the coupled units and push-tow units per hour going East, averaged over the week of 14-Oct-2018.

	RWS-Class number of passages East 14-Oct-2018																			
Hour	C1b	C1L	C2b	C2L	C3b	C3L	C4	B01	B02	B03	B04	BI	BII-1	BII-2b	BII-2L	BII-4	BII-6b	BII-6L	BIIa-1	BIIL-1
0	0.000	0.000	0.000	0.000	0.000	0.000	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.143	0.286	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.571	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.143	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.714	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.714	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.143	0.000	0.429	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.286	0.000	0.429	0.857	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.571	0.571	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.286	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	1.000	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.429	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143
14	0.000	0.000	0.000	0.286	0.143	1.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.429	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.143	0.143	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.000	0.857	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.857	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.571	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.571	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.143	0.000	0.429	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.286	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.143
23	0.000	0.000	0.000	0.000	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000

Table C.16: Intensity for the motorised vessels per hour going East, averaged over the week of 14-Oct-2018.

	RWS-Class number of passages East 14-Oct-2018													
Hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Other
0	0.143	0.000	0.286	0.000	0.000	0.000	0.143	0.143	1.429	1.286	0.000	0.857	0.000	0.000
1	0.000	0.000	0.000	0.143	0.143	0.286	0.429	0.143	2.000	1.143	0.000	0.571	0.143	0.143
2	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.429	1.143	0.571	0.000	0.286	0.286	0.571
3	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.143	2.571	1.286	0.143	0.714	0.143	0.000
4	0.000	0.000	0.000	0.000	0.000	0.429	0.143	0.143	1.857	1.143	0.143	0.429	0.143	0.571
5	0.000	0.000	0.286	0.286	0.286	0.000	1.286	0.571	3.143	1.000	0.000	0.286	0.143	0.571
6	0.000	0.000	0.143	0.714	0.286	0.857	1.143	1.000	3.429	0.857	0.000	0.143	0.429	0.143
7	0.000	0.000	0.000	0.571	0.286	1.000	1.286	0.857	4.143	0.429	0.143	0.143	0.143	0.429
8	0.000	0.000	0.000	0.143	0.143	0.286	1.571	0.429	3.714	0.857	0.000	0.143	0.000	0.571
9	0.143	0.000	0.429	0.143	0.571	0.143	2.143	0.714	4.000	0.571	0.429	0.286	0.571	0.429
10	0.000	0.000	0.429	0.429	0.714	0.714	1.714	0.857	3.000	1.429	0.000	0.000	0.286	0.429
11	0.000	0.000	0.429	0.143	0.571	0.429	1.143	0.000	2.429	0.714	0.143	0.286	0.286	0.143
12	0.000	0.143	0.571	0.143	0.143	0.286	1.714	0.571	3.000	0.714	0.000	0.571	0.286	0.429
13	0.143	0.000	0.143	0.000	0.143	1.286	1.143	0.429	3.429	1.000	0.000	0.143	0.143	0.286
14	0.000	0.143	0.286	0.286	0.714	0.857	2.000	0.714	4.429	1.143	0.000	0.143	0.286	0.714
15	0.000	0.000	0.143	0.429	0.571	0.714	1.429	0.143	3.000	0.857	0.000	0.143	0.286	0.571
16	0.000	0.000	0.143	0.429	1.000	0.571	2.429	0.429	3.143	0.429	0.143	0.000	0.429	0.429
17	0.000	0.000	0.143	0.286	0.143	0.571	2.000	0.571	2.714	0.714	0.143	0.286	0.143	0.857
18	0.000	0.000	0.143	0.000	0.286	0.571	1.857	0.429	1.571	1.000	0.000	0.429	0.143	0.571
19	0.000	0.000	0.571	0.143	0.000	0.714	0.714	0.286	3.143	0.571	0.000	0.143	0.429	0.286
20	0.000	0.000	0.286	0.571	0.286	0.286	0.857	0.143	2.714	1.143	0.143	0.286	0.286	0.714
21	0.000	0.000	0.286	0.286	0.143	0.714	0.714	0.000	1.000	1.000	0.143	0.286	0.143	0.000
22	0.000	0.143	0.286	0.143	0.000	0.143	0.143	0.000	1.714	0.857	0.000	0.143	0.143	0.429
23	0.000	0.000	0.714	0.143	0.143	0.143	0.286	0.000	2.429	0.857	0.000	0.000	0.143	0.143

Table C.17: Intensity for the coupled units and push-tow units per hour going West, averaged over the week of 14-Oct-2018.

	RWS-Class number of passages West 14-Oct-2018																			
Hour	C1b	C1L	C2b	C2L	C3b	C3L	C4	B01	B02	B03	B04	BI	BII-1	BII-2b	BII-2L	BII-4	BII-6b	BII-6L	BIIa-1	BIIL-1
0	0.000	0.000	0.000	0.000	0.000	0.714	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.143	0.143	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143
2	0.000	0.000	0.000	0.143	0.000	0.429	0.143	0.000	0.000	0.000	0.000	0.143	0.000	0.143	0.000	0.143	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.571	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.143	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.286	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.571	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.429	0.571	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.143
8	0.000	0.000	0.000	0.143	0.143	0.286	1.143	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.286	0.143	0.571	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	1.000	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.143
11	0.000	0.000	0.000	0.143	0.429	1.286	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.429	0.000	1.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.143	0.571	0.857	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.143	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.143	1.143	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.143	0.143	0.286	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	1.000	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.143	0.429	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.143	0.714	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.286	0.714	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	1.000	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.143	0.286	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.143	0.714	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table C.18: Intensity for the motorised vessels per hour going West, averaged over the week of 14-Oct-2018.

RWS-Class number of passages West 14-Oct-2018														
Hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Other
0	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.143	2.429	0.429	0.000	0.000	0.286	0.571
1	0.000	0.000	0.000	0.000	0.000	0.143	0.143	0.000	1.714	0.571	0.000	0.143	0.143	0.857
2	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.143	2.143	0.571	0.143	0.429	0.000	0.714
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	1.857	0.143	0.286	0.714	0.000	0.571
4	0.000	0.000	0.143	0.000	0.000	0.000	0.143	0.143	1.714	0.714	0.286	0.143	0.143	0.429
5	0.000	0.000	0.000	0.000	0.000	0.143	1.000	0.429	2.714	0.714	0.000	0.286	0.000	0.000
6	0.000	0.000	0.143	0.286	0.429	0.429	1.143	0.571	3.000	2.000	0.286	0.143	0.143	0.286
7	0.000	0.000	0.429	0.143	0.143	0.143	1.000	0.571	2.286	1.571	0.000	0.000	0.000	0.429
8	0.000	0.000	0.429	0.571	0.143	0.429	1.571	0.429	4.000	1.143	0.000	0.286	0.429	0.571
9	0.000	0.000	0.571	0.571	0.000	1.143	1.571	1.286	3.429	0.857	0.000	0.143	0.571	0.286
10	0.000	0.143	0.143	0.143	0.714	1.000	2.286	0.714	4.571	0.714	0.143	0.000	0.286	0.571
11	0.000	0.143	0.286	0.286	1.000	0.571	2.571	0.714	3.143	0.714	0.000	0.571	0.143	0.286
12	0.000	0.000	0.429	0.429	0.286	0.857	2.286	0.286	3.857	1.857	0.000	0.714	0.429	0.571
13	0.000	0.000	0.571	0.286	0.286	1.000	1.857	0.000	1.857	1.000	0.000	0.286	0.571	0.286
14	0.000	0.143	0.143	0.571	0.429	0.429	1.429	0.429	4.857	0.429	0.000	0.429	0.571	0.000
15	0.000	0.143	0.143	0.143	0.429	1.000	1.143	0.571	2.857	0.714	0.143	0.286	0.286	0.143
16	0.000	0.000	0.143	0.143	0.429	0.286	1.143	0.286	5.143	1.714	0.000	0.286	0.429	0.286
17	0.000	0.000	0.429	0.286	0.143	0.143	1.429	0.000	2.286	0.714	0.143	0.714	0.571	0.429
18	0.000	0.000	0.000	0.286	0.429	0.429	1.143	0.000	2.286	1.000	0.000	0.571	0.000	0.000
19	0.000	0.000	0.000	0.286	0.429	0.143	0.857	0.286	4.571	0.857	0.143	0.286	0.000	0.571
20	0.000	0.000	0.143	0.286	0.143	0.000	0.429	0.429	3.571	0.571	0.000	0.143	0.143	0.286
21	0.000	0.000	0.143	0.143	0.000	0.571	0.571	0.429	3.857	1.429	0.000	0.143	0.000	0.286
22	0.000	0.000	0.000	0.000	0.143	0.000	0.857	0.286	3.143	1.429	0.000	0.000	0.000	0.857
23	0.000	0.000	0.000	0.000	0.143	0.143	0.571	0.143	2.857	0.571	0.000	0.714	0.286	0.571

C.3.4. Week 4: 21-Oct-2018

Table C.19: Intensity for the coupled units and push-tow units per hour going East, averaged over the week of 21-Oct-2018.

	RWS-Class number of passages East 21-Oct-2018																			
Hour	C1b	C1L	C2b	C2L	C3b	C3L	C4	B01	B02	B03	B04	BI	BII-1	BII-2b	BII-2L	BII-4	BII-6b	BII-6L	BIIa-1	BIIL-1
0	0.000	0.000	0.000	0.000	0.000	0.857	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.286	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.143	0.000	0.429	0.857	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.429	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.286	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.429	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.143
6	0.000	0.000	0.000	0.000	0.000	0.429	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.143	0.857	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.286	0.000	0.286	0.429	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.143	1.000	1.000	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.571	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.143	0.429	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.429	0.286	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143
13	0.000	0.000	0.000	0.143	0.000	1.143	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143
14	0.000	0.000	0.000	0.286	0.143	1.429	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.571	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.714	0.286	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.286	0.143	0.286	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.286	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.143	0.000	0.429	0.857	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.143	0.000	0.571	0.857	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.143	0.571	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.143	0.286	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table C.20: Intensity for the motorised vessels per hour going East, averaged over the week of 21-Oct-2018.

	RWS-Class number of passages East 21-Oct-2018													
Hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Other
0	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.286	2.143	0.857	0.143	0.143	0.000	0.429
1	0.000	0.000	0.143	0.000	0.000	0.000	0.143	0.000	1.571	0.429	0.143	0.286	0.143	0.286
2	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.143	1.286	0.429	0.286	0.429	0.000	0.714
3	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	2.000	0.429	0.143	0.571	0.000	0.000
4	0.000	0.000	0.143	0.000	0.000	0.000	0.143	0.000	1.571	0.857	0.143	0.714	0.000	0.429
5	0.000	0.000	0.000	0.143	0.143	0.429	1.000	0.429	2.429	0.286	0.143	0.000	0.143	0.143
6	0.000	0.000	0.000	0.286	0.143	0.286	0.857	0.143	2.143	1.286	0.000	0.429	0.000	0.429
7	0.000	0.143	0.571	0.143	0.000	0.143	1.429	0.429	2.857	0.857	0.000	0.000	0.429	0.286
8	0.000	0.000	0.429	0.286	0.143	0.714	1.286	0.571	2.857	1.286	0.000	0.286	0.000	0.714
9	0.000	0.000	0.143	0.000	0.143	0.571	1.571	0.714	3.000	1.714	0.000	0.286	0.143	0.143
10	0.000	0.286	0.429	0.143	0.286	0.857	1.571	0.857	4.714	2.143	0.000	0.429	0.571	0.143
11	0.000	0.000	0.286	0.571	0.571	0.857	2.143	0.857	4.143	1.429	0.000	0.429	0.429	0.286
12	0.000	0.000	0.286	0.429	0.571	0.429	1.143	0.714	4.000	1.143	0.000	0.429	0.000	0.286
13	0.000	0.000	0.571	0.143	0.286	1.000	1.000	1.286	2.143	1.143	0.143	0.286	0.571	0.857
14	0.000	0.000	0.143	0.429	0.286	1.429	1.286	0.286	3.286	1.286	0.000	0.286	0.286	0.143
15	0.000	0.000	0.000	0.714	0.143	0.286	1.714	0.714	3.429	0.571	0.000	0.286	0.286	0.000
16	0.000	0.143	0.429	0.143	0.286	0.429	1.143	0.857	2.571	1.429	0.143	0.143	0.286	0.143
17	0.000	0.000	0.143	0.571	0.143	0.571	2.286	0.429	2.429	0.714	0.000	0.286	0.143	0.000
18	0.000	0.000	0.143	0.143	0.143	0.429	1.143	0.429	3.714	1.143	0.000	0.571	0.571	0.000
19	0.000	0.000	0.000	0.000	0.429	0.000	0.714	0.286	3.429	0.714	0.000	0.143	0.143	0.000
20	0.000	0.000	0.143	0.286	0.143	0.429	0.571	0.714	3.714	0.286	0.000	0.286	0.143	0.286
21	0.000	0.000	0.286	0.000	0.143	0.000	0.143	0.143	1.714	0.857	0.000	0.429	0.429	0.143
22	0.000	0.000	0.000	0.000	0.000	0.143	1.143	0.000	3.714	0.857	0.000	0.571	0.000	0.571
23	0.000	0.000	0.143	0.000	0.000	0.143	0.429	0.000	2.143	1.286	0.000	0.286	0.000	0.143

Table C.21: Intensity for the coupled units and push-tow units per hour going West, averaged over the week of 21-Oct-2018.

	RWS-Class number of passages West 21-Oct-2018																			
Hour	C1b	C1L	C2b	C2L	C3b	C3L	C4	B01	B02	B03	B04	BI	BII-1	BII-2b	BII-2L	BII-4	BII-6b	BII-6L	BIIa-1	BIIL-1
0	0.000	0.000	0.000	0.000	0.000	0.286	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.143	0.000	0.286	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.143	0.571	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.143	0.143	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.143	0.000	0.429	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.571	1.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.143	0.857	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.571	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.571	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.143	0.000	0.429	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.143	0.000	0.857	1.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.143	0.714	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143
12	0.000	0.000	0.000	0.000	0.000	0.429	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143
13	0.000	0.000	0.000	0.286	0.286	0.429	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.143
14	0.000	0.000	0.000	0.000	0.000	0.714	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.571	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.143	0.143	0.714	1.143	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.000	1.571	0.429	0.000	0.000	0.000	0.000	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.714	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.286	0.286	0.429	0.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.857	0.571	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.143	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.714	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.429	0.714	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table C.22: Intensity for the motorised vessels per hour going West, averaged over the week of 21-Oct-2018.

	RWS-Class number of passages West 21-Oct-2018													
Hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Other
0	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.286	2.143	0.857	0.143	0.143	0.000	0.429
1	0.000	0.000	0.143	0.000	0.000	0.000	0.143	0.000	1.571	0.429	0.143	0.286	0.143	0.286
2	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.143	1.286	0.429	0.286	0.429	0.000	0.714
3	0.000	0.000	0.000	0.000	0.000	0.000	0.286	0.000	2.000	0.429	0.143	0.571	0.000	0.000
4	0.000	0.000	0.143	0.000	0.000	0.000	0.143	0.000	1.571	0.857	0.143	0.714	0.000	0.429
5	0.000	0.000	0.000	0.143	0.143	0.429	1.000	0.429	2.429	0.286	0.143	0.000	0.143	0.143
6	0.000	0.000	0.000	0.286	0.143	0.286	0.857	0.143	2.143	1.286	0.000	0.429	0.000	0.429
7	0.000	0.143	0.571	0.143	0.000	0.143	1.429	0.429	2.857	0.857	0.000	0.000	0.429	0.286
8	0.000	0.000	0.429	0.286	0.143	0.714	1.286	0.571	2.857	1.286	0.000	0.286	0.000	0.714
9	0.000	0.000	0.143	0.000	0.143	0.571	1.571	0.714	3.000	1.714	0.000	0.286	0.143	0.143
10	0.000	0.286	0.429	0.143	0.286	0.857	1.571	0.857	4.714	2.143	0.000	0.429	0.571	0.143
11	0.000	0.000	0.286	0.571	0.571	0.857	2.143	0.857	4.143	1.429	0.000	0.429	0.429	0.286
12	0.000	0.000	0.286	0.429	0.571	0.429	1.143	0.714	4.000	1.143	0.000	0.429	0.000	0.286
13	0.000	0.000	0.571	0.143	0.286	1.000	1.000	1.286	2.143	1.143	0.143	0.286	0.571	0.857
14	0.000	0.000	0.143	0.429	0.286	1.429	1.286	0.286	3.286	1.286	0.000	0.286	0.286	0.143
15	0.000	0.000	0.000	0.714	0.143	0.286	1.714	0.714	3.429	0.571	0.000	0.286	0.286	0.000
16	0.000	0.143	0.429	0.143	0.286	0.429	1.143	0.857	2.571	1.429	0.143	0.143	0.286	0.143
17	0.000	0.000	0.143	0.571	0.143	0.571	2.286	0.429	2.429	0.714	0.000	0.286	0.143	0.000
18	0.000	0.000	0.143	0.143	0.143	0.429	1.143	0.429	3.714	1.143	0.000	0.571	0.571	0.000
19	0.000	0.000	0.000	0.000	0.429	0.000	0.714	0.286	3.429	0.714	0.000	0.143	0.143	0.000
20	0.000	0.000	0.143	0.286	0.143	0.429	0.571	0.714	3.714	0.286	0.000	0.286	0.143	0.286
21	0.000	0.000	0.286	0.000	0.143	0.000	0.143	0.143	1.714	0.857	0.000	0.429	0.429	0.143
22	0.000	0.000	0.000	0.000	0.000	0.143	1.143	0.000	3.714	0.857	0.000	0.571	0.000	0.571
23	0.000	0.000	0.143	0.000	0.000	0.143	0.429	0.000	2.143	1.286	0.000	0.286	0.000	0.143

C.4. Vessel draught

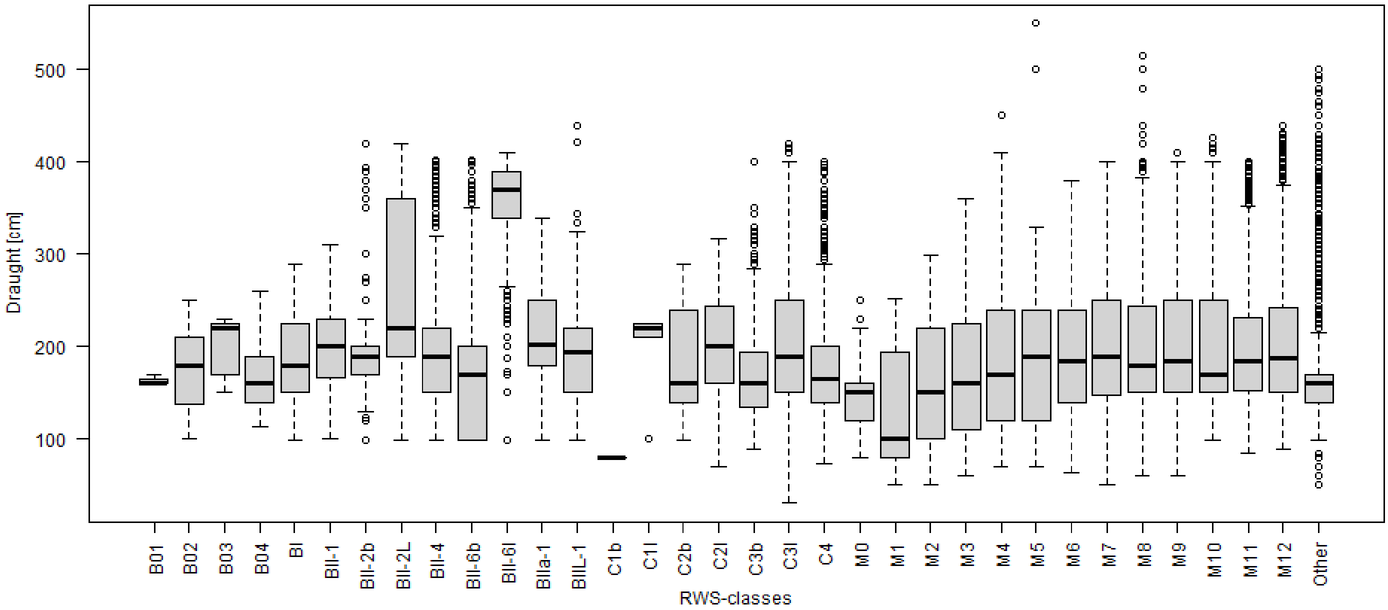

Figure C.6: Boxplot of the 2018 loaded draught per RWS-class.

Table C.23: Draught data per RWS-class over the week of 22-Jul-2018. The number of registered movements was represented as the sample number n, μ represents the mean draught with a standard deviation σ. The simulation value for the draught was determined as $\mu + 2\sigma$ but smaller than the maximum draught measured and NA was used for the vessels-classes with no registered vessel movements during the week of 22-Jul-2018.

22-Jul-2018	**Loaded draught data [cm]**						**Empty draught data [cm]**					
RWS-Class	n	μ	Max.	Min.	σ	$\mu + 2\sigma$	n	μ	Max.	Min.	σ	$\mu + 2\sigma$
BII-2b	NA	NA	NA	NA	NA	NA	2	165	170	160	7	170
BII-2L	3	213	220	200	12	220	NA	NA	NA	NA	NA	NA
BII-4	48	224	330	210	17	258	48	149	230	99	48	230
BIIL-1	2	188	197	180	12	197	2	180	210	150	42	210
C2l	10	238	260	220	14	260	7	160	250	120	44	248
C3b	5	191	220	170	20	220	3	119	135	99	18	135
C3l	110	206	270	120	30	266	25	145	240	99	31	207
C4	44	210	265	112	35	265	30	138	200	99	35	200
M0	NA	NA	NA	NA	NA	NA	4	140	165	120	21	165
M1	5	206	220	180	17	220	6	100	100	100	0	100
M2	33	214	250	110	27	250	37	105	125	80	12	125
M3	38	206	265	100	38	265	23	110	135	100	12	134
M4	34	211	255	100	29	255	23	110	150	93	14	138
M5	124	211	500	100	38	287	46	110	135	99	11	132
M6	249	214	318	80	27	268	126	129	271	99	27	183
M7	64	211	260	140	24	259	23	128	150	99	18	150
M8	549	207	363	100	29	265	257	135	340	99	33	201
M9	157	214	376	131	36	286	63	131	320	87	33	197
M10	15	187	240	150	24	235	11	157	200	99	27	200
M11	73	202	255	108	33	255	9	128	170	99	26	170
M12	54	205	255	89	32	255	22	144	200	99	24	192
Other	5	224	238	210	10	238	123	147	220	50	32	211

Note: For the RWS-classes B01, B02, B03, B04, BI, BII-1, BII-6b, BII-6l, BIIa-1, C1b, C1l, and C2b no draught data was determined because there where less than 2 observations, which was considered unreliable.

Table C.24: Draught data per RWS-class over the week of 09-Sep-2018. The number of registered movements was represented as the sample number n, μ represents the mean draught with a standard deviation σ. The simulation value for the draught was determined as $\mu + 2\sigma$ but smaller than the maximum draught measured and NA was used for the vessels-classes with no registered vessel movements during the week of 09-Sep-2018.

09-Sep-2018	**Loaded draught data [cm]**						**Empty draught data [cm]**					
RWS-Class	n	μ	Max.	Min.	σ	$\mu + 2\sigma$	n	μ	Max.	Min.	σ	$\mu + 2\sigma$
BII-2b	NA	NA	NA	NA	NA	NA	4	192	200	170	15	200
BII-2L	3	208	220	200	10	220	NA	NA	NA	NA	NA	NA
BII-4	36	214	220	200	5	220	37	153	250	99	45	243
BIIL-1	4	172	185	150	15	185	NA	NA	NA	NA	NA	NA
C2l	13	213	250	150	25	250	5	161	180	123	27	180
C3b	11	191	240	140	32	240	13	117	150	99	23	150
C3l	110	196	250	130	30	250	41	138	200	90	27	192
C4	50	205	397	114	45	295	39	132	200	99	27	186
M0	2	160	160	160	0	160	5	153	180	125	26	180
M1	4	185	200	175	11	200	3	93	100	80	12	100
M2	39	202	245	160	22	245	41	115	261	50	32	179
M3	38	207	250	110	31	250	25	107	140	100	11	129
M4	43	206	240	160	24	240	34	118	200	100	24	166
M5	108	202	250	140	24	250	38	115	215	90	22	159
M6	268	200	304	103	27	254	113	124	230	74	24	172
M7	73	204	255	110	25	254	25	133	215	99	25	183
M8	674	196	375	110	28	252	323	137	340	99	26	189
M9	189	202	351	134	31	264	77	134	230	60	29	192
M10	16	187	220	160	20	220	11	139	165	99	22	165
M11	76	190	240	125	29	240	8	121	160	99	26	160
M12	63	195	240	92	28	240	21	144	180	99	23	180
Other	2	220	230	210	14	230	124	152	220	99	25	202

Note: For the RWS-classes B01, B02, B03, B04, BI, BII-1, BII-6b, BII-6l, BIIa-1, C1b, C1l, and C2b no draught data was determined because there where less than 2 observations, which was considered unreliable.

Table C.25: Draught data per RWS-class over the week of 14-Oct-2018. The number of registered movements was represented as the sample number n, μ represents the mean draught with a standard deviation σ. The simulation value for the draught was determined as μ + 2 σ but smaller than the maximum draught measured and NA was used for the vessels-classes with no registered vessel movements during the week of 14-Oct-2018.

14-Oct-2018	**Loaded draught data [cm]**						**Empty draught data [cm]**					
RWS-Class	n	μ	Max.	Min.	σ	$\mu + 2\sigma$	n	μ	Max.	Min.	σ	$\mu + 2\sigma$
BI	NA	NA	NA	NA	NA	NA	3	113	140	99	24	140
BII-2b	2	165	170	160	7	170	4	142	170	99	34	170
BII-2L	3	180	190	170	10	190	NA	NA	NA	NA	NA	NA
BII-4	15	173	185	160	11	185	17	139	180	99	34	180
BIIL-1	2	162	170	153	12	170	3	147	150	140	6	150
C2l	13	178	197	160	12	197	4	135	180	99	34	180
C3b	12	161	193	138	20	193	8	132	150	110	13	150
C3l	127	162	210	125	21	204	56	140	185	84	23	185
C4	97	169	200	105	19	200	70	130	200	99	25	180
M0	NA	NA	NA	NA	NA	NA	2	112	125	100	18	125
M1	3	168	170	165	3	170	4	85	100	80	10	100
M2	37	172	230	138	17	206	34	107	125	85	12	125
M3	38	169	200	110	19	200	34	113	150	99	14	141
M4	56	168	270	130	24	216	30	111	150	80	15	141
M5	100	162	200	120	20	200	40	116	185	99	21	158
M6	230	167	310	98	23	213	134	130	286	85	34	198
M7	88	164	255	120	22	208	35	124	165	90	22	165
M8	631	163	331	120	22	207	340	130	180	99	22	174
M9	207	169	350	110	24	217	98	133	364	87	32	197
M10	14	158	185	135	14	185	8	131	160	99	24	160
M11	79	162	290	108	23	208	19	118	150	92	22	150
M12	62	159	200	112	20	199	14	142	180	99	23	180
Other	NA	NA	NA	NA	NA	NA	135	145	185	99	26	185

Note: For the RWS-classes B01, B02, B03, B04, BII-1, BII-6b, BII-6l, BIIa-1, C1b, C1l, and C2b no draught data was determined because there where less than 2 observations, which was considered unreliable.

Table C.26: Draught data per RWS-class over the week of 21-Oct-2018. The number of registered movements was represented as the sample number n, μ represents the mean draught with a standard deviation σ. The simulation value for the draught was determined as $\mu + 2\,\sigma$ but smaller than the maximum draught measured and NA was used for the vessels-classes with no registered vessel movements during the week of 21-Oct-2018.

21-Oct-2018	**Loaded draught data [cm]**						**Empty draught data [cm]**					
RWS-Class	n	μ	Max.	Min.	σ	$\mu + 2\,\sigma$	n	μ	Max.	Min.	σ	$\mu + 2\,\sigma$
BI	NA	NA	NA	NA	NA	NA	2	145	150	140	7	150
BII-2b	NA	NA	NA	NA	NA	NA	2	168	170	167	2	170
BII-2L	2	164	167	160	5	167	NA	NA	NA	NA	NA	NA
BIIL-1	4	151	160	140	9	160	2	148	155	140	11	155
C2l	14	159	180	110	17	180	5	146	175	120	28	175
C3b	9	159	175	138	14	175	7	127	155	99	23	155
C3l	130	155	265	116	18	191	62	139	170	80	18	170
C4	107	161	260	118	17	195	92	135	170	99	24	170
M1	4	150	150	150	0	150	3	87	100	80	12	100
M2	33	152	180	113	13	178	31	111	170	85	16	143
M3	34	153	200	100	19	191	33	111	150	100	13	137
M4	33	153	175	100	15	175	32	106	140	100	11	128
M5	87	152	265	120	18	188	40	108	155	90	14	136
M6	202	156	310	105	25	206	122	125	200	85	21	167
M7	96	152	190	120	15	182	30	123	150	99	19	150
M8	645	153	235	100	14	181	325	131	315	99	23	177
M9	222	157	185	110	15	185	104	136	351	99	43	222
M10	14	153	170	140	8	169	5	141	150	123	11	150
M11	87	150	175	100	15	175	26	118	150	88	21	150
M12	53	155	180	130	11	177	13	140	170	99	22	170
Other	NA	NA	NA	NA	NA	NA	100	146	200	99	28	200

Note: For the RWS-classes B01, B02, B03, B04, BII-1, BII-4, BII-6b, BII-6l, BIIa-1, C1b, C1l, C2b and M0 no draught data was determined because there where less than 2 observations, which was considered unreliable.

For M8 type vessels the loaded draught decreases with 15 mm with every unit decrease in discharge.

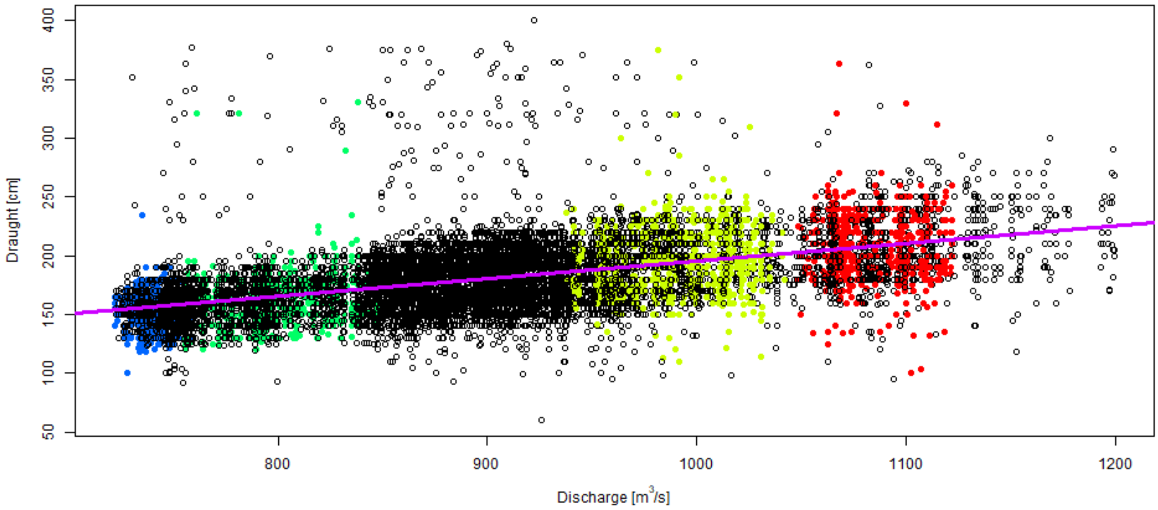

Figure C.7: Vessel loaded draught and river discharge regression for the M8 RWS-class vessel. The colours represent data points from the weeks of 22-Jul-2018 (red), 09-Sept-2018 (yellow), 14-Oct-2018 (green) and 21-Oct-2018 (blue).

Table C.27: Loaded draught regression analysis.

RWS-class	Intercept	Regression coefficient	p-value
BII-2L	48.6	0.156	<0.001
BII-4	35.7	0.173	<0.001
BIIL-1	53.6	0.130	<0.001
C2l	19.6	0.196	<0.001
C3b	73.5	0.112	<0.001
C3l	48.5	0.145	<0.001
C4	61.2	0.140	<0.001
M0	144.3	0.009	0.792
M1	22.3	0.176	<0.001
M2	35.9	0.166	<0.001
M3	34.7	0.163	<0.001
M4	11.8	0.193	<0.001
M5	25.1	0.174	<0.001
M6	32.9	0.168	<0.001
M7	21.7	0.177	<0.001
M8	45.8	0.150	<0.001
M9	44.7	0.155	<0.001
M10	82.5	0.100	<0.001
M11	53.7	0.135	<0.001
M12	55.3	0.139	<0.001

Note: For the RWS-classes B01, B02, B03, B04, BI, BII-1, BII-2b, BII-6b, BII-6l, BIIa-1, C1b, C1l, C2b and Other no data economic limit discharge was determined because there where less than 40 observations, which was considered unreliable.

C.5. Transported weight

Table C.28: Relationship between the RWS-class vessels loaded percent unit and the river discharge, regression analysis. The regression showed that the relationship for BIIL-1, M0 and M10 was not significant.

RWS-class	Intercept	Regression coefficient	p-value
BII-2L	-7.59	0.050	<0.001
BII-4	-8.50	0.050	<0.001
BIIL-1	-5.80	0.052	0.023
C2l	-17.40	0.087	<0.001
C3b	-12.20	0.047	<0.001
C3l	-7.90	0.048	<0.001
C4	-4.64	0.042	<0.001
M0	88.84	-0.042	0.284
M1	-4.84	0.077	<0.001
M2	-17.77	0.086	<0.001
M3	-23.13	0.087	<0.001
M4	-29.78	0.094	<0.001
M5	-27.70	0.091	<0.001
M6	-26.75	0.081	<0.001
M7	-21.30	0.072	<0.001
M8	-18.07	0.058	<0.001
M9	-14.16	0.052	<0.001
M10	23.55	0.010	0.352
M11	-9.82	0.035	<0.001
M12	-8.47	0.036	<0.001

Note: For the RWS-classes B01, B02, B03, B04, BI, BII-1, BII-2b, BII-6b, BII-6l, BIIa-1, C1b, C1l, C2b and Other no regression data was determined because there where less than 40 observations, which was considered unreliable.

C.6. Delay time cost

Table C.29: Transport cost per RWS-class, distinguished in hourly tariffs and price per kilometre.

RWS-class		Hourly tariff [€/h]				Kilometre tariff [€/km]		
		Loaded	Empty	Waiting	**Average**	Loaded	Empty	**Average**
Coupled units	C1b	60.73	60.42	42.21	54.45	6.16	4.86	5.51
	C1L	58.25	60.51	42.42	53.73	5.52	4.76	5.14
	C2L	164.08	156.25	106.24	142.19	13.99	10.03	12.01
	C2b	148.84	153.58	105.76	136.06	11.93	10.66	11.30
	C3L	210.11	199.82	123.82	177.92	15.23	12.15	13.69
	C3b	196.45	194.75	12.52	171.24	13.35	11.47	12.41
	C4	256.06	234.9	157.73	216.24	18.83	12.96	15.89
Push-tow units	B01	73.23	71.32	40.51	61.69	6.80	5.50	6.15
	B02	78.37	76.39	44.25	66.63	6.74	5.76	6.25
	B03	81.10	78.73	46.76	68.86	6.92	5.68	6.30
	B04	84.99	82.15	48.97	72.03	7.17	5.55	6.36
	BI	121.21	118.55	82.46	107.40	9.20	7.67	8.43
	BII	150.31	142.28	87.36	126.65	11.03	9.03	10.03
	BIIa-1	158.45	145.83	90.86	131.71	11.41	8.90	10.15
	BIIL-1	168.67	157.25	100.64	142.18	12.67	9.87	11.27
	BII-2L	246.43	241.33	140.54	209.43	19.06	15.30	17.18
	BII-2b	242.82	231.61	137.38	203.94	16.69	14.39	15.54
	BII-4	448.35	401.08	237.72	362.38	38.43	23.48	30.96
	BII-6b	598.63	472.30	294.4	455.09	58.49	27.08	42.79
	BII-6L	558.08	471.43	293.82	441.10	45.97	26.98	36.48
Motorized vessels	M0	-	-	-	-	-	-	-
	M1	41.40	40.85	29.57	37.27	3.81	3.30	3.55
	M2	50.77	49.63	34.55	44.98	4.04	3.46	3.75
	M3	57.53	56.30	37.90	50.58	4.46	3.89	4.18
	M4	63.31	62.22	40.92	55.48	5.17	4.30	4.73
	M5	75.79	74.13	48.49	66.13	6.23	4.97	5.60
	M6	97.85	95.24	65.04	86.04	7.21	5.92	6.56
	M7	137.55	132.47	93.72	121.25	9.50	7.59	8.54
	M8	161.44	154.23	107.15	140.94	10.32	8.53	9.42
	M9	191.12	181.70	120.17	164.33	11.98	9.40	10.69
	M10	206.67	184.04	137.63	176.11	12.11	10.61	11.36
	M11	227.84	218.12	149.13	198.36	13.70	11.94	12.82
	M12	252.96	242.50	166.33	220.59	15.51	12.67	14.09

C.7. SIMDAS data input

Table C.30: The loaded vessels fraction per RWS-class travelling East (to the Pannerdensche Kop) and West (to the Maas-Waal canal), averaged over the week of 22-Jul-2018. NA was used for the directions and vessels-classes with no registered vessel movements during the week of 22-Jul-2018.

RWS-Class	**Fraction loaded vessels, 22-Jul-2018**	
	East going	West going
BII-2b	NA	0.000
BII-2L	1.000	NA
BII-4	0.938	0.062
BIIL-1	0.667	0.000
C2b	NA	0.000
C2l	1.000	0.222
C3b	1.000	0.571
C3l	0.984	0.667
C4	0.973	0.216
M0	0.333	0.000
M1	0.200	0.667
M2	0.250	0.767
M3	0.406	0.862
M4	0.429	0.864
M5	0.600	0.875
M6	0.725	0.591
M7	0.913	0.537
M8	0.837	0.528
M9	0.877	0.561
M10	0.364	0.733
M11	0.976	0.805
M12	0.778	0.650
Other	0.027	0.055

Note: For the RWS-classes B01, B02, B03, B04, BI, BII-1, BII-6b, BII-6l, BIIa-1, C1b and C1l no data was determined because there where no observations.

Table C.31: The loaded vessels fraction per RWS-class travelling East (to the Pannerdensche Kop) and West (to the Maas-Waal canal), averaged over the week of 09-Sep-2018. NA was used for the directions and vessels-classes with no registered vessel movements during the week of 09-Sep-2018.

RWS-Class	**Fraction loaded vessels, 09-Sep-2018**	
	East going	West going
B04	NA	0.000
BI	0.000	1.000
BII-2b	NA	0.000
BII-2L	1.000	NA
BII-4	0.973	0.000
BII-6b	NA	0.000
BIIL-1	NA	1.000
C2l	1.000	0.375
C3b	1.000	0.235
C3l	0.958	0.519
C4	0.977	0.174
M0	0.286	NA
M1	0.400	1.000
M2	0.233	0.784
M3	0.395	0.920
M4	0.396	0.828
M5	0.679	0.815
M6	0.845	0.524
M7	0.900	0.583
M8	0.851	0.494
M9	0.939	0.489
M10	0.615	0.571
M11	0.977	0.825
M12	0.955	0.525
Other	0.000	0.034

Note: For the RWS-classes B01, B02, B03, BII-1, BII-6l, BIIa-1, C1b, C1l and C2b no data was determined because there where no observations.

Table C.32: The loaded vessels fraction per RWS-class travelling East (to the Pannerdensche Kop) and West (to the Maas-Waal canal), averaged over the week of 14-Oct-2018. NA was used for the directions and vessels-classes with no registered vessel movements during the week of 14-Oct-2018.

RWS-Class	**Fraction loaded vessels, 14-Oct-2018**	
	East going	West going
BI	0.500	0.000
BII-2b	NA	0.333
BII-2L	0.750	NA
BII-4	1.000	0.000
BIIL-1	0.000	0.667
C2l	1.000	0.600
C3b	1.000	0.467
C3l	0.975	0.471
C4	0.988	0.148
M0	0.333	NA
M1	0.333	0.500
M2	0.268	0.867
M3	0.316	0.765
M4	0.522	0.800
M5	0.597	0.857
M6	0.701	0.559
M7	0.859	0.559
M8	0.838	0.483
M9	0.954	0.409
M10	1.000	0.273
M11	0.979	0.647
M12	1.000	0.632
Other	0.000	0.000

Note: For the RWS-classes B01, B02, B03, B04, BII-1, BII-2b, BII-6b, BII-6l, BIIa-1, C1b, C1l and C2b no data was determined because there where no observations.

Table C.33: The loaded vessels fraction per RWS-class travelling East (to the Pannerdensche Kop) and West (to the Maas-Waal canal), averaged over the week of 21-Oct-2018. NA was used for the directions and vessels-classes with no registered vessel movements during the week of 21-Oct-2018.

RWS-Class	**Fraction loaded vessels, 21-Oct-2018**	
	East going	West going
B04	0.500	NA
BI	0.500	0.000
BII-2b	1.000	0.000
BII-2L	1.000	NA
BIIL-1	0.667	0.667
C2l	1.000	0.444
C3b	1.000	0.222
C3l	0.968	0.398
C4	0.980	0.109
M0	0.500	NA
M1	0.000	1.000
M2	0.273	0.774
M3	0.361	0.677
M4	0.243	0.857
M5	0.524	0.844
M6	0.753	0.500
M7	0.927	0.634
M8	0.849	0.467
M9	0.902	0.460
M10	0.900	0.556
M11	0.983	0.545
M12	0.970	0.636
Other	0.000	0.000

Note: For the RWS-classes B01, B02, B03, BII-1, BII-4, BII-6b, BII-6l, BIIa-1, C1b, C1l and C2b no data was determined because there where no observations.

Table C.34: Vessel SIMDAS-classification (Ten Hove & Bilinska, 2017).

CEMT-class	RWS-class	SIMDAS ID	UDMIN [m/s^2]	UDMAX [m/s^2]	Drift E / L [rad/s]	Drift angle [°]
Coupled units						
I	C1b	-	-	-	-	-
I	C1L	-	-	-	-	-
IVb	C2L	1	-0.04 / -0.035	0.03 / 0.02	0.0163 / 0.0128	37.0
Vb	C3L	4	-0.04 / -0.03	0.03 / 0.02	0.0157 / 0.0122	36.0
VIa	C2b	2	-0.04 / -0.035	0.03 / 0.02	0.0163 / 0.0128	37.0
VIa	C3b	3	-0.04 / -0.03	0.03 / 0.02	0.0227 / 0.0175	36.0
VIb	C4	5	-0.04 / -0.03	0.03 / 0.02	0.0122 / 0.0087	35.0 / 40.0
Push-tow units						
-	B01	-	-	-	-	-
-	B02	6	-0.02	0.02	0.0611 / 0.0506	40.0
-	B03	-	-	-	-	-
-	B04	7	-0.02	0.02	0.0611 / 0.0506	40.0
IV	BI	8	-0.03	0.02	0.0297 / 0.0227	40.0
Va	BII	-	-	-	-	-
Va	BIIa-1	-	-	-	-	-
Va	BIIL-1	13	-0.03	0.02	0.0227 / 0.0175	40.0
VIa	BII-2b	9	-0.04 / -0.03	0.03 / 0.02	0.0227 / 0.0175	36.0
VIb	BII-4	11	-0.04 / -0.03	0.03 / 0.02	0.0122 / 0.0087	35.0 / 40.0
Vb	BII-2L	10	-0.04 / -0.03	0.03 / 0.02	0.0157 / 0.0122	36.0
VIIa	BII-6b	12	-0.04	0.03	0.0087	35.0
VIc	BII-6L	-	-	-	-	-
Motorized vessels						
0	M0	14	-0.02	0.02	0.0611 / 0.0506	40.0
I	M1	15	-0.02	0.02	0.0611 / 0.0506	40.0
II	M2	16	-0.03	0.02	0.0576 / 0.0436	40.0
III	M3	17	-0.03	0.02	0.0576 / 0.0436	40.0
III	M4	18	-0.03	0.02	0.0454 / 0.0349	40.0
III	M5	19	-0.03	0.02	0.0349 / 0.0262	40.0
IVa	M6	20	-0.03	0.02	0.0297 / 0.0227	40.0
IVa	M7	21	-0.03	0.02	0.0252 / 0.0201	40.0
Va	M8	22	-0.03	0.02	0.0227 / 0.0175	40.0
Va	M9	23	-0.035	0.02	0.0209 / 0.0190	35.0
VIa	M10	24	-0.035	0.02	0.019	35.0
VIa	M11	25	-0.035	0.02	0.019	35.0
VIa	M12	26	-0.035	0.02	0.019	35.0