ESTABLISHING THE REQUIRED LOCK CAPACITY AND CONFIGURATION IN CASE OF CANALISATION OF THE RIVER WAAL

AN EXPLORATORY STUDY

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ABSTRACT

The river Waal is part of an economic important transport-corridor that connects the ports of Antwerp, Rotterdam and Amsterdam to Germany. Ongoing processes such as (1) climate change, (2) large scale river bed erosion and (3) up-scaling of vessels threaten the future navigability of the river. This will lead to massive economic damages as taken in 2018 (Strengs et al., 2020). Canalisation of the river by means of weir-lock complexes is a considered by *Rijkswaterstaat* to improve inland navigation during periods of low discharge and prevent economic damages. This leads to the primary goal of this study; investigate the required lock capacity to provide smooth and reliable passage of the river Waal now and in the future.

A literature review was conducted to assess the future development of the drivers of the worsening navigation conditions and to gain insight in market- and fleet developments. The developments in the drivers underline the urgency for measures. The development of the fleet navigating on the river Waal is characterised by up-scaling for the past 20 year. This trend is expected to continue the coming years. Future market developments are very uncertain due to the energy transition and the nitrogen crisis, making it very difficult to make accurate projections on future fleet intensities and compositions. Therefore a range of traffic intensities is used to characterise future fleets that encounter the lock complexes.

The number and locations of the lock complexes is investigated by analysing available nautical depths and water levels along the river Waal for several stationary discharges at Lobith. Water levels are set up to a level such that navigation for all vessels (fully loaded) is possible. From a financial perspective it is most attractive to minimise the number of weir-lock complexes, however this is contrary to flood safety aspects on the river Waal. Installation of two weir lock complexes is considered plausible taking into account minimising the number of weir-lock complexes and flood safety.

The moment of closure of the weir is of major importance as the lock complex is operational during low discharges only. The moment of closure defines whether a certain vessel is able to pass the lock complex or not. This observation has led to the description of three approaches to define the moment of closure based on the a threshold discharge at Lobith.

Vessel traffic simulations are conducted in SIVAK III to investigate the performance of multiple lock configurations in terms of average waiting time and service level. SIVAK III is able to simulate the passage of vessels at an individual level in a network of waterways and locks. A fleet analysis on a representative data set is conducted to provide SIVAK III with fleet intensities, fleet mixes and arrival patterns.

Representative fleet data, was found in IVS data (Informatie Volg Systeem translates to information tracking system) recorded in 2019 Jan-Jun. The fleet is considered representative as the fleet is recent (for an accurate fleet mix) and when the water levels and discharges are similar to the ones in case of the canalised case (for correct fleet intensity). Fleet intensities for future fleet scenarios on the river Waal are estimated for a time horizon of 2050.

Simulation results showed that the service level criterion is stronger than thee waiting time criterion. For the upstream (rkm 905) lock complex is recommended to use a lock complex with 4 chambers with dimensions 28.4x305m, but with in mind the option for a 5th chamber in the future. This lock complex is able to handle the current fleet +10% intensity within the considered requirements. A 5th lock chamber of the same size can handle an increased intensity of +30% including strong up-scaling effects. For the downstream lock complex (rkm 941) it is recommended to use a lock complex with 4 chambers and dimensions 25x330m. The lock complex is able to handle the current intensity +30%.

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1

INTRODUCTION

1.1. RESEARCH MOTIVATION

The river Waal, between the Pannerdense Kop and the Boven-Merwede, is part of the Rhine branches and is the busiest waterway in the Netherlands (see Figure 1.1). The river is an economically important link in the transport corridor Rotterdam-Germany as over 120000 commercial vessels are counted annually (based on IVS data). However, the navigability and thus the transport function of the river is under pressure, especially in periods of low discharge. Future climate scenarios are not in favour of the navigability and threaten to worsen the navigability even more (De Jong, 2019). The most recent severe drought resulted in an estimated 2.7 bln. euro in economic damages (The Netherlands and Germany included) due to navigability restrictions on the river Waal (Strengs et al., 2020). Measures are required to prevent economic damages in the future. A technical potential measure, suggested by *Rijkswaterstaat*, is canalisation of the river Waal by means of weir-lock complexes (WLC's). The weirs are then used to increase water levels in periods of low discharge, whilst the locks allow for the passage of vessels. This has resulted in the demand for an exploratory study on the assessment and estimation of required lock capacity in case of canalisation of the river Waal.

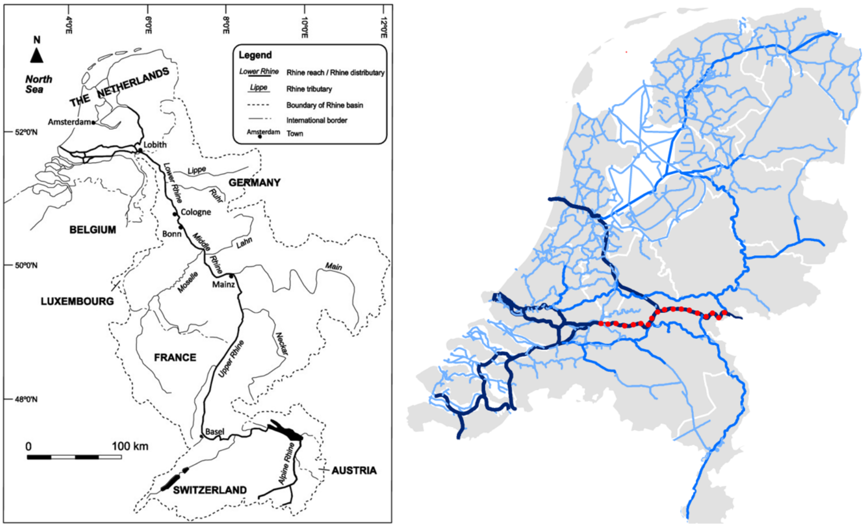

Figure 1.1: Left panel: River Rhine catchment (Toonen et al., 2016); **Right panel:** Dutch waterway network; darkest colours refer to the main waterways. The red dots indicate the river Waal trajectory (CBS, 2021).

1.2. NAVIGABILITY DURING LOW DISCHARGE

1.2.1. STANDARDS ON MINIMUM NAUTICAL DEPTH AND RIVER WIDTH

Two important standards regarding navigability on the river Waal are the minimum maintained navigation depth and -width. The minimum and maintained navigation depth is based on the agreed low discharge (ALD) in Dutch; "overeengekomen lage afvoer (OLA)" , which is 1020 m^3/s (measured Lobith, see Figure 1.1 left panel for the location of Lobith). Note that Lobith is located along the river Rhine and that discharges and water levels measured at this location are often translated to discharges and water levels for the downstream river Waal (see Figure 1.1 right panel for the trajectory of the river Waal). ALD is defined as the average discharge with an undershoot frequency of 20 days per year (Stuurman & Koolwijk, 2003). This corresponds to approximately 5% of the year. The agreed low water level (ALR), in Dutch; "Overeengekomen lage rivierstand (OLR)", is the water level that corresponds with the ALD and is used as a reference level for setting navigation depths. The maintained navigation depth for the Waal is ALR -2.80 m (Doornekamp, 2019). The minimum width that is maintained is 170 m (Doornekamp, 2019).

1.2.2. DEFICITS ON MINIMUM NAUTICAL DEPTH

Centraal Overleg Vaarwegen (COV) wrote an alarming letter for the minister of Infrastructure and Water Management, pointing out that the Central Commission for the Navigation of the Rhine (CCNR) agreements are not met anymore for the river Waal (Schulz, 2018). In the agreement is stated that a depth of 2.80 m and a navigable width of 150 m should be available during ALR conditions. Depth deficits till almost 0.5 m are reported on the river Waal for years 2017 and 2018 (De Jong, 2020a). Note that 2018 was an exceptionally dry year, as becomes clear from Figure 1.2. The low discharge period in 2018 has an estimated return period of 60 years (De Jong, 2019). In the driest foreseen climate scenario ($W_{H,dry}$) the discharge corresponding to an undershoot probability of 5% will reduce to 820 m^3/s and 740 m^3/s in respectively 2050 and 2085 (De Jong, 2019). This implies that radical measures are required in order to maintain the agreed upon depth of 2.80 m in these scenarios.

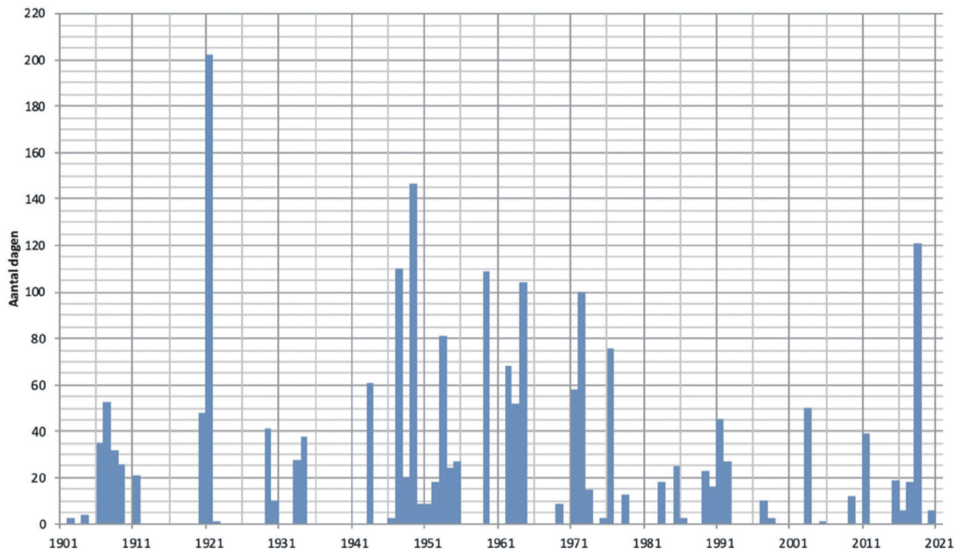

Figure 1.2: Number of days/year that the discharge is below 1000 m^3/s measured at Lobith (van Winden & van Huizen, 2021)

1.2.3. EFFECTS OF LOW DISCHARGE ON VESSEL TRAFFIC

A reduced discharge during a period of drought leads to a decrease in nautical depth and a decrease in available navigation width. Both effects contribute to delays on shipments and potential cases of congestion. A reduced nautical depth forces skippers to reduce their load capacity. In other words the load factor (= loading capacity / transported load) reduces when the nautical depth reduces (Dorsser et al., 2020). Verschuren considered the effects of drought on the navigability of the river Waal and concluded that the river Waal has reached its maximum traffic capacity at discharge of 800 m^3/s at Lobith. Congestion occurs for that discharge, meaning that ten or more vessels are navigating in a train unable to overtake each other permanently. For a discharge of 1020 m^3/s harmonically moving congestion occurs, meaning that seven or more vessels are navigating in a train waiting for space to initiate an overtake manoeuvre (Verschuren, 2020). A reduced navigational width prevents vessels from overtaking each other and aggravates congestion (Verschuren, 2020).

1.3. FINANCIAL AND ECONOMICAL IMPACT

Both, a reduced loading capacity and increase in traffic intensity, contribute to increased transport costs, leading to financial and economic damages. The former section outlined that reduced discharges lead to delays and a decrease in load factor. The average load factor is approximately 0.6-0.7 under unrestricted conditions, under limited nautical depth the average load factor may drop below 0.5. In a worst case scenario operations of certain types of vessels are ceased, as occurred during the drought in 2018 (Dorsser et al., 2020). As a consequence the costs per ton transported cargo increases, because a larger number of vessels is required to transport the same amount of cargo. Assuming that the transport demand is not related to discharge variations on the river Waal. In the the summer of 2018 the traffic intensity increased on the river Waal during a prolonged period of low discharge (Verschuren, 2020). Increased intensities lead to congestion and delays, leading the financial and economic damages.

Ecorys reports an estimated economical loss of 140-345 mln. euro as a consequence of poor navigability in The Netherlands during the 2018 drought. The river Waal is mentioned as one of the main bottlenecks along with the river IJssel and river Lek. The economical losses are at the expense of producers and/or consumers (van Hussen et al., 2019). *Erasmus Centre for Urban, Port and Transport Economics (UPT)* quantified the financial damages taken by the inland waterway transport (IWT) sector and the shippers as a consequence of the 2018 period of low discharge on the river Rhine. Results are presented for the Netherlands and Germany. A total financial loss of 2.7 bln. euro is reported, of which 0.3 bln. euro for the Netherlands and 2.4 bln. euro for Germany (Strengs et al., 2020). About 80% of the total financial damages can be related to a decline in production of products at the shippers.

1.4. LONG TERM CONSEQUENCES OF POOR NAVIGABILITY

Under a changing climate it is likely that the conditions for the IWT sector worsen in the future. Periods of low discharge are expected to occur more frequently and last longer (De Jong, 2019). When no measures are taken the annual costs for the IWT sector will increase as a consequence of prolonged low discharge periods. Also the reliability, as a consequence of delays, of the IWT sector will decrease. Both consequences potentially lead to an undesired modal shift from water to road or rail (Strengs et al., 2020).

A modal shift is not desired from a sustainability perspective as inland navigation is a relatively sustainable modality in terms of CO_2 emission (Klein et al., 2021). The left panel in Figure 1.3 illustrates that CO_2 emissions the IWT sector are about half the CO_2 emissions in road transport. A modal shift towards electric rail transport would be beneficial in the context of CO_2 emission, however a recent prognosis on rail capacity between Rotterdam and Germany predicts capacity problems for 2040 and 2050 even without a modal shift (ProRail, 2021). This implies that a shift towards electric rail transport is not obvious.

Inland navigation has a share of 35% of the modal split in the *PoR* according to the right panel in Figure 1.3. In addition, *PoR* aims to realise a modal shift from road- to rail- and inland waterway transport, in order to avoid further congestion of the road network ("Havenvisie Rotterdam", 2019), which underlines the importance of the IWT sector. So to prevent the long term consequence; a modal shift towards less sustainable modalities, it is important to facilitate a well navigable river Waal for the IWT sector.

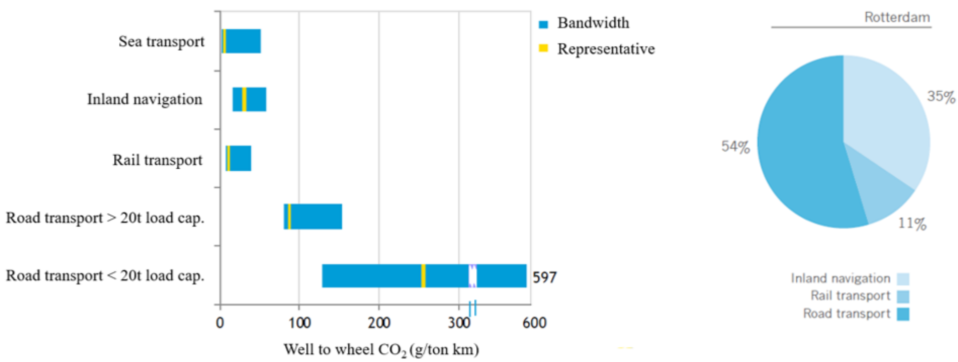

Figure 1.3: Left panel: CO_2 Emissions for bulk and general cargo in g/tonkm in 2018 (Klein et al., 2021), **Right panel:** Modal split for hinterland container transport of PoR in 2013 (Figee & Volker, 2016).

1.5. MITIGATION MEASURES

In order to prevent financial and economic damages as a consequence of a poor navigable river Waal, measures are required. Canalisation is considered one of those measures to increase navigability and reduce damages taken in periods of low discharge. However, there are other paths to reduce financial and economic damages that can be considered. It is stressed out that canalisation is not claimed to be the most suitable solution. This section gives a brief overview of some of these measures.

Measures that mitigate the negative effects of climate change on the IWT sector can be categorised in three types of measures; (1) customer measures, (2) carrier measures and (3) public measures (Demirel, 2011). Customer measures include measures such as increased stocks to overcome dry periods or relocating production or storage sites to locations that are less dependent on inland navigation. Carrier measures include measures that affect the fleet composition, such as changes in vessel size and design. Finally, public measures include infrastructural investments such as dredging, the construction of longitudinal training walls and canalisation by means of WLC's. A potential fourth mitigation measure is found in information management. Meaning investing in accurate, real-time and predictive information on for instance nautical depths, shipping routes and local flow patterns (Krekt et al., 2011). This should help skippers in decision making on routing and to asses the maximum draught for a trip.

In 2015 a series of longitudinal training walls (LTW) were constructed between Wamel en Ophemert over a length of 10 km as a measure to, among other things, increase the water depth during low discharges (de Ruijsscher, 2020). The LTW divide the river in a main fairway and a side channel. During periods of low discharge the flow into the side channels is limited through water inlet (sill-like gaps in the LTW). This results in a larger discharge through the main channel which raises the water depth. Effects on the nautical depth are maximum at under ALD conditions. The nautical depth is increased by approximately 15 cm in that case with respect to the case without LTW (Snoeij, 2021). This implies that for example a large Rhine vessel can transport an extra 150 tons of cargo (rule of thumb).

1.6. SCOPE

This research focuses on the canalisation of the river Waal in order to improve the navigability of the river Waal in periods of low discharge. The emphasis in this study is on investigating the required lock capacity and to present a first estimate on the capacity required for smooth, reliable and future-proof inland navigation on the river Waal for a time horizon of 2050. The navigability problem is considered a traffic problem that is defined by the prevailing hydraulic conditions, morphological conditions and vessel traffic on the river Waal.

It is stressed that the focus is not on the structural design of the WLC's. Various lock configurations will be assessed based on their capacity to handle a certain traffic intensity. This also implies that the focus is not on related aspects such as: flood protection, morphological impact, ecological impact and fresh water supply and distribution. Nevertheless these aspects are very important to study in detail when designing new WLC's. The impact of canalisation asks for an integral approach in order to capture all relevant aspects.

1.7. PRIMARY OBJECTIVE

The primary objective of this research is to investigate the required lock capacity of the WLC's in order to facilitate smooth, reliable and future-proof inland waterway transport on the river Waal, when canalised. Vessel traffic is considered to be handled smoothly when the average waiting time is less than 30 minutes (Minister of Infrastructure and Milieu, 2012). The reliability of a lock complex is sufficient when 85% of the vessels passing the lock complex is able to pass without having to wait longer than 30 minutes (Rijkswaterstaat, 2019).

1.8. RESEARCH QUESTIONS

This research aims to find an answer to one primary research question that is supported by five sub questions:

"How to configure the river Waal in case of canalisation by means of weir-lock complexes to facilitate smooth, reliable and future proof inland waterway transport?"

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1. What are the main factors that drive the worsening navigability of the river Waal now and in the future?
2. What are the characteristics of the current and future fleets on the river Waal?
3. How to determine the moment of closure of the weir-lock complexes and the retained water levels?
4. How many weir-lock complexes are required in case of canalisation of the river Waal and at what locations?

5. What are the minimum required number of lock chambers and corresponding dimensions to facilitate smooth and reliable traffic flow over the river Waal now and in the future?

1.9. METHODOLOGY

In this section a framework is set out in order to find the answers on the research questions posed in Section 1.8. The core of the framework is presented in a flow chart in Figure 1.4. The contents of Figure 1.4 and the relation with the research questions is illustrated in the remainder of this section.

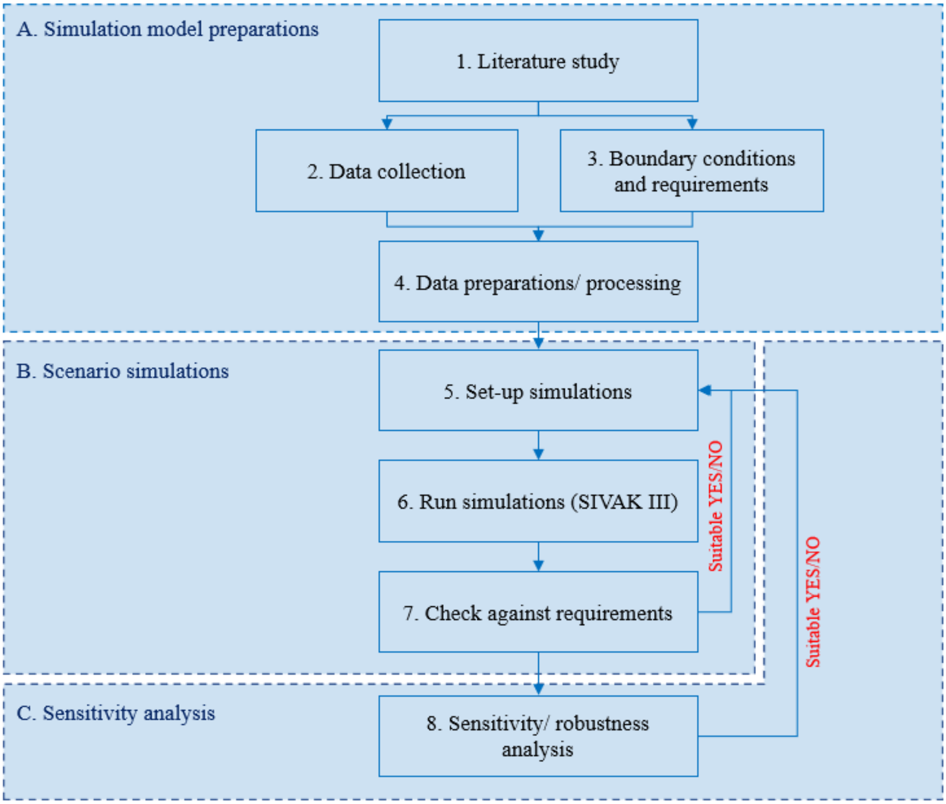

Figure 1.4: Work flow chart

The framework is divided in three main phases: (A) SIVAK III model preparations, (B) scenario simulations and (C) an sensitivity analysis. In phase A the emphasis is on establishing a lay-out for a canalised river Waal and the collection of representative (fleet) data to test the lay-out by means of vessel traffic simulations. In phase B the focus is on running the vessel traffic simulations and checking the output against the requirements. Part C can be considered a sensitivity analysis that verifies the robustness of the lock designs that met the requirements in phase B.

1.10. READING GUIDE

The first chapter introduced the problem and the context of this thesis. Chapter 2 entails a literature study elaborating on mainly the expected development of the drivers of reduced navigability and expected fleet- and market developments. Chapter 3 focuses on the assessment of the moment of closure of the weirs and elaborates on the number of WLC's and their positioning in the river Waal. Chapter 4 describes the SIVAK III model workings, set-up, input and simulated scenarios. Chapter 5 addresses the simulation results followed by chapter 6; containing a reflection on the approaches used and results obtained. In chapter 7 the conclusion is given and in chapter 8 recommendations on further studies regarding this topic are given. This document contains a series of appendices to which is referred in the report.

2

LITERATURE REVIEW

2.1. INTRODUCTION

This chapter summarises the results of a literature review that is performed in order to identify the main processes that contribute to the worsening navigability on the river Waal. This chapter also addresses relevant trends in fleet development and expected market developments affecting future fleet characteristics on the river Waal. This chapter concludes with an answer on research questions 1 and 2.

2.2. GENERAL CHARACTERISTICS OF THE RIVER WAAL

The river Waal is one of the three Rhine branches, together with the river IJssel and river Nederrijn-Lek. The river Waal originates at the Pannerdense Kop (rkm 867) and flows into the Boven-Merwede near Woudrichem (rkm 953), see Figure 1.1. The river Waal is an important transport link between the ports of Rotterdam, Amsterdam and Antwerp and their hinterland. The river is one of the busiest in the world (Figee & Volker, 2016). Over 120000 commercial vessel passages are counted annually on the river Waal, transporting approximately 130 mln. tons of cargo (Schulz, 2018). To put the importance of the river Waal in European perspective; about 70% of all inland waterway transport in Europe is transported over the Rhine (Jonkeren et al., 2007).

The foundation of the intensively used river Waal is the Act of Mannheim (voor Rijnvaart (CCR), 1868), which guarantees amongst other things freedom of navigation on the Rhine. Another reason for favourable navigation conditions is the absence of lock complexes in the river Waal and river Rhine (exceptions are 2 locks upstream of Basel (Switzerland) and the locks on lateral channels in France upstream of rkm 333). Furthermore, from a historical perspective, water depths on the river Rhine and river Waal have been sufficient and stable enough over time to be attractive for inland waterway transport (Demirel, 2011). Some figures on characteristics of the river Waal are given in Table 2.1. These figures should be considered indicative, because of the spatial variability along the river.

Characteristic	**Symbol**	**Value**	**Unit**
Length	L	86	km
Width main channel	B_{ch}	260	m
Width floodplain	B_{fl}	550	m
Bed slope	i_b	0.0001	-
Chézy coefficient main channel	C_{ch}	40	$m^{0.5}s^{-1}$
Chézy coefficient floodplain	C_{fl}	35	$m^{0.5}s^{-1}$
Grain size bed material	D_{50}	0.001	m^3
Average discharge	Q_{avg}	1480	m^3

Table 2.1: Some indicative figures on characteristics of the river Waal (van Vuren, 2005)

2.3. CRITICAL SHALLOWS IN THE RIVER WAAL

The maximum draft of a vessel is determined by the minimum depth in the fairway that a vessel encounters on its route. Between Rotterdam and Duisburg (Germany) the critical (shallowest) location is in the river Waal. *Rijkswaterstaat* publishes the shallowest locations (in Dutch: Minst Gepeilde Diepte, MGD) in the river Waal every day, provided that the water depth in the fairway is less than 350 cm (Rijkswaterstaat, 2021). Skippers use the MGD to determine their maximum possible draft. The reported MGD's for 2017 and 2018 are summarised in Figures 2.1 and 2.2.

Note that the shallows in the fairway are often located at the same locations. The shallows registered most often are found near St. Andries (rkm 928), Nijmegen Haven (rkm 885) and Erlecom (rkm 877). Note that these locations correspond with the locations of the fixed bed layers mentioned in Section 2.4.1. Also note that these locations of shallows are local, meaning that they do not necessarily cover the entire width of the River. Skippers often know were to find the shallows based on experience and may even navigate with a larger draft than prevailing MGD's (De Jong & Van der Mark, 2021).

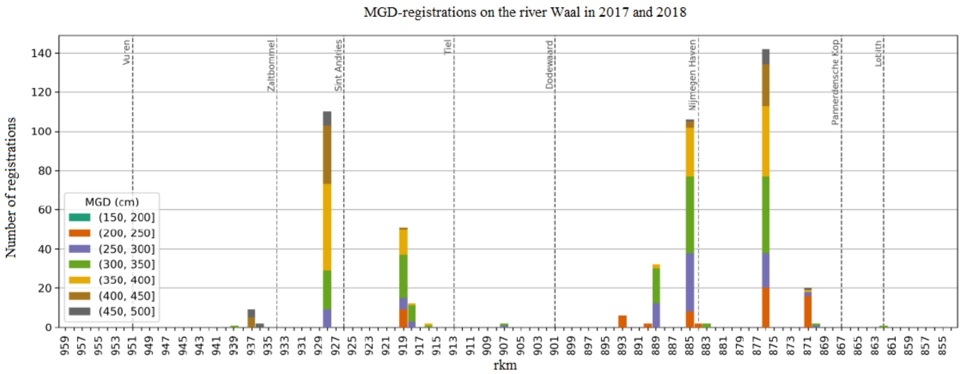

Figure 2.1: MGD-registrations along the river Waal for 2017 and 2018. Adopted from (De Jong, 2020a)

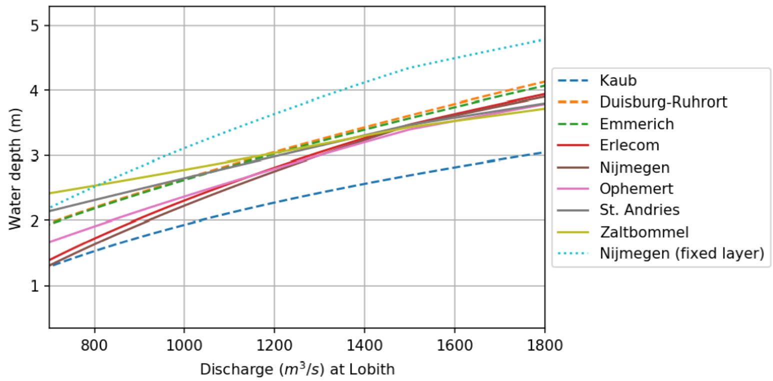

Figure 2.2: Relation between discharge at Lobith and the MGD's measured at several locations along the river Waal and Rhine. Adopted from (De Jong, 2020a)

2.4. DRIVERS OF THE REDUCED NAVIGABILITY

It is important to identify and assess the expected development of the drivers of reduced navigability as they may affect the required lock capacity in the future. The consequences of reduced navigability are illustrated in Chapter 1. Main drivers are:

1. Large scale river bed erosion in combination with fixed (non erodible) river bed sections
2. Extremely low discharges occurring more frequently as a consequence of a changing climate
3. The up-scaling trend of the commercial fleets

The developments of these processes affect the locations, operations and dimensions of the proposed WLC's. In addition, the development and predictions on these processes underline the urgency for measures to improve the navigability of the river Waal.

2.4.1. BED EROSION AND FIXED BED LAYERS

REACH SCALE BED EROSION

Reach scale bed erosion in combination with fixed (non-erodible) river bed sections, makes the layers protrude from the bed, causing local shallows. These shallows are nautical bottlenecks for inland navigation, especially in combination with low discharges.

The river Waal is a heavily engineered river and is fixed in width and plan-form by means of mainly groynes. The construction of the groynes took place between roughly 1850 and 1916 (Ylla Arbós et al., 2021). This intervention narrowed the river Waal, which led to increased average flow velocities and therefore increased sediment transport rates. Consequently, the riverbed in the river Waal erodes as it is adjusting towards a new equilibrium profile (Sloff, 2019; Ylla Arbós et al., 2021).

A second reason for the erosion is the reduced sediment supply from the German part of the river Rhine as a consequence of the construction of weirs and sediment supplements (Ollongren et al., 2019). Figure 2.3 illustrates the eroding bed level for the river Rhine and river Waal over the past century. Erosion rates were highest in the early 1900s (shortly) after the installation of the groyne fields. Erosion rates decreased over time.

In a prognosis by Sloff on the ongoing bed erosion the following figures are reported: upper-Waal (km 868-885) -1.6 cm/y, middle-Waal (km 886-933) -0.6cm/y and lower-Waal (km 934-951) +0.1 cm/y (Sloff, 2019). It is recommended to consider these erosion rates in the the design process of the lock, especially in determining the sill depths.

FIXED LOCAL BOTTOM LAYERS

At several locations in the river Waal (Nijmegen; rkm 883-885, Erlecom; rkm 873-876 and St. Andries; rkm 925-928) the river bed is fixed artificially by means of a fixed bottom or by bottom groynes (Bisschop, 2020; White & Blom, 2021). These measures were applied to increase the width of the fairway in river bends. The interventions succeeded in that aspect (Bisschop, 2020; White & Blom, 2021).

These interventions applied to facilitate inland navigation in the past are currently turning into bottlenecks for inland navigation as the fixed layers do not erode at the same rate as the adjacent alluvial bed does. This leads to reduced nautical depths at the locations of the fixed beds. This problem remains and is likely to aggravate under a continuous erosion process when no measures are taken. Assuming that the fixed layer

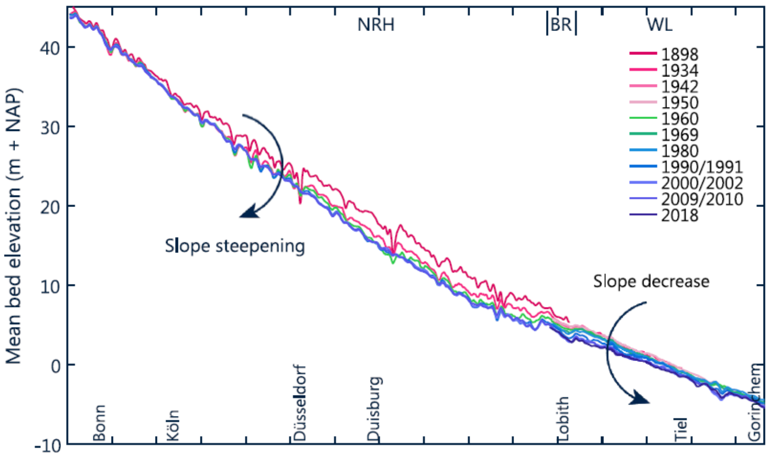

Figure 2.3: River bed erosion on the river Rhine and river Waal (Ylla Arbós et al., 2021)

at Nijmegen is unaltered in 2050 the nautical depth has decreased with 0.1-0.3 m, depending on the discharge at Lobith, see Figure 2.4.

Cables and pipes can also be considered as fixed layers as they are permanently in the river bed. With a degrading river bed the cover over the cables and pipes reduces, which makes them vulnerable to vessels running aground. Dredging is not allowed on top of cables and layers, this makes that locations of cables and pipes crossing the river Waal are often the shallowest locations in the fairway (in Dutch; "minst gepeilde diepten (MGD)"). It is recommended to monitor these fixed bed locations as they are likely to become the draught limiting factor under an eroding bed.

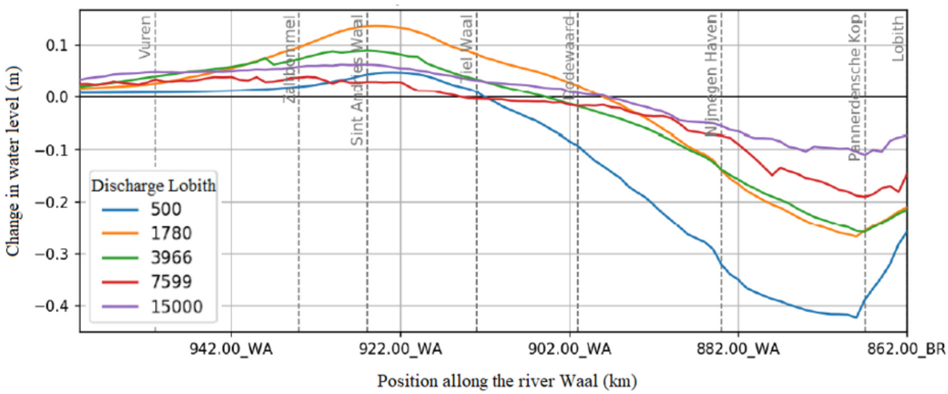

Figure 2.4: Change in water level along the river Waal as a consequence of reach scale bed erosion in 2050 with respect to 2018 (De Jong, 2020b).

2.4.2. CHANGING CLIMATE CONDITIONS

PREDICTED DISCHARGE TREND

Deltares translated the Dutch climate scenarios that followed from the KNMI'14 report into effects on discharge regimes for the river Rhine (Klijn et al., 2015). Figure 2.5 illustrates that monthly averages are expected to decrease during summer periods in 2050 and 2085 in 4 out of 5 scenarios. In 2050 the predicted changes vary form roughly –20% ($W_{H,\,dry}$) to +10% (G_L), and in 2085 from –30% ($W_{H,\,dry}$) to 0% (G_L) with respect to the reference situation.

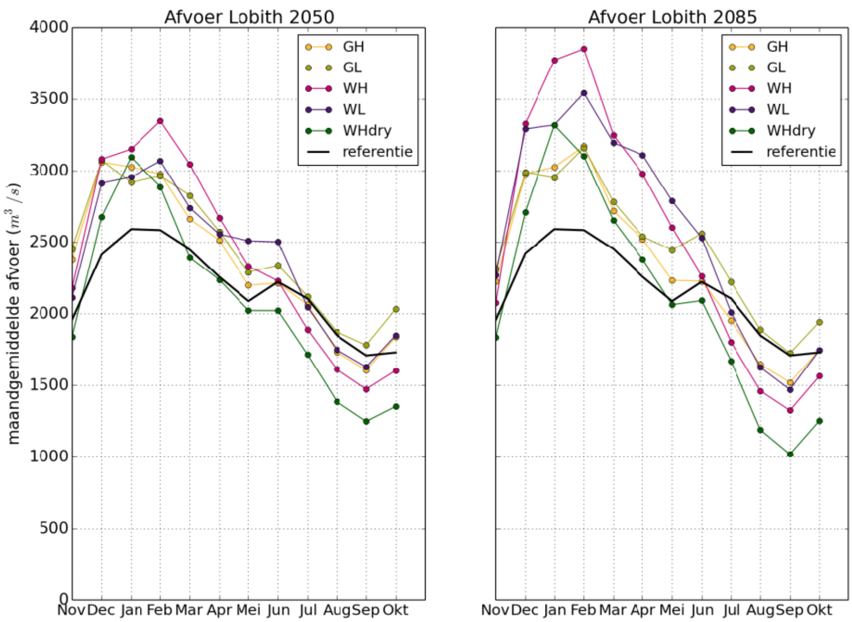

Figure 2.5: Monthly average discharge for the river Rhine measured at Lobith for the KNMI'14 scenarios. Black reference line represents the 2015 situation (Klijn et al., 2015).

FUTURE CHARACTERISTIC LOW DISCHARGES

The average decrease in discharge (as illustrated in Figure 2.5) is expected to be mainly due to an increase in number of days of very low discharges (De Jong, 2019). One of the outputs of the study is shown in Figure 2.6. The figure indicates the number of days per year that a discharge prevails at Lobith for four characteristic years (T1, T2, T10 and T100). Figures are given for the most moderate climate scenario (G_L) and driest scenario ($W_{H,dry}$) for time horizons 2050 and 2085.

From Figure 2.6 is concluded that the number of days with a relatively low discharge decreases in case of scenario G_L for all characteristic years. The decrease is spread over all discharge brackets. An increase in the number of days with an extremely low discharge increases in case of the $W_{H,dry}$ scenario's. This trend holds for both time horizons and all four characteristic years and worsens the navigation conditions on the river Waal. A low discharge period as in 2018 with a return period of 60 years, is expected to occur approximately once per 10 years in scenario $W_{H,dry}$.

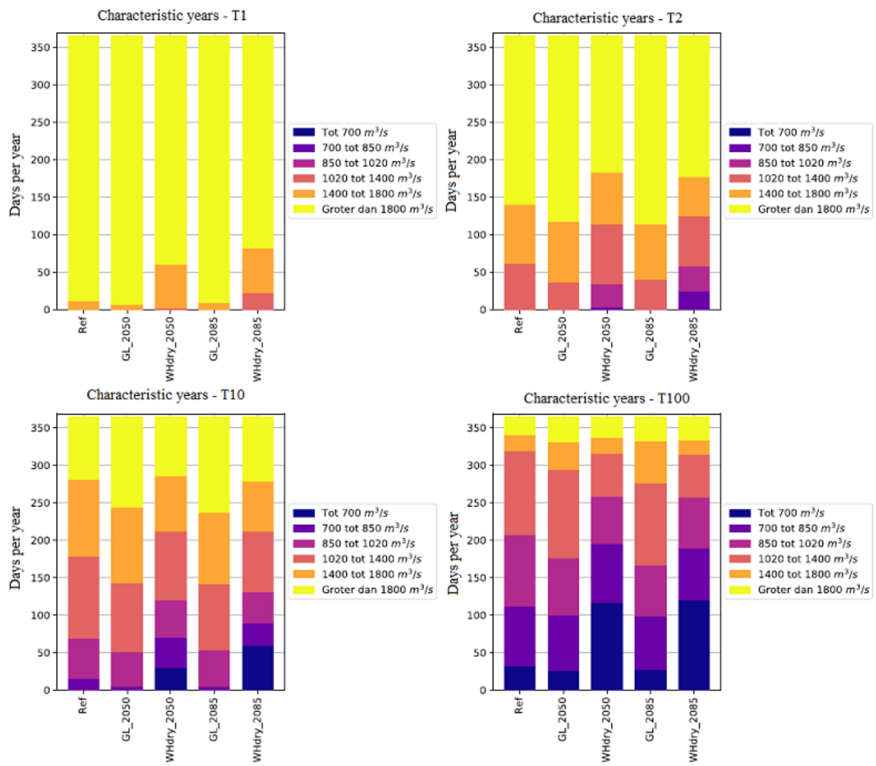

Figure 2.6: Discharges for characteristic years with return periods of 1, 2, 10 and 100 years for a moderate- and dry climate scenario and time horizons of 2050 and 2085 (De Jong, 2019)

SEA LEVEL RISE

The Water levels on the river Waal are affected by water level fluctuations at the North Sea till approximately Tiel, as the river Waal is in open connection with the North Sea through the Nieuwe Waterweg. The tidal amplitude at Zaltbommel (18 km downstream of Tiel) is approximately 10-15 cm.

The sea water level serves as a lower boundary for the prevailing water level at the river Waal. When the sea water level increases, a backwater effect is induced into the upstream parts of the river Waal. The magnitude of increase in sea level determines the extent towards the backwater extents upstream. An increase in sea water of 2 m at the Dutch coastline results in an increase in water level of about 0.2 m at Tiel for a discharge of 2200 m^3/s at Lobith (Haasnoot et al., 2018). For lower discharges effects are expected to be even less as backwater effects are less pronounced for lower discharges.

A second consequence of a rising water level at the downstream boundary, is a decrease in flow velocity, which leads to sediment deposits on the riverbed. The higher the sea level rises the further inland the deposits occur. The deposits could potentially mitigate the currently ongoing reach scale bed erosion (see Section 2.4.1) in the river Waal to some extent. Note that these morphological processes also depend on the measures one takes against sea level rise and processes such as salt intrusion, that come with sea level rise (Haasnoot et al., 2018).

Thus sea level rise may positively affect inland navigation when the sediment depositions can keep up with sea level rise rates, as it is expected to reduce the erosion rate of the river Waal to some extent. River bed erosion continues when sediment depositions can not keep up with the rising water levels on the river Waal. Another result of that scenario is that it increases the nautical depth and thus the navigability of the river Waal (Haasnoot et al., 2018). However effects are expected to be minor upstream of Tiel.

2.4.3. UP-SCALING TREND

The fleet development on the river Waal for the past decades is characterised by 'up-scaling'. Up-scaling means an increase in average vessel size, whilst the number of vessels on the waterways decreases or stays the same. The main reason for this trend is that the shippers seek for the lowest possible price (Looye, 2021). Up-scaling is expected to continue at increased rates the upcoming years, as smaller vessel are expected to be strongly affected by a decline in transport of construction materials and compound feed. On the other hand there is hardly products available in a growth segment for smaller vessels.

A study by Royal HaskoningDHV also addresses up-scaling and predicts that the process will continue till at least 2030. Also a short on smaller vessels is expected after 2030 due to up-scaling (Vermeij & de Vries, 2019). This might be one of the reasons that the up-scaling trends halts. Another reason is that the vessel dimensions might be limited by existing infrastructure. Width can be limited by for example locks, draft by available nautical depths and height by bridges.

2.5. FLEET COMPOSITION RIVER WAAL

2.5.1. VESSEL CLASSIFICATIONS

All waterways and vessels in Western Europe are classified according the CEMT classification system. The classification system is based on the dimensions of the vessels and waterways. This system allows for a uniform set of regulations that apply to several countries in Europe. The river Waal allows for navigation of the largest class of vessels; the VIc class, which represents a six barge push-tow convoy. A more recent classification system is the RWS-2010 system. This classification is considered to be more up-to-date with the current fleet in the Netherlands (Koedijk, 2020). An overview of both classifications and their characteristics is given in Figure A.1 in Appendix A. The RWS-classifications is mainly used in this study.

2.5.2. MULTI-ANNUAL FLEET ANALYSIS (2004-2020)

In this section, a multi-annual analysis (2004-2020) on the fleet on the river Waal based on IVS-data is performed to identify trends in fleet development. IVS (in Dutch: "Informatie- en Volgsysteem voor de Scheepvaart") stands for information- and tracking system for commercial vessels. Vessel data is available for 5 stretches of river on the river Waal, the so called ‘blocks’. For this analysis the busiest block, between Germany and the Meuse-Waal canal, is used (see Figure 2.7).

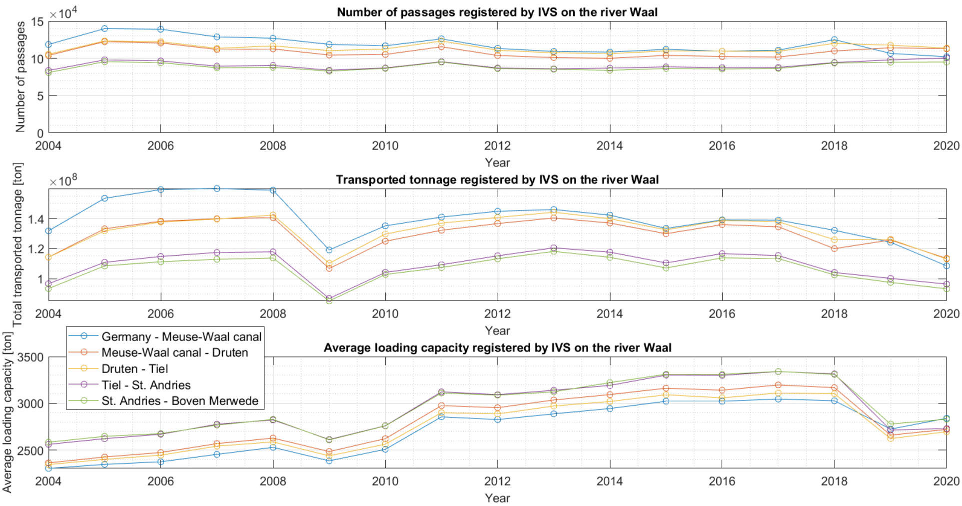

Figure 2.7: Annual figures for passages, transported tonnage and average loading capacity on the river Waal. An estimated 10-20% of the vessels is not included in the data. Figures are based on IVS-data.

It is known that IVS does not completely cover the fleet on the river Waal, as not all vessels are obliged to register themselves via the IVS-system. IVS covers approximately 80-90% of the vessels sailing on the Waal *(E. Bolt, personal communication, April 06, 2021)*.

Figures in this section refer to IVS block 'Germany - Meuse-Waal canal'. The annual average number of registered vessels passing this block is approximately 118000, with a maximum of 140000 in 2006 and a minimum of 102000 in 2020 (see top panel in Figure 2.7). The total number of passages is fairly constant over the considered time period. Peaks in the number of passages are observed in 2011 and 2018. It is likely that these peaks are caused by long periods of low discharge that occurred in these years. Traffic intensity increases when the largest vessels are not able to navigate fully loaded. The cargo is redistributed over several smaller vessels to transport the same amount of cargo.

The differences in number of east- and west going vessels varies only slightly over the considered time period (see Figure A.2 in Appendix A). In 2020 about 48% of the vessels navigates in eastern direction and 52% in western direction. Note that the distribution was the other way around in the years before 2016. No clear reason was found for this shift. The same analysis is performed for the transported tonnage in both directions (see Figure A.3). Approximately 61% of the total transported tonnage is transported in eastern direction and approximately 39% in western direction in 2020. Note that since 2016 the share in tonnage transported in eastern direction has reduced.

The average total transported tonnage is 139 million tons, with a maximum of 160 million tons in 2007 and a minimum of 109 million tons in 2020 (see middle panel in Figure 2.7). The drop in transported tonnage in 2008 can be assigned to the financial crisis, which started in 2008. Between 2010 and 2017 the transported tonnage remained fairly constant. Since 2017 total annual transported tonnage decreases. A combination of recent events such as the COVID-19 crisis, nitrogen crisis and energy transition have led to a reduction in transported tonnage over the Rhine corridor (de Leeuw van Weenum et al., 2020). The nitrogen crisis has resulted in a decrease in transport of construction materials, whilst the ongoing energy transition has resulted in a decrease in transport of coal, minerals and oil products (de Leeuw van Weenum et al., 2020).

The average registered transport capacity has increased rapidly over the last two decades (see Figure 2.7. The average loading capacity of the vessels has increased continuously since 2003 (with the exception of 2009 and 2010). From an average loading capacity of 2305 ton in 2004 to 3046 ton in 2017. The increase of transport capacity is assigned to the up-scaling trend as addressed in Section 2.4.3.

2.5.3. FLEET MIX DEVELOPMENT (2004-2020)

This section summarises the results of an analysis on the vessel distribution on the river Waal to find potential trends in the deployment of certain types of vessels. Figure 2.8 shows the vessel distribution between 2004 and 2020. The areas are sorted based on CEMT-classification, largest vessels on top, smallest vessels at the bottom of the plot. Note that some RWS-class vessel types are hardly visible in the plot due to their minor share. Also note that the solid lines separate CEMT-classes and dotted lines separate RWS-classes. Both statements also apply to Figure 2.8.

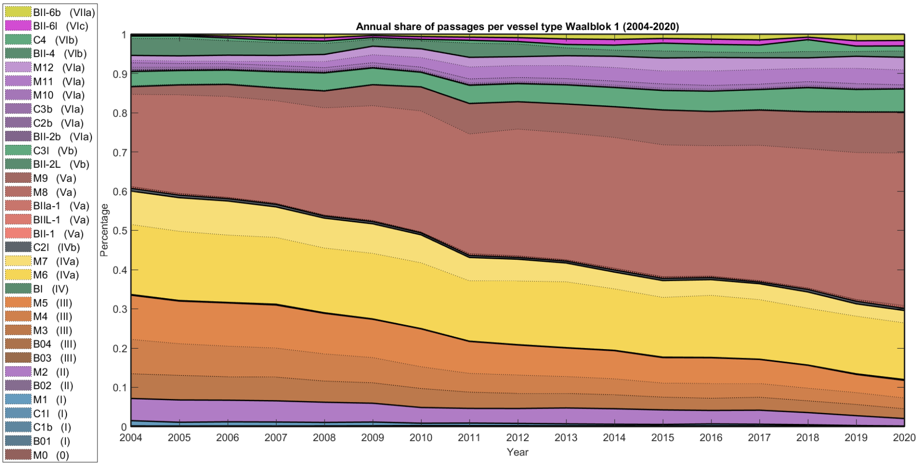

Figure 2.8: Vessel type distributions on the river Waal between 2004-2020 based on IVS-data.

Most striking is the increase in share of the M8 and M9 vessel classes (also CEMT-class Va). Other classes that have increased in share are the M11 and M12 vessels and the 6 barge pushed convoys (BII-6b and BII-6l). Vessel types that show the strongest decrease in share are the M3, M4, M5 types. A less pronounced decrease in share is found in the M6 and M7 classes and in the smallest classes of CEMT I. From these observations is concluded that the share of larger vessels has increased at the expense of the smaller vessel classes. This is a characteristic of the the up-scaling trend as addressed in Section 2.4.3.

A second analysis is conducted to find the dominating vessel classes in case of canalisation. In order to do so, the number of passages per RWS-vessel class is multiplied by the normative surface area of the respective vessel, resulting in the total surface area of the vessel classes. The results are presented in Figure 2.9 in the same way as in Figure 2.8.

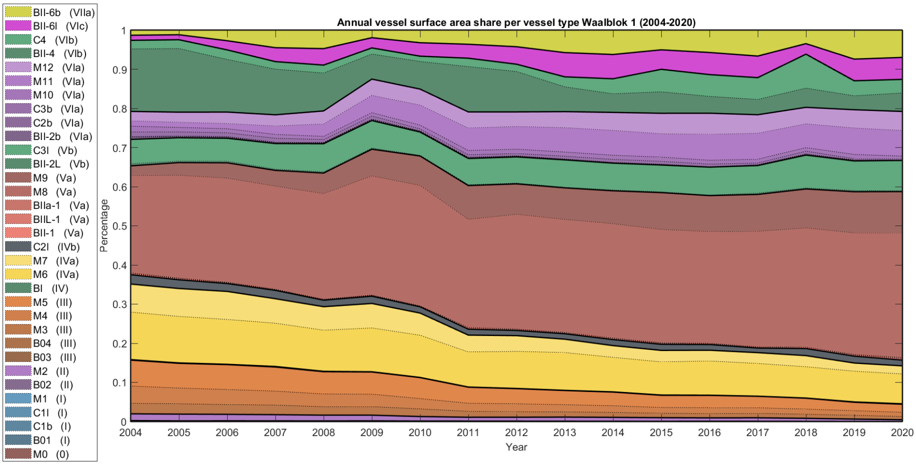

Figure 2.9: Vessel surface area distributions on the river Waal between 2004 and 2020 based on IVS-data

From Figure 2.9 is concluded that the M8 vessel class takes the largest share of the total surface area of the fleet by approximately 30% in 2020. From the figure is also concluded that the surface area is dominated by only a hand full of vessel classes. Mainly by vessel classes that are larger than the M8 class. Vessel classes BII-6b, BII-6l, BII-4, C4, M12, M11, C3I and M9 all take about 5-10% of the total surface area of the fleet. A first estimate of the required lock chamber dimensions can be obtained by combining the dimensions of the dominating vessel types. This method is applied in C.2 to set up several model variants for the vessel traffic simulations.

2.6. EXPECTED FUTURE MARKET DEVELOPMENTS

WLC's are designed and constructed for a lifetime of 100 years minimum, therefore it is useful to be able to say something on the future fleet navigating on the river Waal. However, the future is very uncertain, especially the far future (2030 and beyond) and in the present turbulent times, considering the COVID-19 pandemic, nitrogen crisis and ongoing energy transition. Which makes it difficult to make accurate predictions on the future fleet sailing on the river Waal.

The transported tonnage over inland waterways in the Netherlands is expected to decline by -12.9% to -4.5% towards 2025 (with respect to 2020) (de Leeuw van Weenum et al., 2020). Dry bulk transports are expected to decline due to a reduction in coal transports between the Port of Rotterdam and Germany (-50%) and due to unfavourable forecasts for the compound feed industry (-43%). The liquid bulk segment is expected to be characterised by a decline in transport of petroleum products and an increase in chemicals. A growth of about 20% is expected in the container transport segment towards 2025.

Similar market developments are presented in a large desk study by Royal HaskoningDHV conducted to obtain insight in the expected changes for a time horizon of 2040 (Vermeij & de Vries, 2019). These developments are based on existing literature and interviews with shippers and are listed below:

1. Reduction of fossil fuels;
2. Reduction in compound feed industry;
3. Expected increase in transport of salts for the chemical industry;
4. Shippers in construction products do not expect changes besides up-scaling;
5. The steel industry expects to keep producing at similar rates, however among shippers there are doubts about the capacity of the infrastructure;
6. Increase in transport of containers and growth of the cold supply chain.

Another recent large study into the future market- and IWT developments presents similar developments as listed above (RijkswaterstaatWVL, 2021a). However, the approach used to obtain the results is different. The results presented in IMA2021 are based on WLO scenarios instead of interviews with shippers and desk studies. Models such as BasGoed and BIVAS are applied to quantify and distribute the cargo over the inland waterway network. This approach made it possible to quantify future cargo flows.

On a national scale an annual average growth in inland waterway transport of 0.65% is predicted in case of the WLO 'low' scenario and for the 'high' scenario 1.12% is predicted with respect to 2014. On corridor scale (Rotterdam-Germany) a total growth in tonnage of about 20-30% is expected in 2040 for the WLO 'high' scenario. The corridor includes the river Waal, river Nederrijn, the Pannerdens Kanaal and the river IJssel till the city of Zuthpen. The increase in tonnage is mainly due to an increase in transport of minerals, metals and miscellaneous products (RijkswaterstaatWVL, 2021a). Transported cargo on the river Waal increases by 0-10% for WLO scenario 2040 low and increases by 10-20% in WLO scenario 2040 high in terms of transported tonnage (RijkswaterstaatWVL, 2021a). The expected growth figures are summarised in Table 2.2.

	WLO scenarios with respect to 2018					
	2030L	*2030H*	*2040L*	*2040H*	*2050L*	*2050H*
National	6%	14%	8%	20%	10%	32%
Corridor	-	-	-	20-30%	-	-
River Waal	0-5%*	5-10%*	0-10%	10-20%	0-15%*	15-30%*

Table 2.2: Cargo forecasts on different spatial scales for inland navigation in tons composed from IMA2021 (RijkswaterstaatWVL, 2021a). *Figures are obtained trough linear interpolation.

2.7. LITERATURE ON CANALISATION OF THE RIVER WAAL

Regulating the river Waal in favour of inland navigation by means of WLC's is expected to have a significant impact on several facets of the river system. One could think of the river functions such as flood protection, fresh water supply, ecology and transport. But also the morphodynamics of the river system and the discharge distribution over the river IJssel, Nederrijn and river Waal will be affected. However it is yet unclear how these functions and facets interact with each other in case of the proposed regulation (Yossef et al., 2019).

Other river functions, other than the transport function, may also benefit from canalisation. Increased water levels in periods of low discharge prevent the floodplains from drying out. Canalisation could contribute to reduce large scale bottom erosion as is addressed in Section 2.4.1. Canalisation would allow for fresh water regulation over the river bifurcations at the *Pannerdense Kop* and *IJssel Kop*. These opportunities illustrate that an integral approach is required to fully utilise the potential of canalisation.

Teakema conducted a MSc research that focused on the plausibility of improving inland navigation on the river Waal and the feasibility of canalisation of the river Waal by considering transport costs and WLC construction costs (Taekema, 2017). She considered canalisation a plausible measure for improving inland navigation when shipping costs are lower in case of canalisation, than in case without any measure, both under future climate scenarios. She considered canalisation feasible when the total costs of canalisation are less than the total costs induced by climate change without any measure. She concluded that canalisation is a plausible measure for improving inland navigation when installing one WLC, under the driest climate scenario ($W_{h,dry}$). No decisive conclusion is draw on the feasibility aspect as construction costs of the WLC's, that contribute for a large share to the total costs of canalisation, are highly uncertain.

2.8. CONCLUSION

The content of this chapter answers research sub-question 1 and 2. An answer to both sub-questions is formulated below.

What are the main factors that drive the worsening navigability of the river Waal now and in the future?

Bottlenecks for inland navigation occur when vessels are not able to navigate fully loaded on the river Waal. The smallest nautical depth available on the river Waal determines the maximum load a vessel can transport (assumed that a vessel navigates on the Waal only). Nautical depth limitations on the river Waal are expected to occur more frequently in the future. Primarily due to changing climate conditions, large scale bed erosion on the upper parts of the river Waal in combination with fixed riverbed layers and the increasing vessels sizes (up-scaling). This underlines the urgency for measures.

Several climate scenarios sketch different futures regarding the frequency and magnitude of low discharges at the river Waal. 4 out of 5 considered scenarios illustrate a decrease in monthly average discharge between 0-20% at Lobith in the months of July till October (driest period of the year). For the most moderate climate scenario (G_L) an increase of discharges is expected for the entire discharge regime. For the driest climate scenario ($W_{H,dry}$) an increase in frequency of low discharges and high discharges is expected. A very dry year as in 2018 is expected to occur once per 10 years (in climate scenario $W_{H,dry}$) instead of once per 60 years ,as under present conditions.

Large scale bed erosion is an acknowledged ongoing process which has its origin in fixing the plan-form of the river Waal by means of engineering works such as groynes. The erosion is expected to continue with rates between 0.6-1.6 cm/year between rkm 868 and 933. The large scale erosion trend in combination with present fixed bed layers cause these layers to protrude from the bed. These protruding layers will be the limiting sections on the river Waal in the future. Also the crossing of cables and pipes with the river Waal are going to induce nautical depth limitations as they are also considered fixed in the river bed.

What are the characteristics of the current and future fleets on the river Waal?

An analysis on the vessel loading capacity and vessel type distribution of over the period 2004-2020 underlines the up-scaling trend of the last two decades. The average loading capacity has increased from roughly 2500 ton in 2004 to 3300 ton in 2018, whilst the annual vessel class distribution shows a shift towards the larger vessel types. Up-scaling is still an ongoing trend an is expected to continue for an unknown period of time. Up-scaling is a factor that is included in the vessel traffic simulations in Chapter 4. No other trends than up-scaling were found.

An analysis on the total surface are per vessel type navigating in the river Waal has resulted in an approach to make first estimates on lock chamber dimensions. This method is applied in appendix C.2 to set up several model variants for vessel traffic simulations in SIVAK III.

Accurate future fleet characteristics are required to investigate the performance of a lock complex in the future. However, growth of the IWT sector on the river Waal is uncertain, mainly due to the ongoing energy transition and nitrogen crisis. Developments in both events affect the future cargo flows and fleets. Cargo forecasts, based on WLO scenarios for 2040, are extrapolated to 2050, resulting in an estimate increase in transported tonnage of 0-30% over the river Waal in 2050 (see Table 2.2). This range is used in Chapter 4 to define future fleets.

3

WEIR-LOCK OPERATIONS

3.1. INTRODUCTION

This chapter aims to answer research question 3 and 4. Question 3 consists of two parts; (1) How to assess the moment of closure of the WLC's and (2) if closed, what water levels to retain? Question 4 consists of two parts too; (1) How many WLC's are required and (2) at what locations? Result of this chapter is a potential lay out of a canalised river Waal and corresponding hydraulic boundary conditions regarding the (initiation of) operations of WLC's. Both results are input in the (set-up of) traffic simulations in Chapter 4.

3.2. DISCHARGE THRESHOLD FOR WLC OPERATIONS

The proposed WLC's consist of two main components (1) a movable weir and (2) a lock complex. A movable weir allows for unhindered passage of vessels under free flow conditions and is able to increase the water level upstream of a WLC in closed position. Examples of these movable weirs are found along the Nederrijn and Lek in the Netherlands (see also Section A.3 in Appendix A). For this study it sufficient to assume this conceptual weir type. A threshold to initiate WLC operations is required as the the WLC's are only in operation during low discharge conditions. The discharge at Lobith is used as threshold parameter for which an appropriate value is sought after in this chapter. The next section elaborates on three methods to establish a discharge threshold to initiate operations of the WLC's.

3.3. MOMENT OF CLOSURE WEIRS

3.3.1. METHOD 1 - FINDING AN OPTIMUM

THE TRADE-OFF

The economic damages due to extensive low water periods on the river Rhine in 2018 are one of the reasons to explore canalisation of the river Waal. Meaning that the consequences of the low water events are defined in monetary terms. Therefore an optimisation procedure is given in monetary terms too and is aimed to minimise transport costs given canalisation of the river Waal for a certain discharge threshold at Lobith.

3

The optimisation process is based on a trade-off between (1) the increase in transport costs due to increased travel times as a consequence of lock passages and (2) an increase in transport costs due to an increase in the number of ships that is required to transport the same amount of cargo in the situation of a free flowing river Waal. This implies the assumption of an inelastic cargo demand as is assumed that the same amount of cargo needs to be transport irrespective of the navigation conditions.

PASSAGE TIME WAAL

The first step is to quantify the time required to pass the river Waal given a number of WLC's with a certain capacity to handle vessel traffic. Generally the lower the discharge, the larger the head over the lock complexes and thus the longer the time required to pass a lock complex. On the other hand, the passage time is also affected by the lock configurations, dimensions and number of the lock complexes. Passage times increase when the ratio intensity over capacity increases. Traffic simulation models such as SIVAK III (introduced in Chapter 4) or similar are very useful to quantify passage times. The relations mentioned in this paragraph are schematised in Panel **A** in Figure 3.1.

Each line in Panel **A** in Figure 3.1 represents a scenario on the river Waal. The grey line represents a scenario with many WLC's, the black line a scenario with a few lock complexes and the orange line a scenario without WLC's. The vertical dashed line is set as a fictitious discharge threshold for which the WLC's turn on operational. Vessels pass through the locks for discharges lower than the threshold and through the weirs when larger than the threshold. From Panel **A** it becomes clear that more WLC lead to longer travel times on the river Waal. The passage time is assumed to be constant in the scenario without WLC's. In reality the average passage time of the river Waal decreases for very low discharges as vessel are not able to overtake each other.

TRAFFIC INTENSITY

The second step is to estimate the traffic intensity on the river Waal as a function of the discharge at Lobith for a representative scenario. In case of a free flowing river Waal, without WLC's, traffic intensity will increase as the discharge decreases, see orange line in Panel **B** in Figure 3.1. This is a consequence of a reduced nautical depth and a inelastic cargo demand. Note that the curve in Panel **B** is for illustrative purposes only and that the number of ships available is finite.

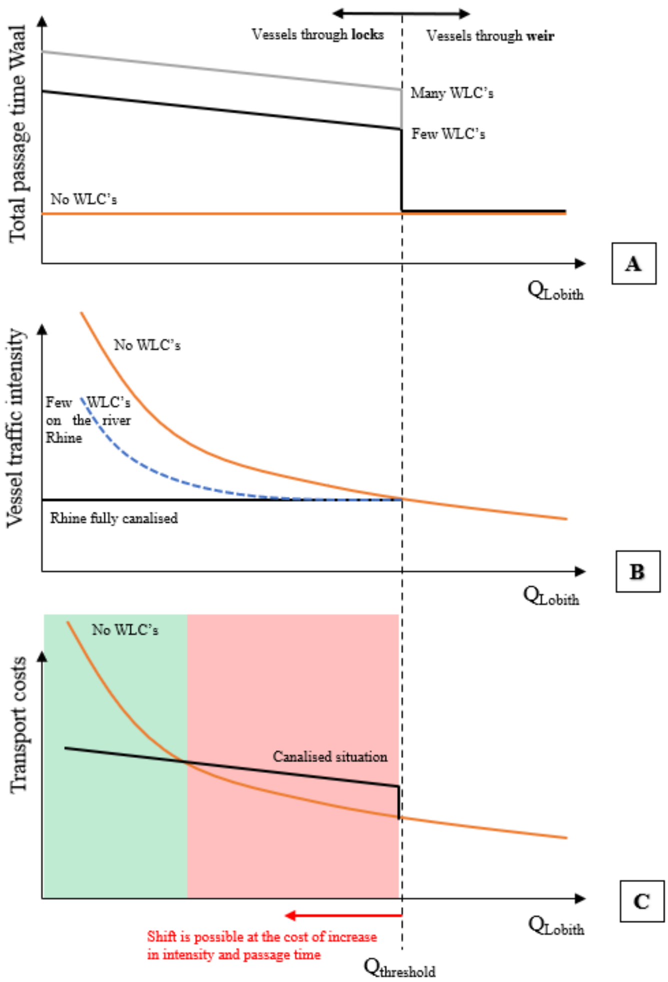

Figure 3.1: Panel A: relation between passage time Waal and discharge at Lobith for different scenarios, **Panel B:** relation between vessel intensity and discharge at Lobith, **Panel C:** relation between transport costs and discharge at Lobith for the case with and without WLC's (plots are based on (de Jong, 2021))

The reach over which the canalisation is applied is a second factor that affects the traffic intensity. By solely canalising the river Waal (as considered in this study), traffic intensity will be reduced, as the nautical depth is artificially increased over the river Waal during periods of low discharge. However, vessels that navigate from e.g. Rotterdam to a destination beyond Kaub (Germany) on the river Rhine, may experience depth restrictions further upstream (beyond the river Waal) and do not benefit from the canalisation on the river Waal. These vessels still navigate with reduced load, leading to an increasing vessel intensity for a decreasing discharge even in a partially canalised scenario. This is shown by the dashed blue line in Panel **B** in Figure 3.1.

In case of full canalisation of the river Waal and Rhine, the vessels mentioned in the example also benefit from canalisation (see black line in Panel **B** in Figure 3.1). So in order to be able to quantify the share of the passing fleet that is affected by the canalisation, a study into the origin and destination of the vessels is required.

TRANSPORT COSTS

The first two steps are combined in step three. Both, passage time and traffic intensity, can be expressed in transport costs as a function of the discharge at Lobith. This is illustrated in Panel **C** in Figure 3.1. The relation between transport costs and the discharge a Lobith is fully defined by the increase in traffic intensity in case of a scenario without WLC's. This situation is represented by the orange line in Panel **C** in Figure 3.1. The transport costs for a case with WLC's are defined by the increase intensity and increase passage time. This situation is represented by the black line in Panel **C** in Figure 3.1.

Panel **C** in Figure 3.1 now distinguishes between a range of discharges for which transport costs are less in canalised scenario with respect to a non canalised scenario (green shaded area), and visa versa (red shaded area). By shifting the threshold discharge for which the WLC's become operational towards the lower discharges, the range of discharges for which the transport costs are higher with WLC's is reduced. However, the shift increases the passage time and traffic intensity, resulting in a change in transport costs and thus a new Panel **B**.

OPTIMUM DISCHARGE THRESHOLD

The annual transport costs corresponding to the canalised scenario from Panel **C** in Figure 3.1 are multiplied by the annual average PDF of the discharge at Lobith (see Panel **D** in Figure 3.2). This results in the average total transport costs given a threshold Q_{Lobith} and a certain number of WLC's with corresponding capacity. An optimum $Q_{Threshold}$, for which the average annual transport costs are minimum, is found by repeating the process described in this chapter for varying threshold value.

Panel **E** in Figure 3.2 illustrates an optimum for $Q_{Threshold}$ as function of the total transport cost per year. Annual transport costs in case without WLC's are constant as they are not a function of $Q_{Threshold}$. Note that the process is repeated for current climate scenario and a future climate scenario. Annual average transport in the future climate scenario are higher than in the current climate scenario as the number of days with a low discharge is larger in the future climate scenario. The difference in transport costs between the case with and without WLC's (indicated by the red arrow in Panel **E** in Figure 3.2) is useful to take into account when considering budgets for construction costs of the WLC's.

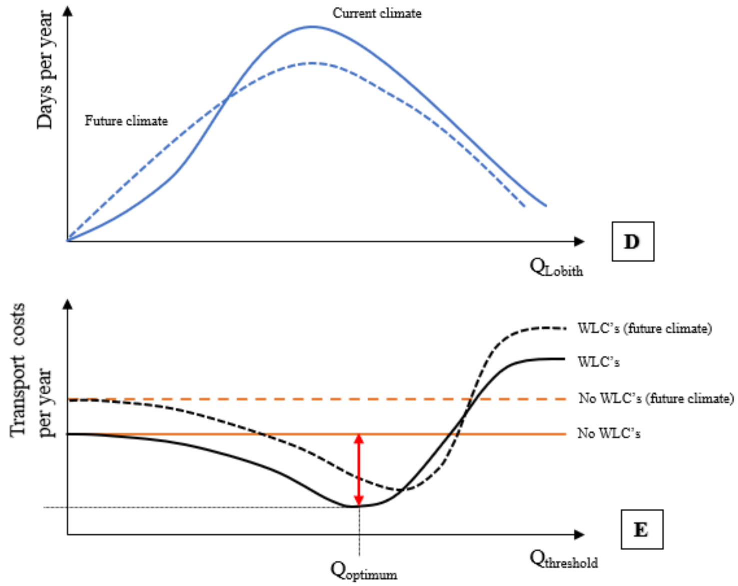

Figure 3.2: Panel D: conceptual discharge distributions, **Panel E:** relation between transport costs per year and discharge at Lobith (plots are based on (de Jong, 2021))

3.3.2. METHOD 2 - ALLOW FOR VESSELS AT ALL TIMES

This method was also applied to the river Meuse. The river Meuse is currently being upgraded from a CEMT Va to a CEMT Vb fairway. Water levels on the river Meuse are regulated by seven WLC's allowing for the normative CEMT Vb vessel class to navigate fully loaded at all times.

To allow all vessels at all times to navigate fully loaded on the river Waal requires a minimum nautical depth of 4.50 m plus UKC for the normative CEMT VIc vessel class (max. draught 4.50 m) (Koedijk, 2020). This is the case for the median discharge (1960

m^3/s) at Lobith. The CEMT VIc class vessels should be able to navigate with maximum draught and a nautical depth over draught ratio of 1.4. This ratio is however rarely met on the entire river Waal for median discharge conditions (ten Hove, 2018).

Figure 3.3 shows probability density functions of the vessels' draught for several discharge brackets based on IVS data from 2019, recorded between Tiel and Druten. The right-hand tail of the distribution illustrates that the share of vessels navigating with a draught of 4.5 m is close to zero. The plot also shows that approximately 1% of the vessels navigates with a draught larger than 4.0 m in the five largest discharge brackets. This implies that the vessels' draught does not further increase for discharges larger than 2000 m^3/s. Note that this is very similar to the median discharge as reported in the previous paragraph.

So, the weirs should close when the discharge at Lobith drops below 1960 m^3/s to allow for all vessels to navigate fully loaded at all times on the river Waal. Note that implicitly is assumed an unaltered discharge distribution over the Pannerdense Kop in the canalised situation. This also implies that 50% of the year vessels have to use the locks instead of the free passage through the weirs.

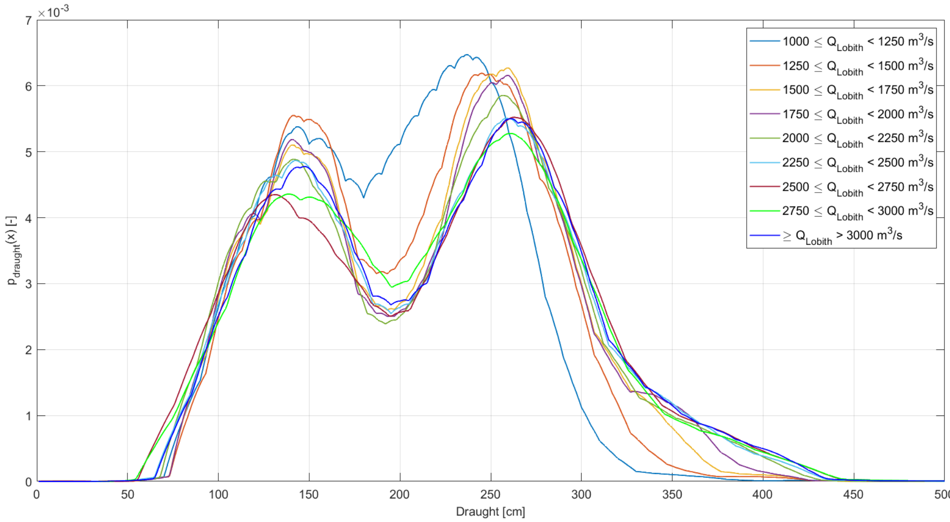

Figure 3.3: Draught distribution of vessels passing location G11W3 (Based on IVS data: Jan-Dec 2019)

3.3.3. METHOD 3 - INTEGRAL APPROACH

Traffic intensity on the river Meuse (between Geertruidenberg and Maas-Waalkanaal) roughly doubles, from 175 to 350 weekly passages, in periods of low water on the river Waal (van der Geest et al., 2021). Skippers prefer to use the river Meuse over the river

Waal when less than 3.20 m draught is available on the river Waal.

The sill depth at lock Grave limits the vessels' draught on the river Meuse to 3.20 m. This means that the skippers opt for the longer route via the river Meuse (2 lock complexes to pass) at the benefit of transporting a larger amount of cargo instead of using the river Waal and Maas-Waalkanaal (1 lock complex to pass) to reach destinations in the province of Limburg (see Figure 3.4).

3

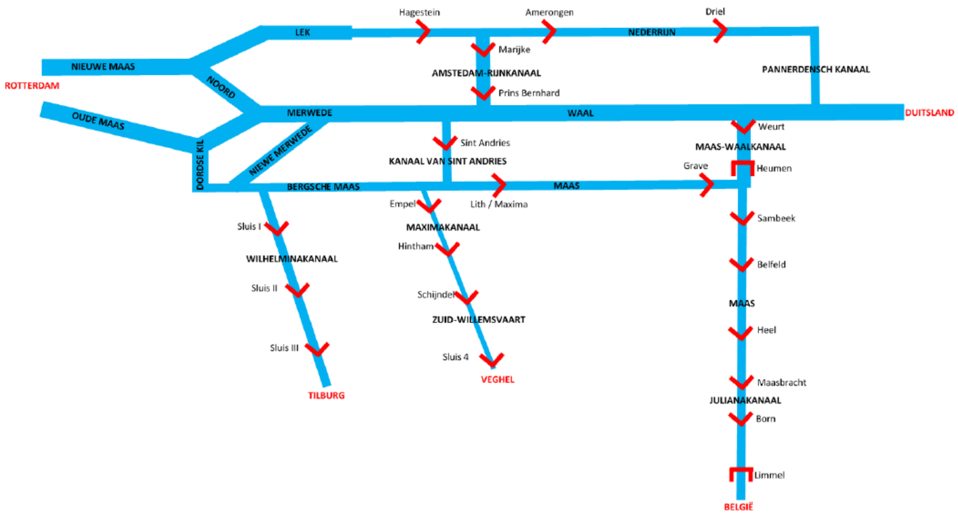

Figure 3.4: Geographical overview of the river Waal, river Meuse and their connections (Lievense, 2020)

Currently plans are made to upgrade the lock complex at Grave to allow for the Vb vessel class with a maximum draught of 3.50 m like the rest of the river Meuse (van der Geest et al., 2021). This implies that it is likely that vessels will use the Meuse connection (instead of the river Waal and Maas-Waalkanaal) when draughts less than 3.50 m are available on the river Waal. So $Q_{\text{Threshold}}$ is defined such that a minimum draught of 3.50 m is guaranteed at all times on the river Waal to prevent vessel taking a detour to reach destinations on the river Meuse and beyond.

It is common that skippers load their vessels in such a way that the maximum draught is equal to the MGD in the river Waal in order to translate the maximum draught to a discharge at Lobith. Meaning that when a MGD of 3.50 m is reported on the river Waal, vessels navigate with a maximum draught of 3.50 m. From Figure 2.2 is read that a discharge of approximately 1600 m^3/s at Lobith results in a MGD and thus maximum draught of 3.50 m. So activating the WLC's at a discharge of 1600 m^3/s prevents detours for vessels with a destination along the Meuse river (beyond lock complex Grave).

To put this in another light, activating the WLC's at a discharge of 1600 m^3/s at Lobith means that 4% of the commercial fleet is not able to pass the river Waal fully loaded. This is illustrated by the empirical cumulative density function of the recorded draughts for a discharge larger than the median discharge (1960 m^3/s) in Figure 3.5. The distribution at this discharge is assumed an ideal draught distribution as vessels are able to navigate at maximum draught as was found in Section 3.3.2.

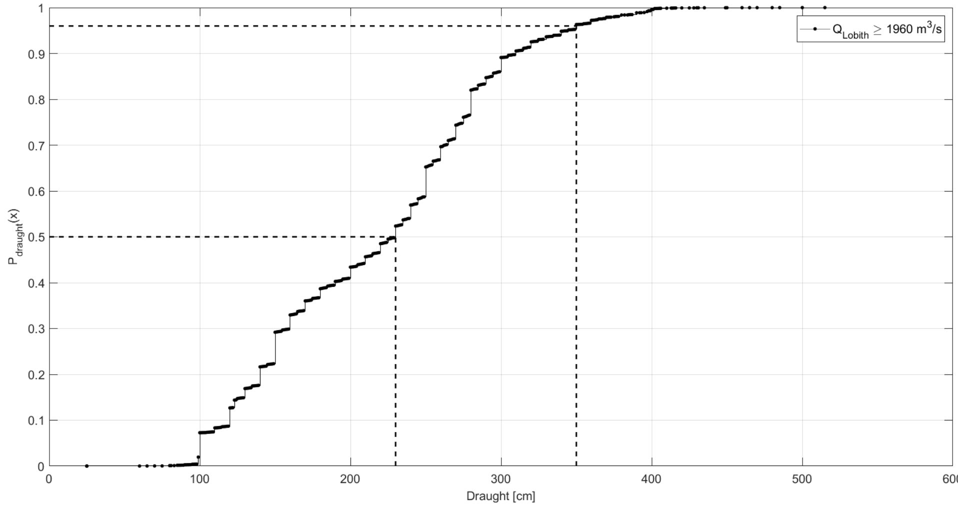

Figure 3.5: Empirical cumulative distribution function of the vessels' draught corresponding to discharges larger than 1960 m^3 at Lobith (based on IVS data between Tiel and Druten 2019).

3.3.4. METHOD OF PREFERENCE

Method one is described most extensively and is also most comprehensive. However, no time was found execute this approach during the writing of this thesis. Further development of this method is recommended to accurately estimate the moment of closure. Methods two and three are considered simplified approaches to estimate the moment of closure. Method two allows for all vessel to pass at all times, whereas method one illustrates the existence of an optimum, illustrating that not all vessels can pass at all times. For this reason is continued with method three; weirs and locks are active when the discharge at Lobith drops below 1600 m^3/s.

3.4. RETAINED WATER LEVELS

Water levels are upstream of the weirs are then raised to a level that allows for all vessels to pass fully loaded. In Section 3.3.2 was found that this is the case for water levels corresponding to a discharge of 1960 m^3/s at Lobith.

3.5. DETERMINATION OF NUMBER OF WLC'S

3.5.1. CRITERIA FOR ESTABLISHING NUMBER OF WEIRS

The number of WLC's to realise on the river Waal is of importance for the lock capacity, as it affects the heads over the locks and thus the passing time for the vessels. A second aspect to take into account is the set up of the water levels upstream of the WLC's. Water levels should not exceed dike heights or threaten the adjacent areas. The construction costs are a third aspect taken into account. From a financial point of view the number of WLC's should be kept to a minimum. Other aspects such as spatial integration and connectivity with other river functions are not considered. Nevertheless, they are relevant to study.

In a financial feasibility analysis regarding canalisation of the river Waal is concluded that a scenario with one WLC is financially most attractive (Taekema, 2017). Followed by a scenario with two WLC's and three WLC's. The analysis includes estimates of construction costs, costs of delay induced by the WLC's and extra shipping costs due to depth limitations (even when weirs are in operation). In which construction costs are dominant (> 80% of total costs), but also highly uncertain.

3.5.2. CURRENT HYDRAULIC CONDITIONS AND BED LEVEL

This section addresses the current conditions regarding discharge, water levels and water depths on the river Waal. Figure 3.6 indicates the water levels (upper panel) and depths (lower panel) for several discharges at Lobith in the 2018 situation on the river Waal. The dashed vertical lines are for referencing and the shaded areas in red indicate the fixed bed layers (as mentioned in Section 2.4.1). The horizontal black line in the lower panel indicates water depth that should be maintained for at the Agreed Low Discharge (see Section 1.2). A few remarks on the selected discharges are listed below.

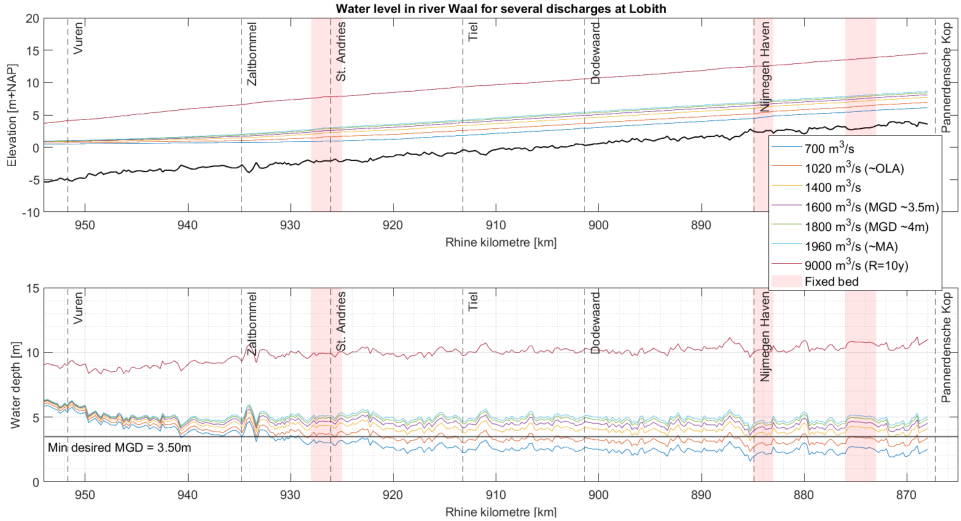

Figure 3.6: Upper panel: water levels for several discharges at Lobith, **lower panel:** water depth for several discharges

- **700** m^3/s: considered an extremely low discharge in the river Rhine;
- **1020** m^3/s: Agreed low discharge (ALD);
- **1400** m^3/s: *Rijkswaterstaat* starts to report *Minst Gepeilde Diepten (MGD's)*;
- **1800** m^3/s: No navigation problems foreseen for inland navigation (De Jong, 2019);
- **1960** m^3/s: Median discharge at Lobith;
- **9000** m^3/s: Discharge with a return period of 10 years.

The longitudinal bottom section in Figure 3.6 can be considered a representative fairway bottom level of the river Waal as in 2018. The bottom level is based on multi-beam measurements (1x1 m resolution) performed in 2018. The measured bottom level was translated into a bottom level that is relevant for navigation purposes, by assigning the 95-percentile value of the multi-beam measurement to each cell in the bottom grid (De Jong & Van der Mark, 2021). Then for each cross section the highest bottom level value in the fairway was taken as representative bottom level (De Jong & Van der Mark, 2021). This approach results in similar depths as the MGD's published by Rijkswaterstaat. This also implies that the bottom is quite conservative as it is based on local shallows.

The water levels in Figure 3.6 for the given discharges are taken from the 'Betrekkingslijnen 2018 Sheet' (Van der Veen & Agtersloot, 2019). The water levels are given under average high tide (as the lower parts of the river Waal are affected by the tides prevailing at the North Sea). 'Betrekkingslijnen' are visual representations of water levels that correspond to a certain discharges at Lobith. These relations are based on measurements and

WAQUA-model simulations (WAQUA is 2D hydrodynamic simulation model) for stationary discharges (Van der Veen & Agtersloot, 2019). Linear interpolation is applied to the water levels to obtain the same spatial resolution as the river bed level.

From the lower panel in Figure 3.6 is also concluded that water depths are sufficient (larger than 3.50 m) downstream of rkm 941 for discharges larger than 700 m^3/s. This means that positioning a WLC further downstream is not necessary for those discharges. Thus rkm 941 is considered a suitable location for a WLC.

3.5.3. BACKWATER EFFECTS

Backwater effects induced by the weirs (as adressed in the next sections) are approximated by a fit to the Bresse method. The use of the this method is justified as the flow in the river Waal is sub-critical (see Appendix B. For application of the method is assumed that 2/3 of the discharge at Lobith flows towards the river Waal and 1/3 flow towards the Pannerdens Kanaal, also in the canalised situation. This distribution is used to estimate the equilibrium flow depths for a given discharge at Lobith to compute backwater effects (see Appendix B). The distribution implies that another control structure at the Pannerdens Kanaal is required as the water levels at the Pannerdense Kop will be affected by the weirs in the river Waal. Meaning that the discharge distribution is also affected. The control structure should be able to maintain the current discharge distribution.

3.5.4. ONE WEIR-LOCK COMPLEX

This section considers a lay-out with one WLC at rkm 941, see Figure 3.7. This is just downstream the location where the nautical depth is less than the minimum required 3.50m for a discharge of 700 m^3/s. Water levels at the upstream side of the WLC are chosen such that the depth at the Pannerdense Kop approximates the depth corresponding to a discharge of 1960 m^3/s. Note that the spatial integration of the WLC in the landscape is not considered.

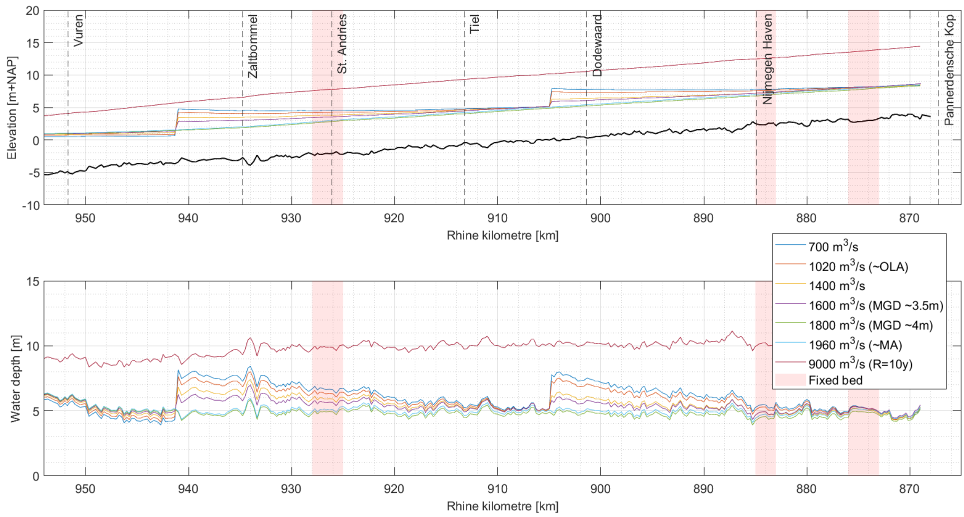

Figure 3.7: Upper panel: water levels for several discharges at Lobith, **lower panel:** water depth for several discharges

The upper panel in Figure 3.7 shows that the water levels directly upstream of the WLC for discharges of 700 and 1020 m^3/s would exceed the water level that corresponds to a discharge of 9000 m^3/s at Lobith in case without WLC. A discharge of 9000 m^3/s at Lobith has a return period of approximately 10 years. This implies that water levels are locally higher than the water levels that occur once per 10 years, for a substantial period every year (see Figure 2.6 for reference). Levees along the the river Waal do have sufficient height to prevent inundations, however they are not designed for extensive periods of high waters. For this reason the lay-out with one WLC is abandoned.

3.5.5. TWO WEIR-LOCK COMPLEXES

This section elaborates on a lay-out with two WLC's, see Figure 3.8. The downstream WLC is located at rkm 941 and the upstream WLC at rkm 905. The locations of the WLC's are chosen such that the river Waal is divided in two almost equal reaches in length. The benefit of this approach is that the water levels directly upstream of the WLC's are kept to a minimum. The water levels do not exceed the water level corresponding to a return period of 10 years, as was the case with one WLC. Water levels directly upstream of the weirs are chosen such that the water levels at the downstream side of the upstream weir and Pannerdensche Kop approximate the depth corresponding to a discharge of 1960 m^3/s.

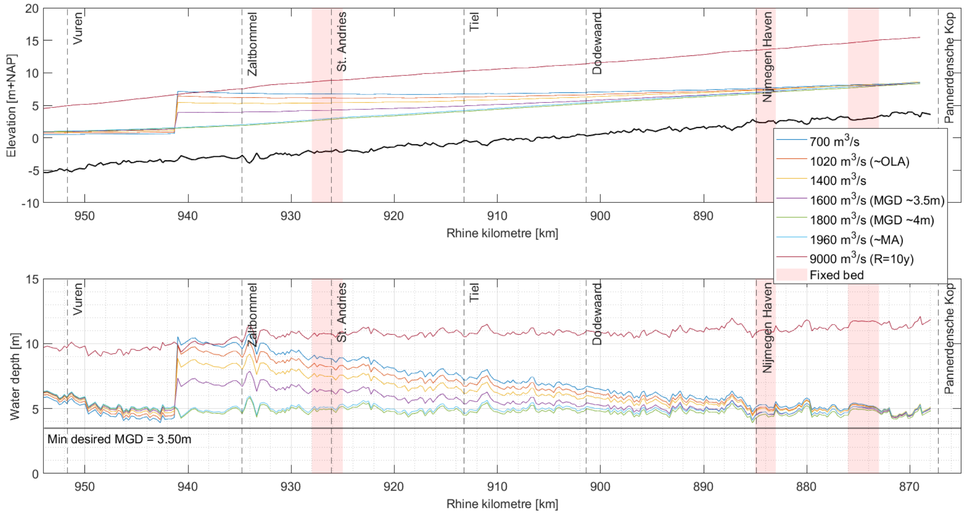

Figure 3.8: Upper panel: water levels for several discharges at Lobith, **lower panel:** water depth for several discharges

The water levels at the up- and downstream sides of the weirs are given in Table 3.1. The largest heads over the weirs occur for the lowest discharges. For an extremely low discharge of 700 m^3 the total head over the weirs is 6.9 m. For a discharge of 1600 m^3 (the threshold of operations of the WLC's) the total head is 2.2m. Note that these figures are indicative. The lay-out with two WLC complexes is plausible and will be used in the remainder of the study.

	Weir rkm 905			**Weir rkm 941**		
Q_{Lobith}	$h_{upstream}$	$h_{downstream}$	Δh	$h_{upstream}$	$h_{downstream}$	Δh
m^3/s	m+NAP	m+NAP	m	m+NAP	m+NAP	m
700	7.9	5.1	2.8	4.7	0.6	4.1
1020	7.4	5.1	2.3	4.2	0.9	3.3
1400	6.3	5.1	1.2	3.4	1.2	2.3
1600	5.9	5.2	0.7	2.8	1.3	1.5

Table 3.1: Water levels and heads over the weirs for the given discharges at Lobith

3.5.6. BED LEVEL IN CANALISED SITUATION

The bed level as described in Section 3.5.2 is used as a bed level this chapter. This bed level represents the bed in the fairway in 2018 in a conservative way. The ongoing large scale bed erosion and potential morphological effects induced by the WLC's is not accounted for in this bed level. The WLC's might reduce the reach scale bed erosion to some extent as flow velocities are reduced in a canalised situation. However flow velocities are already relatively low when the WLC's are operational. The effects of canalisation on the river morphology requires additional research.

3.6. CONCLUSION

An answer on research questions 3 and 4 is formulated based on the contents of the chapter. The research questions are repeated below for convenience:

How to determine the moment of closure of the WLC's and the retained water levels?

This chapter presented three methods to choose a discharge at Lobith for which both weir-lock complexes start operating. Method one describes and optimisation method based on financial considerations. The optimum threshold discharge is defined for the situation when the increase in transport costs are minimum, given a certain river layout (including WLC's) and traffic intensity. On one hand transport costs increase due to increased traffic intensity as a consequence of depth limitations in the free flowing situation. On the other hand transport costs increase due to increased travel times in case of a canalised river. The method is also useful in establishing a budget for construction of the WLC's as the difference in transport costs in a free flowing river and the costs in a canalised situation are cost savings due to canalisation.

Because of time limitations this method was not applied in this study and methods two and three were developed. Method two essentially states that all vessels have to pass at all times, resulting in activation of the locks when the discharge at Lobith drops below 1960 m^3/s. Method 3 considers a more integral approach and is described in the next paragraph. Nevertheless, for future feasibility studies into canalisation of the Waal is recommended to apply method one as it includes the financial aspect of canalisation. The results of this study regarding the required lock capacity could serve as a starting point for such a study.

For this study a more practical estimate of the moment of closure is made. Vessels tend to use the locks of Lith and Grave (river Meuse) instead of the faster route via the river Waal and Maas-Waalkanaal for destinations beyond Grave in case maximum available draught drops below 3.20 m on the river Waal. This is expected to change to a draught of 3.50 m in the future due to an upgrade of lock Grave. So in order to facilitate a direct route via the Maas-Waalkanaal a draught of 3.50 m should be guaranteed on the river Waal at all times. A translation from maximum available draught to discharge at Lobith was made via the MGD's on the river Waal. Resulting in a threshold discharge of

1600 m^3/s. The threshold implies that 4% of the commercial fleet is not able to navigate fully loaded when the locks are being activated.

The median discharge at Lobith (1960 m^3/s) provides sufficient depth to accommodate the maximum draught (4.50 m) of the normative vessels on the river Waal. So when the WLC's are in operation ($Q_{Lobith} \leq 1600 m^3/s$) the water levels are raised to a water level that corresponds to the median discharge at Lobith over the canalised reach.

How many WLC's are required in case of canalisation of the river Waal and at what locations?

The number of WLC's on the river Waal should be kept to a minimum for financial reasons. This chapter illustrated the effects of two different lay-outs of a canalised river Waal on the water levels for several constant discharges at Lobith. A lay-out of one WLC, was found not suitable, because water levels would exceed the water level corresponding to a return period of 10 years for a substantial part of the year (Section 3.5.4). A second lay-out with two WLC's is more plausible as water levels are better manageable 3.5.5. A lay-out with three WLC's is not considered, because of the substantial construction costs per WLC.

The layout with two WLC's as presented in this chapter is at the foundation of the lock capacity study in the next chapters. Figure 3.9 shows the locations of the WLC's on a map. Note that locations of the WLC's in Figure 3.9 are in line with the locations in Figure 3.8. In the remainder of this document is referred to the upstream WLC as **G11W3** and to the downstream lock as **G11W5**.

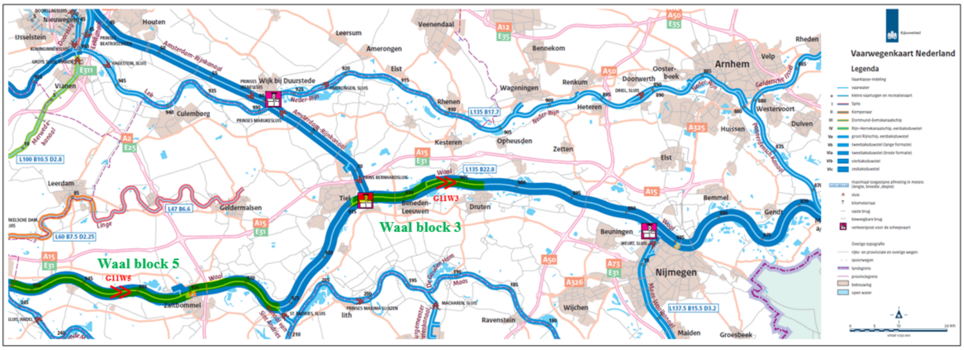

Figure 3.9: Locations of the two WLC's named G11W3 and G11W5 and Waal blocks 3 and 5(adopted from: https://www.rijkswaterstaat.nl/apps/geoservices/geodata/dmc/vaarwegenkaart/productinfo/beschrijvende_documentatie/vaarwegenkaart_2013.pdf)

4

MODEL SET-UP SIVAK III

4.1. INTRODUCTION

This chapter describes the scenario based simulation set-up for the vessel traffic simulations through the two lock complexes defined in Chapter 3. Preliminary lock designs or lay-outs are not available, thus assumptions and estimations regarding operational aspects such as, levelling times, opening and closing times of gates and detection length are required. This chapter clarifies on these assumptions and estimations. Output of the simulations is used in the next chapter to answer research question 5 ; What are the minimum required number of lock chambers and corresponding dimensions to facilitate smooth and reliable traffic flow over the river Waal now and in the future?

4.2. INTRODUCTION TO SIVAK III

A vessel traffic simulation model is a powerful tool for estimating the required lock capacity for locks to be built, as it allows the user obtain insight in the performance of a lock complex for various fleet scenarios. The performance, read lock capacity, of various lock configurations (also referred to as model variants) will be tested on a 'smooth traffic flow-' and a 'reliability' criterion for varying future fleets. This requires a simulation model with the following features:

- The model should allow for a large fleet diversity (vessel dimensions and characteristics);

- The model should allow for multiple lock chambers in one lock complex;
- Ideally the model should allow for simulating the performance of multiple lock complexes in one network
- The model should allow for variations in lock components and operations, such as chamber dimensions and filling and emptying times;
- The model should be able to simulate waiting times and passing times for the lock complexes at an individual scale.

SIVAK III is a software package that has the features as listed above. SIVAK is an abbreviation for 'SImulatiepakket voor VerkeersAfwikkeling bij Kunstwerken' in Dutch, and translates to 'Simulation package for vessel traffic management at waterway objects'. The SIVAK III software is owned by *Rijkswaterstaat* and developed by *Systems Navigator*. SIVAK III is commonly used at *Rijkswaterstaat* to test the performance of existing locks and locks to be built in the Netherlands under varying conditions (Koedijk, 2020).

SIVAK III is able to simulate traffic flows through a network of waterways and locks. The model simulates the passage of individual vessels, randomly generated at one end of the predefined network, via the waterways and locks, towards the other end of the network. SIVAK III requires three main components as input to simulate vessel traffic flows. These components are listed below and are elaborated on in detail in the Sections 4.3 till 4.5.

1. **Network**: The network defines the boundaries and characteristics of the waterways. Which include amongst other things hydraulic conditions prevailing in the waterways and all possible navigation routes.
2. **Locks**: This section requires input that characterises the lock complexes. Number of locking chambers, dimensions of the chambers and details regarding locking regime are required as in put in this section.
3. **Fleets**: This section requires the characteristics of the vessels and fleets that navigate through the network via the locks. Arrival patterns, fleet composition and vessel characteristics are important aspects that are included in this section.

4.3. DEFINING THE FAIRWAY NETWORK

Networks in SIVAK III consist of nodes that are can be located at a certain distance from each other. Connections between the nodes are defined as waterways and locks. In Chapter 3 was found that a lay-out with two lock complexes on the river Waal is most suitable. These lock complexes are considered separately in SIVAK III, meaning that the lock complexes are not connected through a waterway as would be the case in the real world. Figure 4.1 illustrates the difference between the ‘real world network’ and ‘simplified networks’.

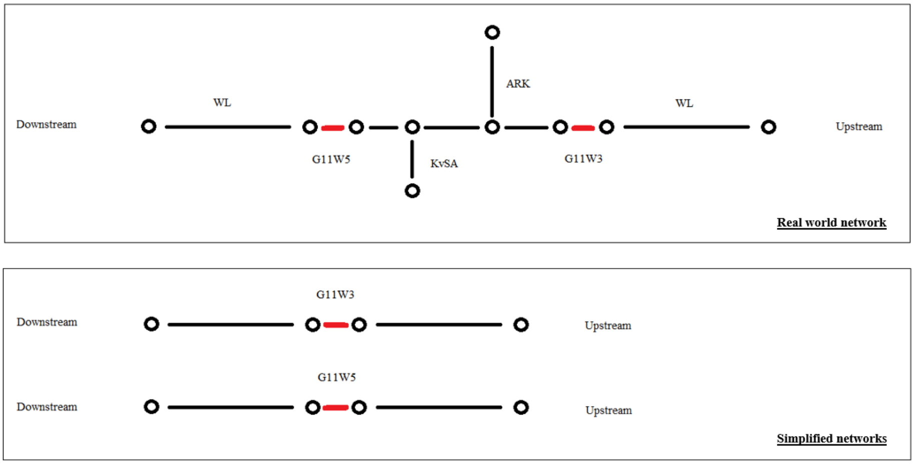

Figure 4.1: Upper panel: One network including two lock complexes, **Lower panel:** Two separate networks both including one lock complex (WL = Waal river, ARK = Amsterdam-Rijnkanaal, KvSA = Kanaal van Sint-Andries, G11W3 = upstream lock complex and G11W5 = downstream lock complex)

The simplification is applied in order to prevent a complex fleet analysis. Vessels can only enter or leave the network at the end-nodes. This means that in the ‘real world network’ vessels can enter or leave the network at four different nodes, whilst in the ‘simplified networks’ vessels can enter or leave at two nodes per network. In the ‘real world network’ 12 routes are possible and in the ‘simplified networks’ 2 routes per network. So this simplification does not require the characterisation of fleets for 12 different routes, which would be extremely time consuming. By splitting the ‘real world network’ in two ‘simplified networks’ fleets need to be defined in only two directions (east-going and west-going vessels) for each lock complex.

The simplification implies that potential network effects are ignored. The arrivals at a certain location along the river Waal can be considered random in the situation without locks. However after construction of two lock complexes this pattern may be disturbed, as locks tend to ‘hold up’ vessels for some time and ‘release’ them at once. This potentially induces a clustered character in the vessel arrival pattern at the next lock complex.

It is expected that the clustered character reduces and disappears as the distance between the two locks increases, because different vessels navigate with different velocities and my overtake. It is also expected that the clustered character reduces with an increasing number of lock chambers per lock complex, as the total number of vessels per locking decreases, whist the frequency of locking increases, resulting in a more randomly distributed arrival pattern at the next lock complex. The split-up in two networks is justified, under the assumption that the distance between the locks (36 km) is sufficient to prevent navigating in groups and that no other network effects occur.

Vessels are generated according to the fleet definitions and arrival patterns (Section 4.5) at the left-end node and right-end node. Every vessel that is generated at one end of the system has to pass the lock complex and leaves the network at the other end. After the moment of generation, vessels navigate over a stretch of water of 2000 m that has a width of 170m, in both directions for both lock complexes. Then the vessels encounter the lock complex which is elaborated on in Section 4.4. Water levels on both sides of the locks depend on the discharges as defined Table 3.1 and are defined as such. For simulations normative water levels are used (see Section 4.4).

4.4. ESTABLISHING LOCK PARAMETERS

4.4.1. LOCK CONFIGURATIONS AND CHAMBER DIMENSIONS

Part of the study is to find a suitable number of lock chambers per WLC. This requires simulations with a varying number of lock chambers. Three chambers is considered a minimum, based on the traffic intensity comparison made with the Volkerak locks in Appendix C.1 and no more than five lock chambers are considered per WLC.

The dimensions of the lock chambers are to be determined too. Therefor a set of 8 different lock chambers is defined as in Table 4.1. The lock chamber dimensions are composed by combining the dimensions of different vessels types taking up most of the space in the lock chambers (see Figure 2.9) on the river Waal. Simulations are conducted with a number of lock chambers that are equal in dimensions to keep the number of model variants limited.

For instance, chamber ID 1 has a width of 25 meter and an effective length of 330 meter. The width of this chamber is equal to the width of the new built (in use since 2019) lock chamber in the Princes Beatrix lock complex located in the Lekkanaal. A chamber this wide allows for a 2 wide push tow convoy (class VIa) and for two M8 vessels next to each other. The minimum prescribed width would be 23.8m (2 times 11.4m vessel width + 0.1 m drift wood between vessel and lock walls on both sides and 0.8 m for manoeuvring) (Koedijk, 2020). The choice for 25 m width was made to allow for more space for vessels to manoeuvre. The extra space with respect to the minimum width should decrease entry and exit times. The length of chamber ID 1 (330 m) is chosen such that three M8 vessels can fit in line in the lock chamber theoretically. SIVAK III considers all vessels as rectangular and positions the rectangles against each other in the lock chambers.

In reality the (in-line) distance between the vessels is in the order of 1 m at minimum *(Operator Volkerak Locks (Rijkswaterstaat VWM), personal communication, October 29, 2021)*.

Chamber ID	Effective chamber width	Effective chamber length	Length margin	Length incl. margin
	[m]	*[m]*		*[m]*
1	25	330	20	350
2	28.4	330	20	350
3	25	245	20	265
4	28.4	245	20	265
5	25	305	20	325
6	28.4	305	20	325
7	34.2	305	25	330
8	25	390	20	410

Table 4.1: Different lock chambers used in SIVAK III simulations

The line of reasoning used in this section is used to arrive at the dimensions of every chamber ID listed in Table 4.1. The reasoning for the remaining dimensions is presented in Appendix C.2. The length margin in Table 4.1 cannot be taken by vessels while locking, this space is for safety and opening and closing of the gates. Guidelines prescribe a minimum of 2 m between stop marks and the gates (Koedijk, 2020). The remaining space is for opening and closing of mitre gates. SIVAK III uses the length including margins as in Table 4.1 to compute water losses.

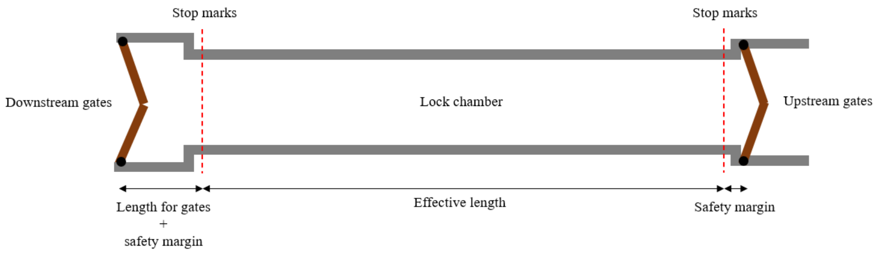

Figure 4.2: Top view of a lock and corresponding length definitions

4.4.2. SILL LEVELS

The sill depths of the lock chambers should be sufficient to prevent damages to the lock chamber and the vessels when vessel enter or exit the lock chamber. It is also taken into account that the sill depth affects the time a vessel needs to enter and exit the lock chamber. The time for vessels to enter and exit the lock chamber depends on the blockage coefficient and whether a vessel is laden or not (Kooman & de Bruin, 1975). The larger the blockage coefficient, the longer the duration of the entry or exit. The blockage coefficient is defined as the wet cross section of the vessel entering the lock divided by the cross section of the lock(head).

First, for a lock complex located in a fairway of class VIb (max. allowed draught 4.50 m) a minimum under keel clearance (UKC) of 100 cm is recommended, resulting in a minimum sill depth of 5.5 m (Koedijk, 2020) with respect to normative low water conditions. There are no guidelines for locks in VIc fairways as they do not exist yet. The river Waal is currently a VIc fairway, however when the locks are operational, 6-barge push tow convoys are not allowed to navigate anymore (see Appendix D.2.2), resulting in a fairway VIb class.

Second requirement relates to the ease of which the vessels enter or leave the lock. The ease of vessels entering or leaving the lock is considered sufficient when the blockage coefficient above the sill is at maximum 0.75 (Koedijk, 2020). The smallest, and thus normative, lock chamber in 4.1 has a width of 25 m and the normative vessel is a 4-barge push tow convoy with a draught of 4.5 m and a width of 22.8 m. When applying the maximum ratio of 0.75 one will find a minimum sill depth of 5.47 m.

The sill depths relates to a normative low water level. The minimum and normative water level at the downstream side of complex G11W3 and G11W5 occurs for a discharge of 700 m^3/s, whilst the minimum at the upstream side occurs for a discharge of 1600 m^3/s. These water levels and corresponding discharges are taken from Table 3.1 and written in the schematics in 4.3 and 4.4.

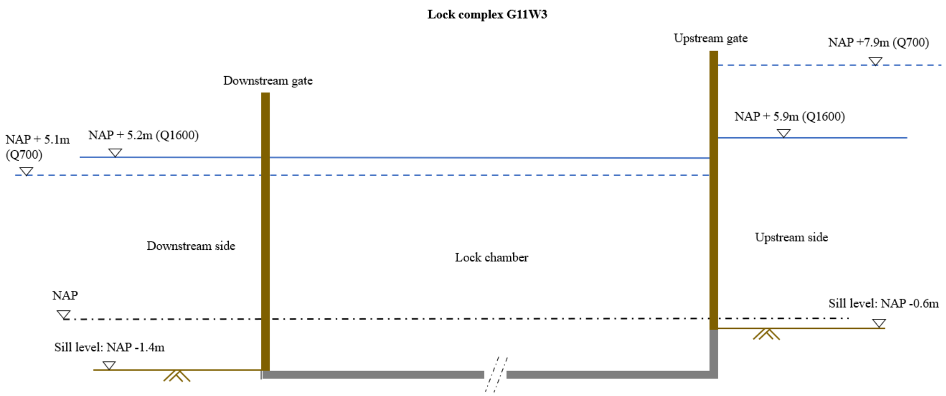

Figure 4.3: Longitudinal section of a lock showing normative water levels and sill depths at lock complex G11W3

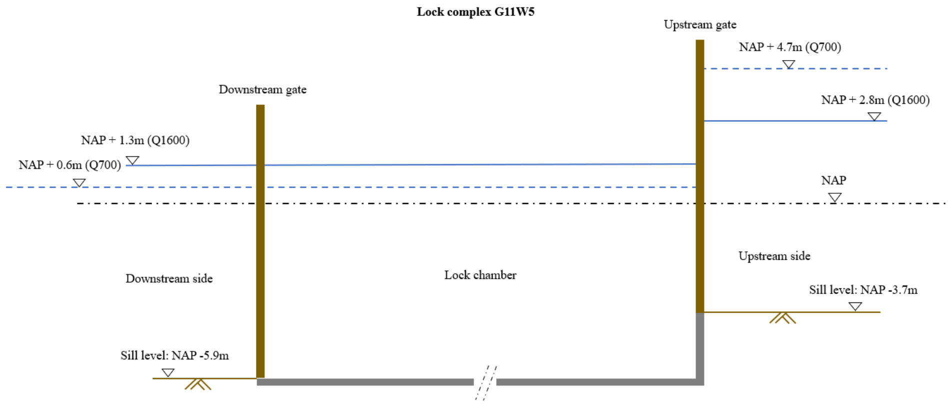

Figure 4.4: Longitudinal section of a lock showing normative water levels and sill depths at lock complex G11W5

The sill levels are chosen such that they are 6.5 m below the normative water levels. This is a larger sill depth than the minimum requirements prescribe. Extra depth is taken into account to facilitate faster lock entries and exits and to allow for potential larger draughts due to up-scaling of the fleet.

4.4.3. GATE TYPE AND OPENING/CLOSING TIME

The locking operation can be divided in the three consecutive events, closure of the gates, levelling and opening of the gates. These three events take a certain time that is unknown yet, as no detailed design of the lock chambers and fill and emptying system exists. Opening and closure of the gates depends on the type of gate that is used, the width of the lock chamber and the mechanical devices that drive the gates. Opening and closure times of the gates vary generally between 2 and 4 minutes (Kooman & de Bruin, 1975; Molenaar & e.a., 2020). Figure 4.2 implicates the use of mitre gates and water retention in one direction. This type of gate is considered suitable for the proposed locks. A reasonable estimate for the opening and closing time for this type of gate is 2 minutes (Kooman & de Bruin, 1975).

4.4.4. LEVELLING TIME

The time required to fill and empty the lock is a compromise between investment costs and the benefit of a shorter passage time. Main factors that are involved in the compromise are the maximum allowed hawser forces, maximum allowed passage time, type and dimensions of filing and emptying system, dimensions of the lock chamber and head over the lock chamber. Generally, levelling times vary between 8 to 12 minutes, with a maximum of 15 minutes for inland navigation locks of the proposed dimensions and corresponding heads (Molenaar & e.a., 2020; Vrijburcht & Glerum, 2000) also *based on personal communication with M. Voorendt (Delft University of Technology) 26-08-2021.* Simulations in SIVAK III are conducted with levelling times as presented in Table 4.2. In the reference scenario an estimated levelling time of 12 minutes is used. The remaining levelling times in Table 4.2 are used in a sensitivity analysis.

Lock complex	Gate opening	Gate closure	Levelling
	[min]	*[min]*	*[min]*
G11W3	2	2	12 (8, 10, 15)
G11W5	2	2	12 (8, 10, 15)

Table 4.2: levelling operation times for several scenarios (levelling times used in the sensitivity analysis are given between brackets)

4.4.5. LOCKING OPERATIONS

LOCKING REGIME

A locking regime regulates the initiation of locking based on a set of criteria. Locking regimes are often used to increase the lock chamber utilisation and thus reduce the number of total locking operations. SIVAK III initiates levelling once a ship has entered the chamber or when a ship comes within range on the closed side of the lock. If other ships are within range of the lock they will be allowed to lock in the current initiated levelling till the lock chamber is full (SystemsNavigator, 2020).

DETECTION RANGE

The detection range is the distance between the lock and the position on the waterway at which a vessel is visible of the fictitious lock operator. Within this range the service order of the arriving vessels is established, as well as the chamber allocation. In reality this line does not exist. The lock operator is responsible for allocating the vessels in time, the moment of contact between lock operator and vessel varies from vessel to vessel, depending among other things on vessel speed, traffic intensity at the lock and experience of the operator. A relative long detection length may increase waiting times for vessels in the lock chamber, as they have to wait for extra arriving vessels. A relative short detection length potentially increases the waiting time because the lock starts levelling too early, as a not yet detected vessel could have joined the locking instead of the next locking. The effects of the detection range on the average waiting time and service level is included in the sensitivity analysis (see Section G.1).

CHAMBER PRIORITY

The settings regarding chamber priority and detection length have not been addressed in previous sections as the others are. Chamber priority refers to the situation when multiple lock chambers are available for a vessel upon arrival at one of the lock complexes. SIVAK III requires a setting on the decision making which lock to enter in such a case. This setting is set to 'Availability' in the reference scenario. Meaning that a vessel will enter the lock chamber that becomes available first.

4.5. FLEET SELECTION AND CHARACTERISTICS

4.5.1. REPRESENTATIVE FLEET IN IVS DATA

The third main input component in SIVAK III entails the characteristics of the representative fleets that navigate through the network as defined in Section 4.3. A representative fleet is considered a fleet is observed recently on the river Waal for water levels corresponding to those in the canalised situation. Note that fleet mix, traffic intensity and characteristics of the fleets vary as the discharge on the Waal varies (Vinke et al., 2022). The response of the traffic intensity, load factor and draught to the discharge at Lobith is outlined in Appendix D.5.

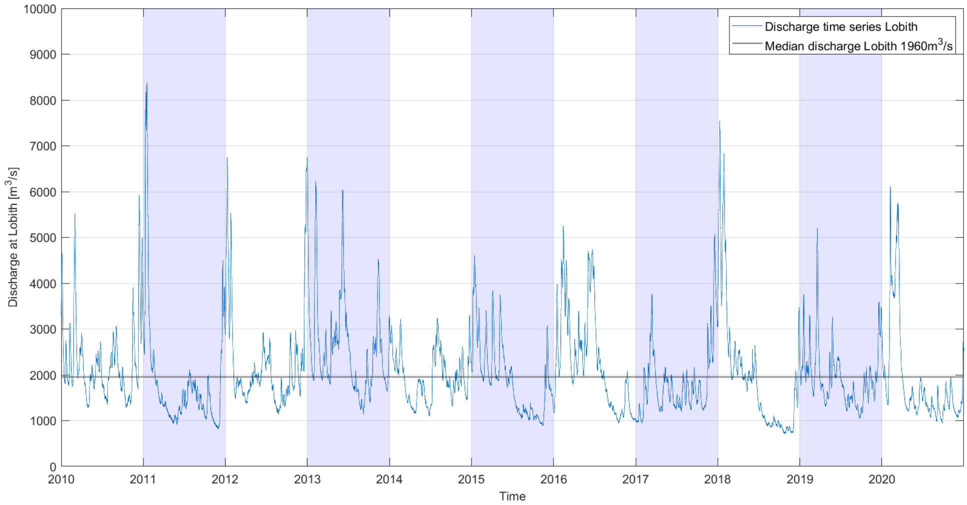

Figure 4.5: Hourly discharge series measured at Lobith (2010-2020). Data taken from https://waterinfo.rws.nl.

IVS data recorded in the months January 2019 till June 2019 is used as a representative fleet mix, fleet characteristics and the arrival patterns at the WLC's. IVS stands for 'Informatie en Volgsysteem voor de Scheepvaart' in Dutch and translates to track and trace system for inland navigation. The data set is provided by *Rijkswaterstaat* and contains vessel registrations and characteristics on an individual level. The discharge in this period is not characterised by prolonged and extreme discharges as illustrated Figure 4.5. Water levels are considered similar to the ones artificially created by the WLC's (see also Section 3.4). In addition, the fleet data is recent, resulting in a representative fleet mix.

The traffic passing the two WLC's is simulated separately as elaborated on in Section 4.3. This means that both WLC's require their own input in SIVAK III. Input data for WLC G11W3 (upstream lock complex) was recorded in 'Waalblok 3' and data for WLC G11W5 (downstream lock complex) was recorded in 'Waalblok 5'. Waalblok 3 is defined as the section of the river Waal between Druten and Tiel, Waalblok 5 between St. Andrieskanaal and Boven-Merwede (see Figure 3.9). The location corresponding to the timestamps that mark the entry of a section is either at the east or west end of the respective section, depending on the navigation direction of a vessel.

The fleet data selected can only be used under the assumption that water levels further upstream on the river Rhine are also similar to the ones that prevailed in the first half of 2019. In the case of a canalised river Waal with active WLC's this means that other control structures on the river Rhine are required to set up water levels as such. In addition the control structures should allow for the passage of the same vessels as have passed through the proposed locks on the river Waal.

4.5.2. FLEET MIXES

Two fleets are defined per lock complex, consisting of an east-going fleet and west-going fleet. Each fleet contains several vessel classes with corresponding characteristics (see Appendix A.1). The vessel characteristics per RWS-vessel class (DWT, draught loaded, draught unloaded, width, length, and height) are included in a database in SIVAK III. Also the number of passages of each type of vessel is entered per week. These figures follow from a fleet analysis performed in Appendix E.

4.5.3. ARRIVAL PATTERNS

In order to establish the moments of arrival at the one of the lock complexes an arrival pattern is defined. An average hourly distribution of arrivals per day of the week is entered in SIVAK III. 'Seasonality factors' are applied in order to include weekly variations. The seasonality factors are defined as the total number of passages in a certain week divided by the average number of weekly passages in the considered time period (Jan-Jun 2019). The weekly variations are defined for the commercial fleet, four types of passenger vessel classes and recreational fleets (if used). Detailed information regarding weekly, daily and hourly arrivals is presented in the fleet analysis in Appendix E.

4.5.4. CORRECTIONS MADE FOR DATA FLAWS

The 17th of March 2019, IVSNext was introduced, a new version of the previously used IVS90 system (van Oerle et al., 2019). IVSNext includes positional registration of vessels by AIS (automatic identification system) in contrast to the previous system. This means that vessel passages are recorded automatically, without human action. The previous IVS90 system relied on reports by the skipper and traffic operators moving a vessel (virtually) from one block to another block (van Oerle et al., 2019). Which is less accurate and more sensitive to (human) errors.

The introduction of IVSNext is clearly visible in the data, as illustrated in Figure 4.6. The upper panel shows the fraction of commercial vessel registrations with and without SK CODE for 'Waalblok 3' for 2019. The lower panel presents the same results in absolute figures. Note that 'SK CODE' is equivalent to 'RWS-vessel class' (M1, M2, etc.). Figure D.16 in Appendix D shows the development of the fleets with and without the 'SK CODE' per navigation direction in 2019. In January and February all commercial vessels registered do have an SK CODE. In March, 7% of the registrations has no SK CODE. No SK CODE also means that no other data is attached to the registration. This percentage increases to 14% in April and the reduces to 13% in May and 12% in June. These percentages appear to be slightly lower than the expected IVS90 coverage of approximately 80% as was mentioned in Section 2.5.2. Note that the Figure 4.6 includes commercial vessels only and that the 80% as mentioned above includes all type of vessels (i.e. recreational vessels, tugs, dredging vessels, etc.).

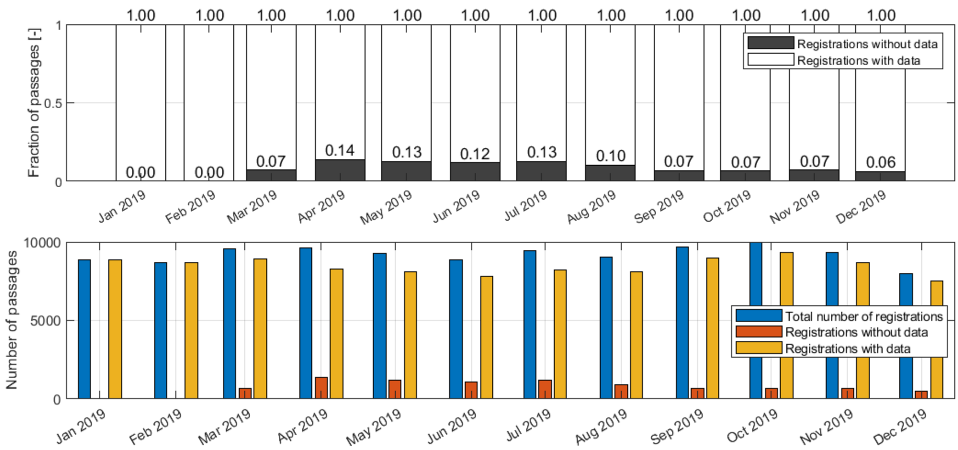

Figure 4.6: Upper panel: fraction of registrations without data commercial vessels only, **lower panel:** registrations in absolute values (based on IVS data G11W3 2019)

4

An explanation for the missing data is found in the fact that the IVSNext connects the position of a vessel (AIS) and the manual input by the skippers (van Oerle et al., 2019). This implies that all commercial vessels are recorded by the AIS system, as it is obliged for a vessel to navigate with the AIS system on board on the Dutch waters, however not every skipper reports its route. This results in vessel registrations by AIS without content (no manual input by the skipper). The registrations without content are redistributed over vessel classes M1 to M8 in order to include the registrations without data in the SIVAK III simulations (see Appendix D).

Besides the registrations without content, there are two other flaws in data set. First, passages of recreational vessels are not recorded accurately in both IVS versions. Recreational vessels are not obliged to report on their route via IVS90 and recreational vessels with a length shorter than 20 m are not obliged to send and AIS signal and are thus often not recorded (“Binnenvaartpolitiereglement Artikel 4.07”, 2017). This means that no recreational vessels were registered until the introduction of IVSNext and after that registrations are very scarce. An estimate of the number of recreational fleets, mainly based on counting campaigns, is given in Section D.2.6 in Appendix D.

Second, for unknown reasons, data is missing on the 17th and 18th of May 2019 in the data. No registrations were found for the 17th of May and only a hand full of registrations for the 18th of May. No reason was found to assume that no vessels have passed those days. Therefore linear interpolation between number of vessels that have passed on the same day one week earlier and one week later was applied to fill the gaps, see also Section D.3.5 Appendix D.

4.6. MODEL VARIANTS AND SIMULATION SCENARIOS

4.6.1. SIMULATION TIME

The performance of the model variants is tested on two criteria as described in Section 4.2. To verify whether the average waiting time is less than 30 minutes the the normative period is relevant. The normative period is defined as the four consecutive weeks with the highest traffic intensity (weeks 17 till 20 in Figure 4.7). The duration of the simulations required to test on the 85% service level requirement is 25 weeks (week 1 till 25 in Figure 4.7).

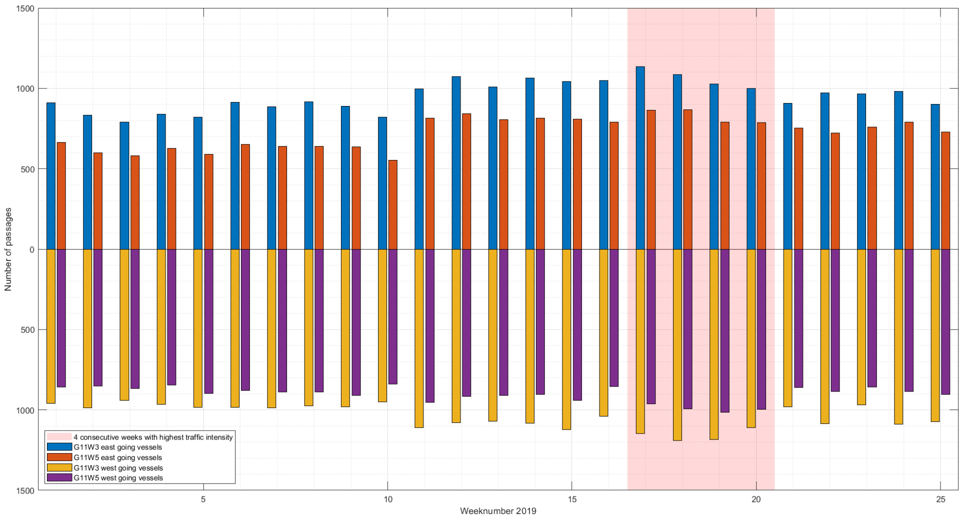

Figure 4.7: Total number of east- and west-going vessels at G11W3 and G11W5 (based on IVS data 2019 Jan-Jun)

4.6.2. DESCRIPTION OF MODEL VARIANTS IN REFERENCE SCENARIO

The lock chambers in Table 4.1 are at the basis of all the simulations that are conducted. The performance of these lock chambers is tested in variants with 3, 4 and 5 lock chambers, resulting in 24 model variants per lock complexes. Note again; lock chambers are kept equal in dimensions per lock complex to reduce the number of possible model variants. These model variants are ran in scenarios for 4 and 25 weeks to test on the waiting time- and service level criterion.

The canalised river Waal as defined in Chapter 3 in combination with the 2019 fleet as defined in Appendix D is considered the reference scenario. Table 4.3 presents an overview of the model variants in the reference scenario.

To test 30 min. requirement				To test 85% service level requirement			
ID	**Number of chambers**	**Chamber size**	**Run duration**	**ID**	**Number of chambers**	**Chamber size**	**Run duration**
		[m]	*[weeks]*			*[m]*	*[weeks]*
1	3	25x245	4	25	3	25x245	25
2	3	25x305	4	26	3	25x305	25
3	3	25x330	4	27	3	25x330	25
4	3	25x390	4	28	3	25x390	25
5	3	28.4x245	4	29	3	28.4x245	25
6	3	28.4x305	4	30	3	28.4x305	25
7	3	28.4x330	4	31	3	28.4x330	25
8	3	34.2x305	4	32	3	34.2x305	25
9	4	25x245	4	33	4	25x245	25
10	4	25x305	4	34	4	25x305	25
11	4	25x330	4	35	4	25x330	25
12	4	25x390	4	36	4	25x390	25
13	4	28.4x245	4	37	4	28.4x245	25
14	4	28.4x305	4	38	4	28.4x305	25
15	4	28.4x330	4	39	4	28.4x330	25
16	4	34.2x305	4	40	4	34.2x305	25
17	5	25x245	4	41	5	25x245	25
18	5	25x305	4	42	5	25x305	25
19	5	25x330	4	43	5	25x330	25
20	5	25x390	4	44	5	25x390	25
21	5	28.4x245	4	45	5	28.4x245	25
22	5	28.4x305	4	46	5	28.4x305	25
23	5	28.4x330	4	47	5	28.4x330	25
24	5	34.2x305	4	48	5	34.2x305	25

Table 4.3: Model variants for G11W3 (upstream lock complex) and G11W5 (downstream lock complex)

The following assumptions and SIVAK III settings are used to simulate the reference scenario for G11W3 and G11W5 as presented in Table 4.3:

- **Fleet mix:** as in Table D.1 as derived in Appendix D
- **Arrival patterns:** as in Tables D.12 and D.13 as derived in Appendix D
- **Water levels:** as in Section 4.4.2
- **Sill levels:** as in Section 4.4.2
- **Opening/closure gates:** 2 minutes
- **levelling time:** 12 minutes
- **Lock regime:** no regime
- **Chamber priority:** availability
- **Detection range:** 1 km

4.6.3. DESCRIPTION OF MODEL VARIANTS IN FUTURE SCENARIOS

For the future scenarios the same configurations are tested as in the reference scenario. The model variants are presented in Table 4.3. No settings or variables are altered other than discussed in the sections below.

In Section 2.6 was found a maximum growth in transported tonnage in 2050 of 30% in WLO scenario 'high' (see Table 2.2). Note that the reported percentages represent an increase in tonnage, but will be used as an increase in traffic intensity. This results in a rather conservative estimate, as the relation between transported tonnage and traffic intensity is not expected to be linear. This is mainly due the ongoing up-scaling trend as elaborated on in 2.4.3.

An increase in traffic intensity of 30% is taken as an upper boundary. The reference scenario serves as a lower boundary (fleet intensity of 2019). Intensity increases of 10% and 20% are used as intermediate scenarios. Traffic intensities corresponding to those percentages are given in Table 4.4 per lock complex.

Lock complex	**ref.**	**+10%**	**+20%**	**+30%**
G11W3	2194	2413	2633	2852
G11W5	1769	1946	2123	2300

Table 4.4: Average weekly traffic intensities for different traffic intensities in 2050 for commercial fleets only

No data or figures on future changes in fleet composition for fleets navigating on the river Waal were found. Therefore the fleet composition of the Volkerak locks is used to assess the impact of a different fleet composition. This parallel is drawn because all lock complexes involved allow for the same type of vessels (max. VIb vessels).

Figure 4.8 illustrates the differences between the fleets passing the Volkerak locks and the proposed lock complexes (G11W3 and G11W5) on the river Waal. For the vessels with the largest shares (M8, M9 and M6) taking up to 60% of the total share, only minor differences are found. Largest differences in fleet share are found in the M10, M12 and BII-4 push tow convoys. The share of M10 vessels at the Volkerak locks is triple the share at the G11W3 and G11W5 complexes. The share of M12 vessel at the Volkerak locks is about double the share at G11W3 and G11W5. 4-Barge push tow units are rarely seen at the Volkerak locks and take about 5% of the total share at the lock complexes G11W3 and G11W5.

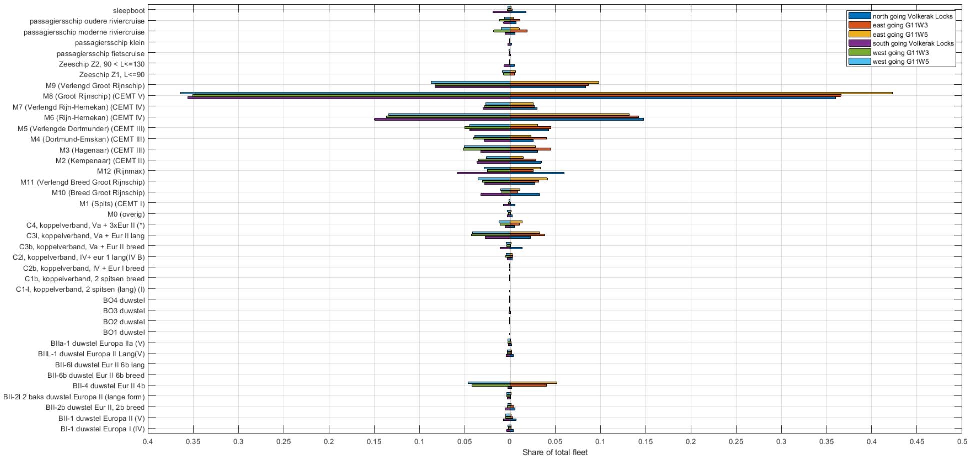

Figure 4.8: Fleet distribution in 2019 per navigation direction for the Volkerak locks, lock complex G11W3 and G11W5. Data Volkerak Locks taken from SIVAK III simulations performed for IMA2021 (RijkswaterstaatWVL, 2021b)

The predicted fleet composition for an opportune economic scenario in 2050 (WLO scenario 2050 'high') at the Volkerak locks is applied in combination with an increase in traffic intensity of 30% with respect to the reference scenario (as in Table 4.4. The predicted fleet composition is taken from SIVAK III simulations conducted in the context of the Integral Mobility Analysis (RijkswaterstaatWVL, 2021a). The resulting fleet compositions for both lock complexes are given in Figures E.1 and E.2 in Appendix E.

A second fleet composition scenario was composed to correct for the very low number of 4-barge push tow units passing through the Volkerak locks. The changes in share with respect to the original predicted fleet mix as described in the previous paragraph are given in Table 4.5.

RWS vessel class	Share difference
BII-4 duwstel Eur II 4b	0.06
BII-1 duwstel Europa II (V)	-0.01
C3b, koppelverband, Va + Eur II breed	-0.01
M2 (Kempenaar) (CEMT II)	-0.02
M6 (Rijn-Hernekan) (CEMT IV)	-0.02

Table 4.5: Corrections as applied in the modified WLO2050H fleetmix with respect to the original Volkerak fleetmix in scenario WLO2050H

Note that up-scaling effects are strong in this scenario, as it includes a relative large shares of M10, M12 and 4-barge push tow units compared to the current fleet mix on the river Waal. The average surface area of the vessels increases by 20% for vessels passing

G11W3 and with 13% for vessels passing G11W5 in this scenario with respect to the current fleet mix. To put this in perspective; the increase in average vessels surface area is expected to be 13% at the Volkerak locks in scenario WLO2050H with respect to the current fleet mix at the Volkerak locks. The future scenarios as discussed in this section and simulated in SIVAK III are summarised in Table 4.6. A Full overview of all simulations conducted, including those for the sensitivity analysis, are presented in E.2.

ID	Scenario	Year	Traffic intensity	Fleet composition
1	Reference	2019	-	-
2	Future	2050	+10%	-
3	Future	2050	+20%	-
4	Future	2050	+30%	-
5	Future	2050	+30%	Volkerak (WLO2050H)
6	Future	2050	+30%	Modified Volkerak (WLO2050H)

Table 4.6: SIVAK III scenario simulation overview

4.7. ESTABLISHING NUMBER OF SIMULATION REPLICATIONS

The generation of vessels and the corresponding characteristics is a stochastic process in SIVAK III. This implies that not every simulation has the exact same output. Therefore every simulation is repeated several times to obtain an averaged output. A convergence test is conducted to estimate the number of replications required for sufficient accurate results (see Appendix E). The convergence test is applied to a model variant with three lock chambers (25x245m) and a model variant with four lock chambers (25x330m). The error in average waiting time for applying 5 replications is in the order minutes for the model variant with three lock chambers and in the order of 0.1 minutes for the model variant with four chambers. Details on the analysis are presented in Appendix E in Section E.3.

5

SIMULATION RESULTS

5.1. INTRODUCTION

This chapter answers the final research question 5; What are the minimum required number of lock chambers and corresponding dimensions to facilitate smooth and reliable traffic flow over the river Waal now and in the future? Focus is on the 30 minutes average waiting time, also referred to as waiting time requirement, and the 85% service level requirement. The simulation results for both lock complexes, G11W3 and G11W5 are considered separately in this chapter.

5.2. REFERENCE SCENARIO

5.2.1. SIMULATION RESULTS FOR UPSTREAM LOCK COMPLEX G11W3

WAITING TIME REQUIREMENT

The average waiting time is tested against 30 minute waiting time requirement in this section. Figure 5.1 presents the average waiting time for all the model variants that are subject to the fleet as in the normative period (four consecutive weeks with highest traffic intensity). From Figure 5.1 is concluded that a lock complex with 3 chambers is not sufficient to meet the waiting time requirement.

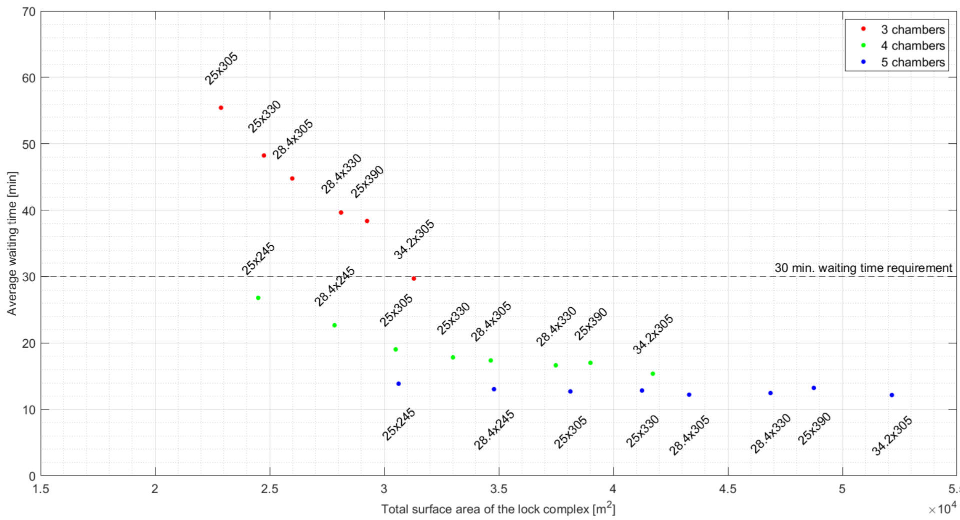

Figure 5.1: Average waiting time for all model variants at lock complex G11W3 in the normative period (4 weeks)

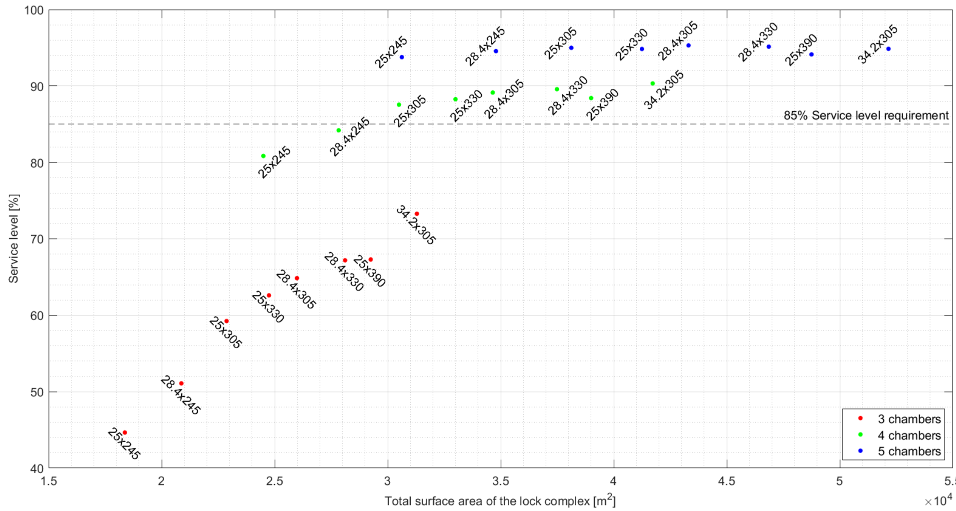

Figure 5.2: Average service levels for all model variants at lock complex G11W3 over 25 weeks

SERVICE LEVEL REQUIREMENT

The different model variants are tested against the 85% service level requirement in this section. Simulations are run for 25 weeks in this case. Figure 5.2 presents the service levels that are achieved per model variant. Three lock chambers are not sufficient to handle the traffic flow within the requirement. The same holds for the two smallest chambers in a model variant with four chambers. All model variants with five chambers do meet the requirement.

CONCLUSION

In the previous section is considered the output of the reference scenarios for lock complex G11W3 regarding the 30 minutes waiting time requirement and the 85% service level requirement. Both requirements should be met. This is never the case for a model variant with three lock chambers and is always the case with five lock chambers. The lock chambers with a length of 245 m in model variants with four chambers are not suitable, as they do not meet the service level requirement. This implies that the minimum required number of chambers is four, with minimum dimensions of 25x305 m in order to meet both requirements. The average waiting time for this model variant is 19.0 minutes and a service level of 87.6% (also summarised in Table 5.1).

scenario	values	chambers	length	width	avg. waiting time	avg. service level
[-]	*[-]*	*[-]*	*[m]*	*[m]*	*[min]*	*[%]*
ref	-	4	305	25	19	87.6

Table 5.1: Minimum required number of lock chambers with minimum dimensions that meet the requirements under the considered reference scenarios for lock complex **G11W3**.

5.2.2. SIMULATION RESULTS FOR DOWNSTREAM LOCK COMPLEX G11W5

WAITING TIME REQUIREMENT

Figure 5.3 shows the average waiting time for the model variants in lock complex G11W5 in the reference scenario. From Figure 5.3 is concluded that a model variants with three lock chambers are sufficient to handle the reference fleet intensity. Exceptions are the lock chambers with a length of 245m. Note that model variants with 3 chambers are not suitable for lock complex G11W3, as traffic intensities are higher at lock complex G11W3.

SERVICE LEVEL REQUIREMENT

Figure 5.4 shows the service levels that are achieved per model variant in the reference scenario. From Figure 5.4 is concluded that the model variant with 3 chambers and dimensions 34.2x305 m is at the boundary of the requirement with a service level of 85%. However the width of the chamber may not be to convenient in reality, as vessels are not able to moor when in the middle of the chamber. Furthermore a slight increase in traffic intensity will lead to exceedance of the service level limit. So 3 chambers are possible for this complex, however expected to be impractical in reality.

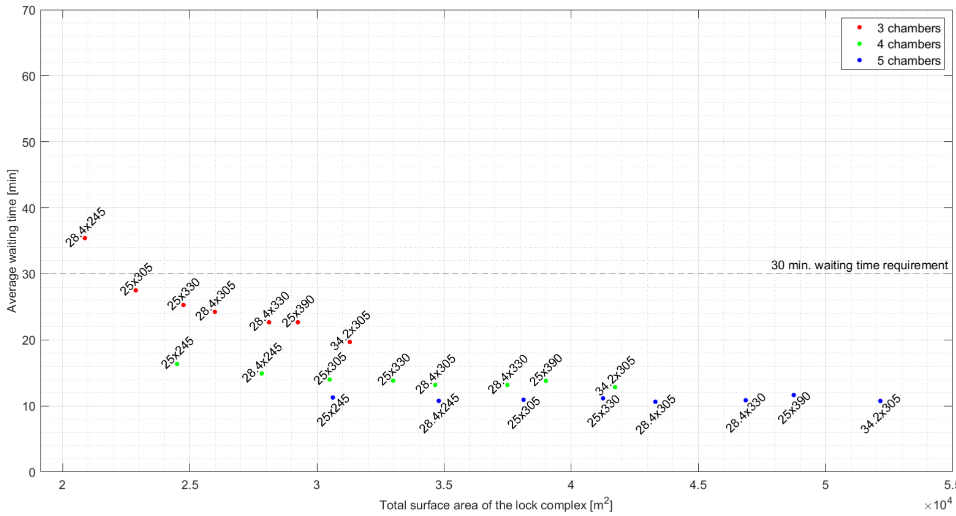

Figure 5.3: Average waiting time for all model variants at lock complex G11W5 in the normative period (4 weeks)

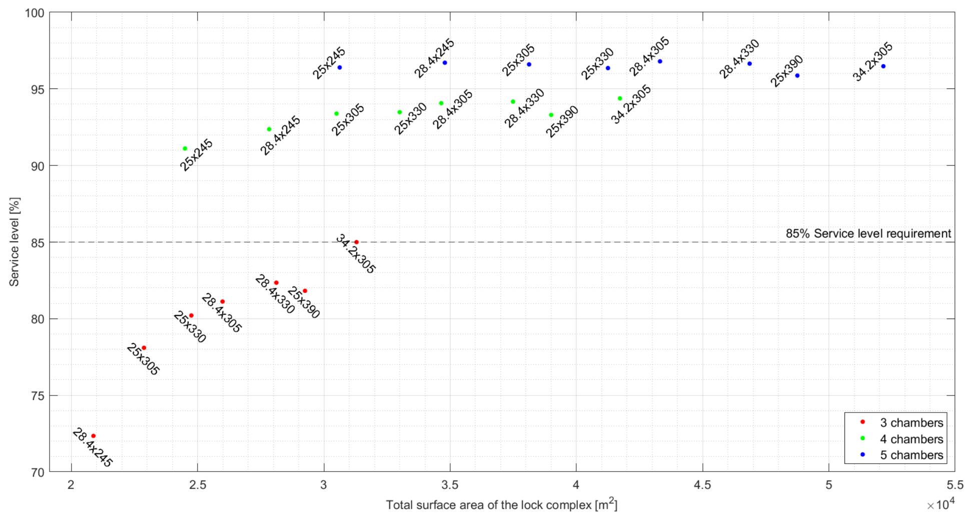

Figure 5.4: Average service levels for all model variants at lock complex G11W5 over 25 weeks

CONCLUSION

A minimum of three lock chambers (34.2x305m) is required to handle the reference traffic intensity in the reference case at lock complex G11W5, taking into account both criteria. This also means that the required capacity is less than for lock complex G11W3. Which is in the line with the expectation as the average traffic intensity is about 24%

larger at lock complex G11W3.

scenario	values	chambers	length	width	avg. waiting time	avg. service level
[-]	*[-]*	*[-]*	*[m]*	*[m]*	*[min]*	*[%]*
ref	-	3	305	34.2	19.7	85.0

Table 5.2: Minimum required number of lock chambers with minimum dimensions that meet the requirements under the considered reference scenarios for lock complex **G11W5**.

5.3. FUTURE SCENARIOS

5.3.1. SIMULATION RESULTS FOR UPSTREAM LOCK COMPLEX G11W3

WAITING TIME REQUIREMENT

Average waiting times increase as the traffic intensity increases. Figure 5.5 illustrates the effects of increased traffic intensities on the average waiting time in the normative period. The figure does not present the dimensions of the chambers as in Figures 5.1 till 5.4 to prevent overlap of texts. Instead a curve is fitted (single term power law) through the scenarios with an equal number of chambers to distinguish between different future scenarios.

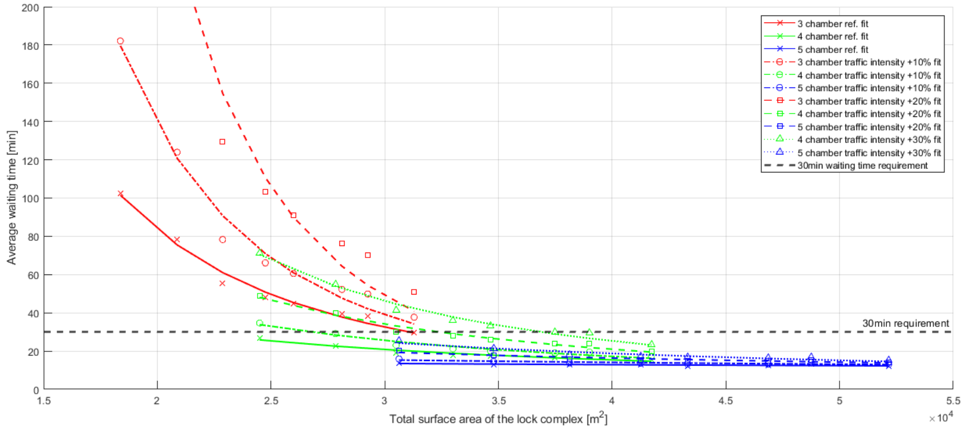

Figure 5.5: Average waiting time for all model variants for varying vessel traffic intensities

The increase in average waiting time is strongest for the locks with the least surface area, see Figure 5.5. A lock complex with 3 lock chambers is not sufficient to handle an increase in traffic intensity of 10% or more. A lock complex with 5 lock chambers is able to handle increased traffic intensities up to an increase of 30% within the 30 minute average waiting time requirement. For all future scenarios it is possible to apply a lock complex with 4 chambers. The minimum dimensions depend on the increase in traffic intensity in the respective future scenario.

Figure 5.6 illustrates the effects of two different fleet mix scenarios as described in Section 4.6.3 in combination with an increase in traffic intensity of 30% with respect to the reference scenario. The predicted fleet mix at the Volkerak locks in scenario WLO2050H shows similar results as the as the reference scenario with the current fleet mix on the river Waal. The fleet mix with an increased share of 4-barge push tow units results in a rather strong increase in average waiting time. This is a consequence of strong up-scaling effects due strong increases in share of M10 and M12 vessels and 4-barge push-tow units at the expense of smaller vessel types (see Section 4.6.3).

A lock complex with 3 lock chambers does not meet the waiting time requirement in the reference scenario, thus not further considered in this section. A lock complex with 4 lock chambers is not suitable in the future scenario with an increased intensity of 30% and the modified Volkerak fleet mix. Model variants with 5 lock chambers are suitable under all considered fleet intensities and compositions, except for the two smallest chambers size in model variants with 5 chambers in case of the modified Volkerak WLO2050H fleet mix.

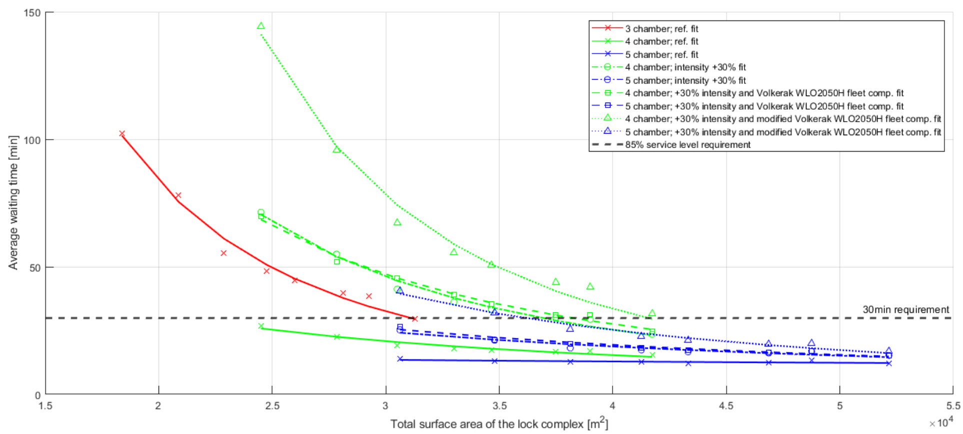

Figure 5.6: Average waiting time for all model variants for different fleet compositions

SERVICE LEVEL REQUIREMENT

Figure 5.7 shows the effects of an increased intensity on the average service level for all the model variants. Model variants with 3 lock chambers are not suitable considering the service level requirement. Model variants with 4 chambers do not meet the requirement when traffic intensity increases by more than 10%. A model variant with 5 lock chambers is most robust as all model variants meet the service level requirement, except the model variant with the smallest lock chambers.

Figure 5.8 illustrates the effects of an increased traffic intensity of 30% in combination with different fleet mixes on the average service level. Model variants with 3 lock chambers are excluded from the plot as they do not meet the requirement in the reference scenario. Model variants with 3 or 4 chambers are not suitable in the considered future scenarios as they do not meet the service level requirement. Most of the model variants with 5 lock chambers are suitable for the WLO2050H Volkerak fleet mix, however not for the modified WLO2050H Volkerak fleet mix.

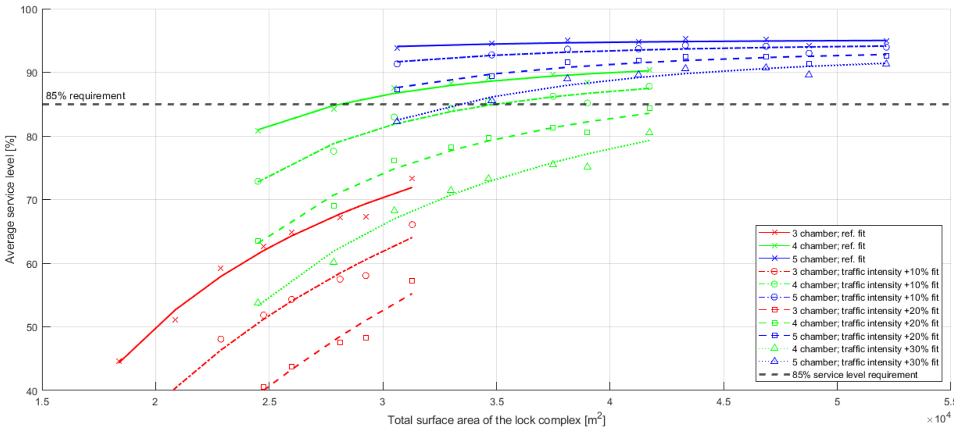

Figure 5.7: Service level for all model variants for varying vessel traffic intensities

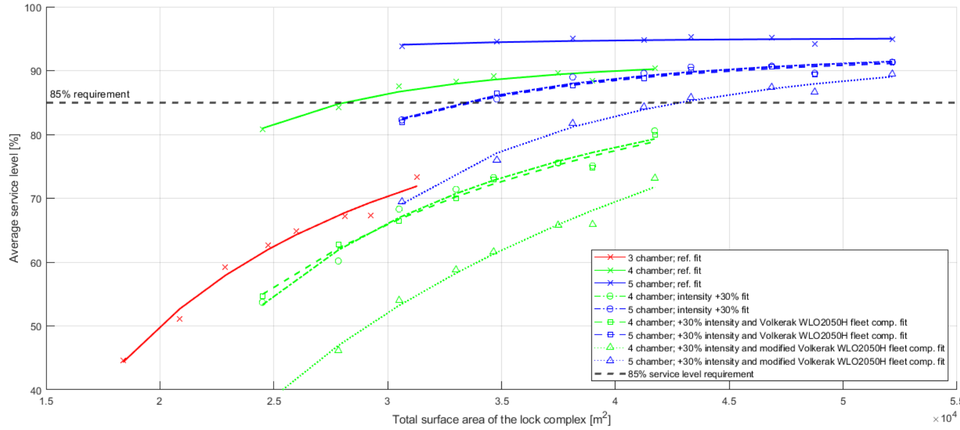

Figure 5.8: Service level for model variants for varying fleet compositions

CONCLUSION

The previous sections have considered five future scenarios; three intensity scenarios and two fleet mix scenarios. The minimum required number of lock chambers and corresponding minimum dimensions are presented in Table 5.3 per scenario for lock complex G11W3. The reference case required 4 chambers (305x25m), whilst an increase of 10% in fleet intensity requires 4 chambers of 305x28.4 m at minimum. This is an increase of 14% in surface area of the lock complex. Increasing the fleet intensity with 20% and 30% results in a minimum of 5 lock chambers to meet the waiting time and service level requirements.

scenario	**values**	**chambers**	**length**	**width**	**avg. waiting time**	**avg. service level**
[-]	*[-]*	*[-]*	*[m]*	*[m]*	*[min]*	*[%]*
intensity	+10%	4	305	28.4	20.08	85.4
intensity	+20%	5	245	25	20.11	87.32
intensity	+30%	5	305	25	18.16	89
intensity + fleet mix	+30% + Volkerak WLO2050H	5	245	28.4	21.35	86.5
intensity + fleet mix	+30% + Modified Volkeark WLO2050H	5	305	28.4	21.12	85.78

Table 5.3: Minimum required number of lock chambers with minimum dimensions that meet the requirements under the considered future scenarios for lock complex **G11W3**.

5.3.2. SIMULATION RESULTS FOR DOWNSTREAM LOCK COMPLEX G11W5

WAITING TIME REQUIREMENT

Results for lock complex G11W5 are interpreted the same way as the results in Section 5.3.1 plots are given in Appendix G.

SERVICE LEVEL REQUIREMENT

Results for lock complex G11W5 are interpreted the same way as the results in Section 5.3.1 plots are given in Appendix G.

CONCLUSION

Four lock chambers are required in all future fleet scenarios for lock complex G11W5. The service level requirement is governing in all scenarios. Four relative small chambers are required in case of an increase in intensity of 10-20%.

scenario	**values**	**chambers**	**length**	**width**	**avg. waiting time**	**avg. service level**
[-]	*[-]*	*[-]*	*[m]*	*[m]*	*[min]*	*[%]*
intensity	+10%	4	245	25	20.21	87.7
intensity	+20%	4	245	28.4	22.84	85.39
intensity	+30%	4	330	25	23.6	85.21
intensity + fleet mix	+30% + Volkerak WLO2050H	4	305	25	21.28	85.81
intensity + fleet mix	+30% + Modified Volkeark WLO2050H	4	330	28.4	21.66	85.59

Table 5.4: Minimum required number of lock chambers with minimum dimensions that meet the requirements under the considered future scenarios for lock complex **G11W5**.

5.4. CONCLUSION

An answer to research question 5 is formulated based on the contents of this chapter. The research question is repeated below for convenience:

What are the minimum required number of lock chambers and corresponding dimensions to facilitate smooth and reliable traffic flow over the river Waal now and in the future?

5.4.1. REFERENCE SCENARIO

Note that the results presented in this section are the outcome of a scenario study and are valid for the assumptions made and starting point chosen in previous sections.

In the reference scenario; representing the fleet mix and intensity on the river Waal as in 2019 Jan-Jun, 4 lock chambers are required for the most upstream lock complex G11W3 and 3 for lock complex G11W5. The difference in number of lock chambers is due to different traffic intensities at the locations of the locks. The corresponding dimensions and values of the performance indicators are given in Table 5.5. Note that this are not necessarily the ideal dimensions of the chambers as this study has considered a set of 24 model variants. Optimum dimensions may be found in between model variants.

scenario	chambers	length	width	avg. waiting time	avg. service level
[-]	*[-]*	*[m]*	*[m]*	*[min]*	*[%]*
G11W3 ref	4	305	25	19	87.6
G11W5 ref	3	305	34.2	19.7	85.0

Table 5.5: Minimum required number of lock chambers with minimum dimensions that meet the requirements under the considered reference scenarios for the proposed lock complexes.

5.4.2. FUTURE SCENARIOS

The performance of (the same) 24 model variants is tested against several future fleet scenarios. Future traffic intensity scenarios are based on estimates defined in Section 2.6. For estimates on future fleet mixes a parallel is drawn with the Volkerak locks. A future fleet mix for the Volkerak locks was estimated in the context of the Integral Mobility Analysis 2021 (RijkswaterstaatWVL, 2021b) and is used to test a second and third fleet mix. The minimum number of chambers and corresponding dimensions required in the future scenarios are presented in tables 5.3 and 5.4 for G11W3 and G11W5.

The number of chambers required for complex G11W3 depends on the intensity scenario. A 10% increase in intensity requires a lock complex with 4 chambers. An increase to 20% or 30% requires a lock configuration with 5 locks. It is recommended to apply a lock complex with 4 lock chambers with dimensions 28.4x305 m and take into account space for expansion to a complex with 5 lock chambers. Then depending on the size of the potential 5th lock chamber, the entire lock complex can handle up to an intensity increase of 30% with strong up-scaling effects.

The minimum required number of lock chambers for lock complex G11W5 is 4 in all future scenarios. Therefore expanding to a 5th lock chamber is not applicable as is the case for G11W3. So the choice for the dimensions of the lock complex depend on the expected future fleet scenarios. Applying a lock complex with 4 chambers with dimensions 25x330 m is considered a safe choice for a time horizon of 2050 as this defines the upper bound of WLO scenario 2050H. Also keep in mind that the intensity increases are rather conservative as explained in Section 4.6.3.

5.4.3. SENSITIVITY ANALYSIS

The sensitivity analysis has shown that the estimated impact of recreational vessel on the average waiting time and service levels is negligible. This is in the line of expectation as the commercial fleet dominates the river Waal with an weekly average number of passages varying between 1800 and 2200. Whilst the estimated number of weekly passages is about 110 for the recreational fleet. In addition, recreational vessels are generally a fraction of the size of a commercial vessel.

The results also illustrated that the levelling time has a substantial impact in the average waiting time and service level. Reducing the assumed levelling time from 12min to 10min or 8min does not result in a reduction of minimum number of required chambers. However it does reduced the minimum required surface area for G11W3 by 20%. For G11W5 reductions of 17-33% are found for respectively 10 and 8min levelling time. Note that these percentages are with respect to the reference case. It is recommended to obtain more insight in the levelling times that can be achieved in a more detailed study.

6

DISCUSSION

This chapter reflects on the methods and results that are conducted in this thesis and addresses the most important assumptions, limitations and uncertainties encountered. Also the relevance of the results is illustrated for the work field.

- Important assumption in this thesis is that the fleet composition remains fairly constant towards 2050. However, one can question the validity of that assumption under the ongoing developments such as the energy transition, nitrogen crisis and autonomous shipping. The latter was not mentioned before in this study, but may alter the fleet composition substantially. Autonomous shipping may even lead to a new concepts of inland water way transport. One could think of small autonomous vessels transporting cargo in a convoy and separate like swarm of flies when close to destinations in the smaller waterways. These developments are plausible during the life time of new built lock complexes. A new transport concept like that may ask for a new approach on lock designs, that is to be investigated.
- Representation of the waterway network in SIVAK III does not fully represent the reality. The split-up of the network in two separate simplified networks excludes network effects such as vessel clustering due to the passage of lock complex and platooning. This potentially affects the arrival times and thus waiting times at the locks. This may lead to underestimates of average waiting times at the locks. Network effects can be included by considering the locks in one network at the cost of an extensive fleet analysis at all the end nodes and intersections in the network.

- The IVS data used is not completely representative for the proposed canalised situation as fleet composition and fleet intensity depend on the available nautical depth corresponding to the available discharge. Water levels are kept on a constant level in the canalised situation. This was certainly not the case between January and June 2019 (registration period of the used IVS data). The discharge variations Jan-Jun 2019 have led to changes in fleet composition in the respective period. No corrections were made for change in fleet composition due to these discharge variations. Second argument for an incorrect representation of the fleet in the canalised case is the rather short time period used to extract data from. Temporal events in 2019 may have affected the fleet from January to June.

- The quality of the IVS data used requires some remarks as well. It is generally known that IVS data does not cover all vessels passing a vessel traffic post. Estimates on missing data vary around 20%. In March 2019 IVSNext was introduced. The new tracking system includes tracking by AIS, which is considered much more accurate in locating the position of vessels than the previous system. The number of registrations substantially increased after the introduction of IVSNext with respect to months prior to the introduction of IVSNext. No concluding reason was found for the increase in intensity. However, it is suspected that missing data in the previous version of IVS is covered by AIS in the IVSNext system. This implies that fleet intensities prior to March are underestimated by about 10-15%, leading to underestimations of service levels in the SIVAK III output.

- The future scenarios regarding fleet intensity are expected to be rather conservative as increase in transported tonnage on the river Waal is interpreted proportional to increase in vessel intensity. This is not necessarily true as the fleet composition also changes over time. Up-scaling of the fleet for example increases the average load capacity of the vessels. This results in less vessels required to transport the same amount of cargo. Therefor it is expected that the increase in fleet intensity is overestimated for the time horizon of 2050. The time horizon is another limitation of the study. Generally locks are build for a period of minimum 100 years, whilst this study considers scenarios till 2050. Fleet predictions for a time horizon of 2120 are considered impossible and therefore not considered.

7

CONCLUSION

The objective of this study is summarised by the main research question below which is considered answered by presenting the answers to the sub questions. Note that these answers are also presented in the chapters they were discussed.

"How to configure the river Waal in case of canalisation by means of weir-lock complexes to facilitate smooth, reliable and future proof inland waterway transport?"

What are the main factors that drive the worsening navigability of the river Waal now and in the future?

Bottlenecks for inland navigation occur when vessels are not able to navigate fully loaded on the river Waal. The smallest nautical depth available on the river Waal determines the maximum load a vessel can transport (assumed that a vessel navigates on the Waal only). Nautical depth limitations on the river Waal are expected to occur more frequently in the future. Primarily due to changing climate conditions, large scale bed erosion on the upper parts of the river Waal in combination with fixed riverbed layers and the increasing vessels sizes (up-scaling). This underlines the urgency for measures.

Several climate scenarios sketch different futures regarding the frequency and magnitude of low discharges at the river Waal. 4 out of 5 considered scenarios illustrate a decrease in monthly average discharge between 0-20% at Lobith in the months of July till October (driest period of the year). For the most moderate climate scenario (G_L) an increase of discharges is expected for the entire discharge regime. For the driest climate scenario ($W_{H,dry}$) an increase in frequency of low discharges and high discharges is expected. A very dry year as in 2018 is expected to occur once per 10 years (in climate scenario $W_{H,dry}$) instead of once per 60 years ,as under present conditions.

Large scale bed erosion is an acknowledged ongoing process which has its origin in fixing the plan-form of the river Waal by means of engineering works such as groynes. The erosion is expected to continue with rates between 0.6-1.6 cm/year between rkm 868 and 933. The large scale erosion trend in combination with present fixed bed layers cause these layers to protrude from the bed. These protruding layers will be the limiting sections on the river Waal in the future. Also the crossing of cables and pipes with the river Waal are going to induce nautical depth limitations as they are also considered fixed in the river bed.

What are the characteristics of the current and future fleets on the river Waal?

An analysis on the vessel loading capacity and vessel type distribution of over the period 2004-2020 underlines the up-scaling trend of the last two decades. The average loading capacity has increased from roughly 2500 ton in 2004 to 3300 ton in 2018, whilst the annual vessel class distribution shows a shift towards the larger vessel types. Up-scaling is still an ongoing trend an is expected to continue for an unknown period of time. Up-scaling is a factor that is included in the vessel traffic simulations in Chapter 4. No other trends than up-scaling were found.

An analysis on the total surface are per vessel type navigating in the river Waal has resulted in an approach to make first estimates on lock chamber dimensions. This method is applied in appendix C.2 to set up several model variants for vessel traffic simulations in SIVAK III.

Accurate future fleet characteristics are required to investigate the performance of a lock complex in the future. However, growth of the IWT sector on the river Waal is uncertain, mainly due to the ongoing energy transition and nitrogen crisis. Developments in both events affect the future cargo flows and fleets. Cargo forecasts, based on WLO scenarios for 2040, are extrapolated to 2050, resulting in an estimate increase in transported tonnage of 0-30% over the river Waal in 2050 (see Table 2.2). This range is used in Chapter 4 to define future fleets.

How to determine the moment of closure of the WLC's and the retained water levels?

This chapter presented three methods to choose a discharge at Lobith for which both weir-lock complexes start operating. Method one describes and optimisation method based on financial considerations. The optimum threshold discharge is defined for the situation when the increase in transport costs are minimum, given a certain river layout (including WLC's) and traffic intensity. On one hand transport costs increase due to increased traffic intensity as a consequence of depth limitations in the free flowing situation. On the other hand transport costs increase due to increased travel times in case of a canalised river. The method is also useful in establishing a budget for construction of the WLC's as the difference in transport costs in a free flowing river and the costs in a canalised situation are cost savings due to canalisation.

Because of time limitations this method was not applied in this study and methods two and three were developed. Method two essentially states that all vessels have to pass at all times, resulting in activation of the locks when the discharge at Lobith drops below 1960 m^3/s. Method 3 considers a more integral approach and is described in the next paragraph. Nevertheless, for future feasibility studies into canalisation of the Waal is recommended to apply method one as it includes the financial aspect of canalisation. The results of this study regarding the required lock capacity could serve as a starting point for such a study.

For this study a more practical estimate of the moment of closure is made. Vessels tend to use the locks of Lith and Grave (river Meuse) instead of the faster route via the river Waal and Maas-Waalkanaal for destinations beyond Grave in case maximum available draught drops below 3.20 m on the river Waal. This is expected to change to a draught of 3.50 m in the future due to an upgrade of lock Grave. So in order to facilitate a direct route via the Maas-Waalkanaal a draught of 3.50 m should be guaranteed on the river Waal at all times. A translation from maximum available draught to discharge at Lobith was made via the MGD's on the river Waal. Resulting in a threshold discharge of 1600 m^3/s. The threshold implies that 4% of the commercial fleet is not able to navigate fully loaded when the locks are being activated.

The median discharge at Lobith (1960 m^3/s) provides sufficient depth to accommodate the maximum draught (4.50 m) of the normative vessels on the river Waal. So when the WLC's are in operation ($Q_{Lobith} \leq 1600 m^3/s$) the water levels are raised to a water level that corresponds to the median discharge at Lobith over the canalised reach.

How many WLC's are required in case of canalisation of the river Waal and at what locations?

The number of WLC's on the river Waal should be limited to a minimum because of high construction costs. A lay-out of one WLC is considered not suitable, because set-up water levels would exceed the water level corresponding to a return period of 10 years for a substantial part of the year (Section 3.5.4). A second lay-out with two WLC's is more plausible as water levels are better manageable 3.5.5. A lay-out with three WLC's proved to be superfluous, because of the substantial construction costs per WLC. Figure 7.1 shows the locations of the WLC's on a map. The downstream location is chosen such that water level downstream of the lock complex is sufficient to allow for all commercial vessels to pass for a (very low) discharge at Lobith of 700m^3/s at minimum.

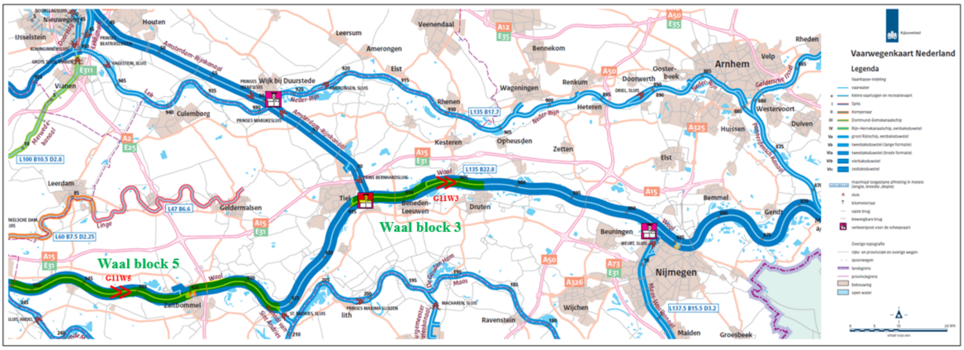

Figure 7.1: Locations of the two WLC's named G11W3 and G11W5 and Waal blocks 3 and 5(adopted from: https://www.rijkswaterstaat.nl/apps/geoservices/geodata/dmc/vaarwegenkaart/productinfo/beschrijvende_documentatie/vaarwegenkaart_2013.pdf)

What are the minimum required number of lock chambers and corresponding dimensions to facilitate smooth and reliable traffic flow over the river Waal now and in the future?

In the reference scenario; representing the fleet mix and intensity on the river Waal as in 2019 Jan-Jun, 4 lock chambers are required for the most upstream lock complex G11W3 and 3 for lock complex G11W5. The difference in number of lock chambers is due to different traffic intensities at the locations of the locks. The corresponding dimensions and values of the performance indicators are given in Table 7.1. Note that this are not necessarily the ideal dimensions of the chambers as this study has considered a set of 24 model variants. Optimum dimensions may be found in between model variants.

scenario	chambers	length	width	avg. waiting time	avg. service level
[-]	*[-]*	*[m]*	*[m]*	*[min]*	*[%]*
G11W3 ref	4	305	25	19	87.6
G11W5 ref	3	305	34.2	19.7	85.0

Table 7.1: Minimum required number of lock chambers with minimum dimensions that meet the requirements under the considered reference scenarios for the proposed lock complexes.

Future scenarios

The performance of (the same) 24 model variants is tested against several future fleet scenarios. Future traffic intensity scenarios are based on estimates defined in Section 2.6. For estimates on future fleet mixes a parallel is drawn with the Volkerak locks. A future fleet mix for the Volkerak locks was estimated in the context of the Integral Mobility Analysis 2021 (RijkswaterstaatWVL, 2021b) and is used to test a second and third fleet mix. The minimum number of chambers and corresponding dimensions required in the future scenarios are presented in tables 5.3 and 5.4 for G11W3 and G11W5.

The number of chambers required for complex G11W3 depends on the intensity scenario. A 10% increase in intensity requires a lock complex with 4 chambers. An increase to 20% or 30% requires a lock configuration with 5 locks. It is recommended to apply a lock complex with 4 lock chambers with dimensions 28.4x305 m and take into account space for expansion to a complex with 5 lock chambers. Then depending on the size of the potential 5th lock chamber, the entire lock complex can handle up to an intensity increase of 30% with strong up-scaling effects.

The minimum required number of lock chambers for lock complex G11W5 is 4 in all future scenarios. Therefore expanding to a 5th lock chamber is not applicable as is the case for G11W3. So the choice for the dimensions of the lock complex depend on the expected future fleet scenarios. Applying a lock complex with 4 chambers with dimensions 25x330 m is considered a safe choice for a time horizon of 2050 as this defines the upper bound of WLO scenario 2050H. Also keep in mind that the intensity increases are rather conservative as explained in Section 4.6.3.

Sensitivity analysis

The sensitivity analysis has shown that the estimated impact of recreational vessel on the average waiting time and service levels is negligible. This is in the line of expectation as the commercial fleet dominates the river Waal with an weekly average number of passages varying between 1800 and 2200. Whilst the estimated number of weekly passages is about 110 for the recreational fleet. In addition, recreational vessels are generally a fraction of the size of a commercial vessel.

The results also illustrated that the levelling time has a substantial impact in the average waiting time and service level. Reducing the assumed levelling time from 12min to 10min or 8min does not result in a reduction of minimum number of required chambers. However it does reduced the minimum required surface area for G11W3 by 20%. For G11W5 reductions of 17-33% are found for respectively 10 and 8min levelling time. Note that these percentages are with respect to the reference case. It is recommended to obtain more insight in the levelling times that can be achieved in a more detailed study.

8

RECOMMENDATIONS

This final chapter addresses a few topics that are recommended in potential follow-up studies.

Extent of canalisation

This study was limited to canalisation of the river Waal only. Meaning that bottlenecks regarding insufficient nautical depth are taken away on the river Waal only. However vessels travelling further upstream the river Rhine may encounter 'new' nautical depth limitations and thus may only benefit partially from the locks. It is recommended to study to where these new bottlenecks occur and whether it is viable to use WLC's further upstream of the river Waal (on the German Rhine).

Financial aspects

Canalisation as proposed in this study is to improve the navigability on the river Waal. One of the main reasons that have led to the idea of canalisation of the river Waal is to prevent financial and economical damages in the future. However the financial aspect is often neglected in this study as was assumed that canalisation is financially feasible. The importance of inclusion of the financial aspect is illustrated in Chapter 3. In which was found that the ideal moment of the activation of the weirs is a compromise between increased transport costs due to low water in a free flowing river and increased transport costs due to increased travel times in a canalised situation. This implies that the operations and hydraulic boundary conditions of the weir are affected by financial aspects.

So in order to find a more accurate required lock capacity in case of canalisation this financial aspect needs to be included as well.

Future fleets

It is recommended to sharpen the foundation of future fleet estimates on the river Waal used in this study. No studies or data were found on future fleet intensities or fleet compositions on the river Waal. Therefore intensities are roughly estimated an for future fleet compositions; predictions for the Volkerak locks were used. It is recommended to increase the accuracy of the fleet composition and intensity by means of similar methods as used in the *Integrale Mobiliteitsanalyse 2021* (Dat.mobility & Districton, 2021). In which cargo forecasts are linked to inland transport projections.

Integral approach

Canalisation by means of WLC's is a measure that has a large impact on the environment. Canalisation is beneficial for the navigability of the river Waal, but can also have other positive effects. Increased water levels during periods of low discharge prevent flood plains from drying out. Canalisation may also reduce the ongoing river bed erosion on the river Waal to some extent as canalisation reduces the flow velocities. Setting up water levels in periods of low discharge may allow for easy fresh water extraction. Other facets that are expected to be affected in case of canalisation are river morphology, discharge distribution at the Pannerdense Kop, flood protection structures and ecology. These are all important aspects that need to be taken into account in case of canalisation. It is recommended to study the effects of canalisation on at least the above mentioned aspects.

Other measures to improve navigability

As stated a few times, canalisation is a radical measure that can be considered a very last option. It is a very effective way in improving and regulating navigability, however it is very expensive and has a major impact on the environment that has to be determined yet. Therefore it also recommended to look into other solutions to improve navigability on the river Waal that may have less impact on the direct environment and surroundings. A few directions are pointed out in Section 1.5.

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Appendices

A

MULTI ANNUAL FLEET ANALYSIS

A.1. VESSEL CLASSIFICATION

	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

Figure A.1: CEMT- and RWS-vessel classes and their respective dimensions (Verschuren, 2020)

A.2. EAST- AND WEST GOING VESSELS AND TONNAGE

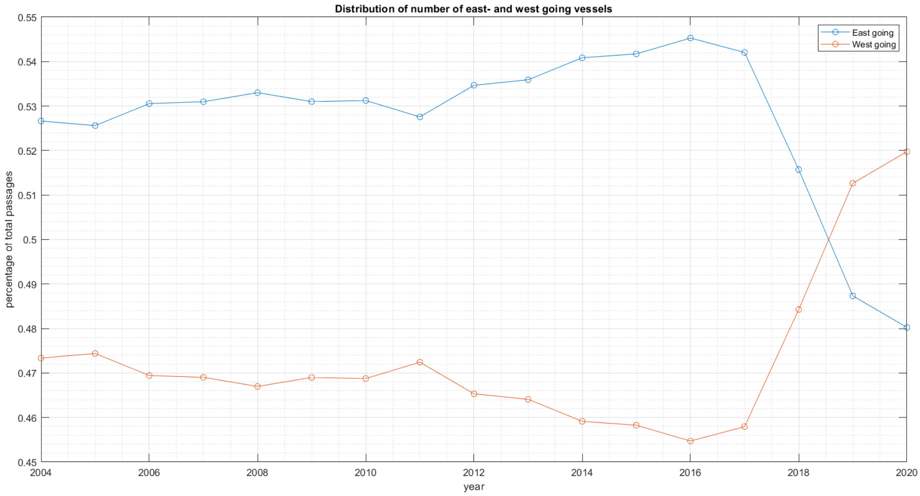

Figure A.2: Annual percentage of vessels sailing in eastern- and western direction on the river Waal

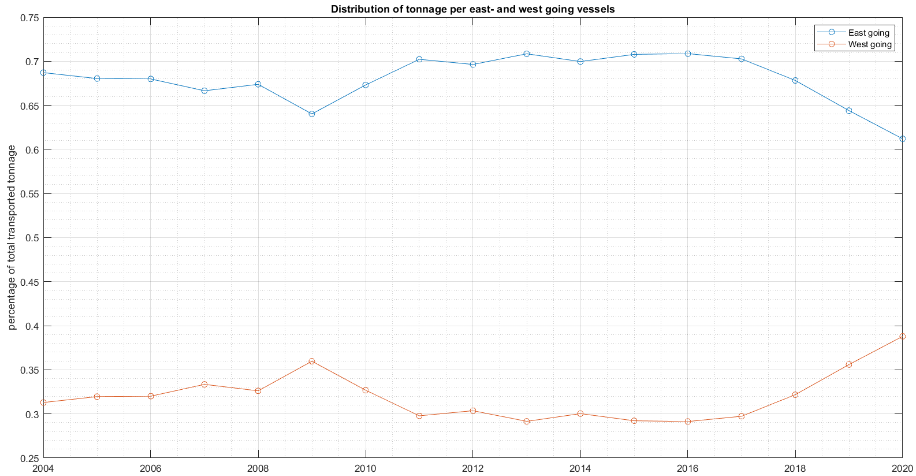

Figure A.3: Annual percentage of tonnage that is transported in eastern- and western direction

A

A.3. CANALISATION NEDERRIJN-LEK

A.3.1. PURPOSE

This chapter is concluded with a short study regarding the canalisation of river Nederrijn-Lek (see Figure A.4), which is also part of the Rhine branches river system. The water levels in the Nederrijn-Lek are regulated by three nearly identical WLC's. The WLC's regulate the discharge distribution over the IJsselkop for the purpose of fresh water supply toward the IJssel Lake and improved navigation on the river IJssel and Nederrijn-Lek during low discharges.

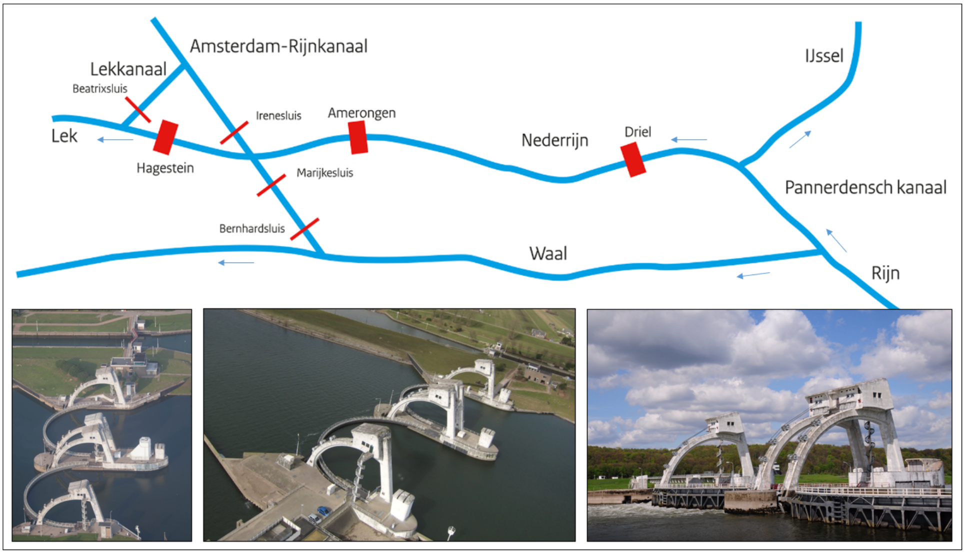

Figure A.4: Rhine branches and the three identical WLC's. From left to right: Hagestein, Amerongen and Driel.

The WLC's are located (from upstream to downstream) at Driel (1970), Amerongen (1965) and Hagestein (1960). The weirs are constructed next to the original river bed for all three WLC's, which altered the flow path of the river slightly. The three weirs are of a visor gate type, implicating that the weir can be fully lifted, which allows for vessels passing the weirs in fully lifted position. This feature makes this series of WLC's interesting to study in more detail. The weirs are accompanied with one lock chamber to allow vessels to pass when the visor gate is lowered. The width of the lock chamber is 18 m and equal for all WLC's. The length of the lock chamber of WLC Hagestein is 220m, the others equal 260 m in length.

The Nederrijn-Lek is a CEMT-class Vb waterway upstream of the Lekkanaal and VIa downstream of Lekkanaal, meaning that the largest vessels sailing on the Nederrijn-Lek are CEMT-class VIa. A minimum depth of 2.80 m and fairway width of 80 m to 130 m prevail on the Nederrijn-Lek during ALD conditions (Doornekamp, 2019). The average annual traffic intensity is about 15-25% of the average annual intensity of the river Waal as illustrated in Figure A.5.

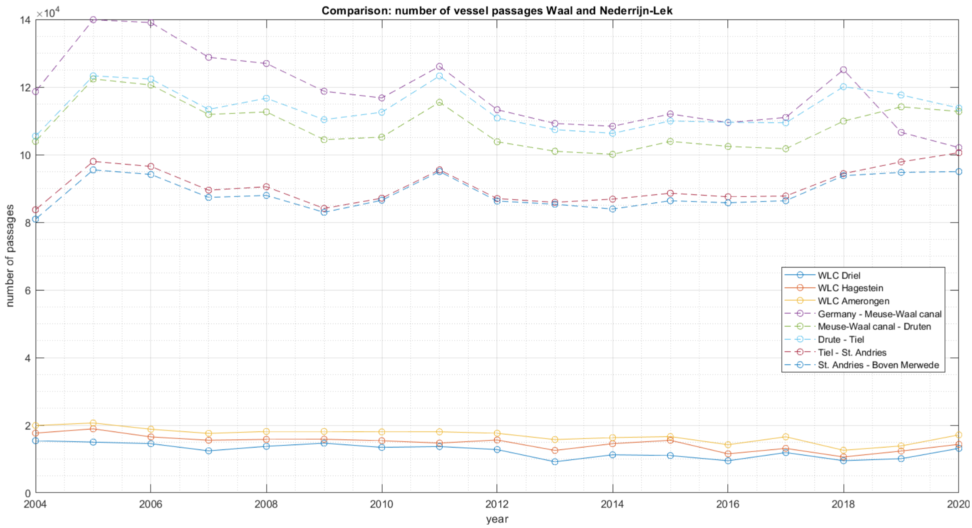

Figure A.5: Comparison in annual number of passages river Waal and Nederrijn-Lek

A.3.2. OPERATIONS

The weirs are controlled based on the discharge measured at Lobith. For discharges larger than 3630 m^3/s all visors are fully lifted. For discharges between 3630 m^3/s and 2600 m^3/s the two downstream weirs (Hagestein and Amerongen) are in operation. For a discharge lower than 2600 m^3/s the most upstream weir (Driel) is in operation. When the discharge at Lobith drop below 1590 m^3/s all weirs are fully closed. However in all cases a discharge of minimum 30 m^3/s should be pass the weir at Driel for water management purposes (Rijkswaterstaat, 2020). Figure A.6 shows the water level elevation for several discharges at Lobith. Note that this are the same discharges as presented for the river Waal in Section 3.5.2.

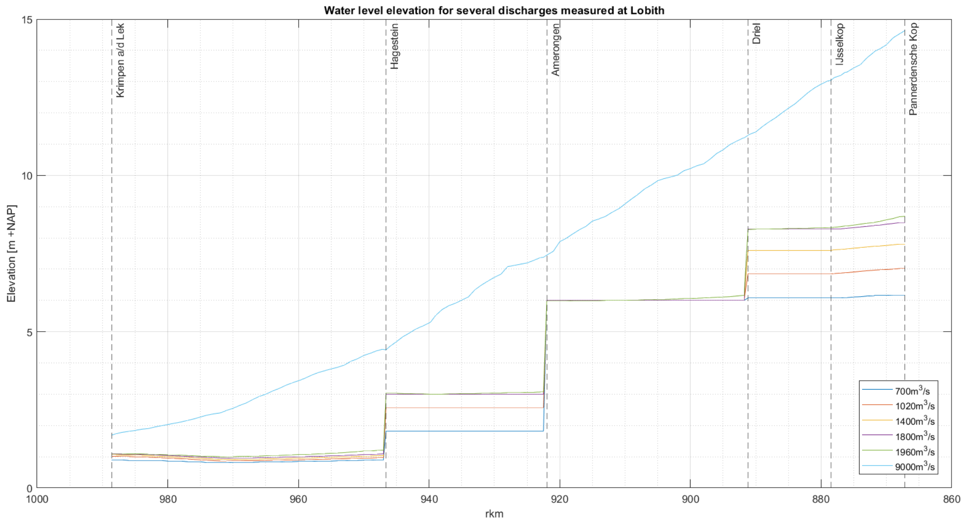

Figure A.6: Water levels at the river Nederijn-Lek for several discharges (Van der Veen & Agtersloot, 2019)

From the plot is concluded that the water level between the weir at Driel and the weir at Amerongen is maintained at a constant level of 6 m +NAP. Upstream of Driel the water level decreases with a decreasing discharge. Downstream of Amerongen and Hagestein a similar trend is visible. The water levels between the weirs is fairly constant. Pronounced backwater effects are not visible. The water level differences over the WLC's is dependent on the discharge at Lobith, varying from 0.1 m (at Driel for a discharge of 703 m^3/s) to 4.15 m (at Amerongen for a discharge of 703 m^3/s). Water levels downstream of Hagestein are affected by the tides prevailing at the North sea. The tidal range may reach 1.5 m at downstream of Hagestein. Tidal effects are averaged in Figure A.6.

A.3.3. MORPHOLOGICAL IMPACT

The river Nederrijn-Lek is normalized by groynes in a similar fashion as the river Waal. This intervention has lead to reach scale bed erosion over the entire river. Furthermore, the construction of the three WLC's has led to morphological changes in the riverbed. The WLC's were constructed artificial stretches of the river, next to the original river. The artificial stretches were deeper than the original river bed (indicated by the red shaded areas in Figure A.7), which resulted in sedimentation in these deeper parts and erosion in the downstream parts of the artificial river stretches. In addition, when the weirs are lowered position, they are effective sediment traps. Sediments settle due to reduced flow velocities at the upstream part of the weir, leading to sedimentation. At the downstream side of the weirs erosion patterns are visible (most likely due to the lack of sediment supply). The development of the bed level since is recorded since 1933 and presented in Figure A.7.

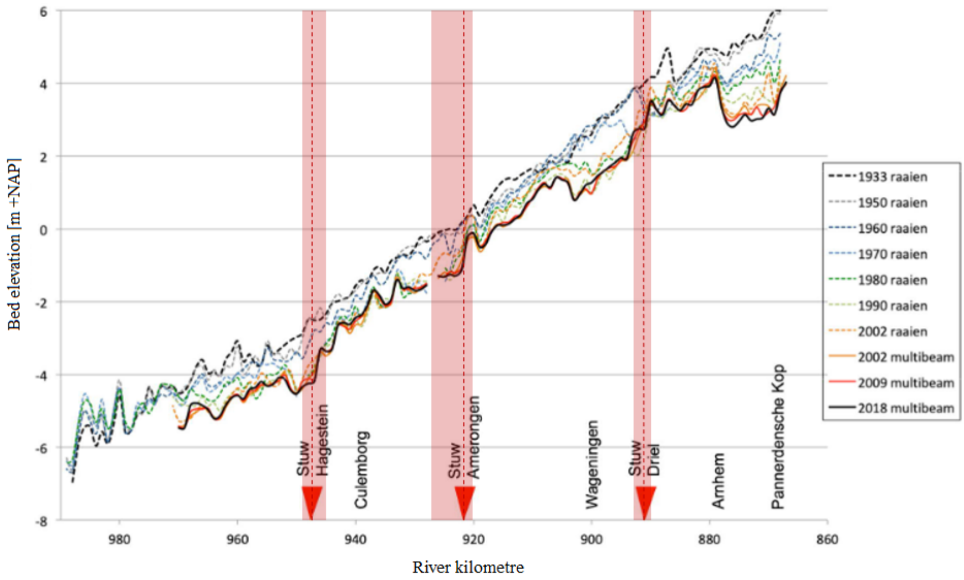

Figure A.7: Bed level development river Nederrijn-Lek (1933-2018). The red shaded areas indicate the deeper artificial stretches of the river that were used construct the WLC's in (ten Brinke, 2019)

B

HYDRAULIC CONDITIONS RIVER WAAL

B.1. SUB-CRITICAL FLOW

Flow in the river Waal is sub-critical, meaning that the fit to the Bresse method is justified to estimate backwater levels. This is illustrated for a free flowing under median discharge at Lobith (Q_{MA}) river Waal in Equation B.1. Resulting in a Froude number of 0.22, indicating sub-critical flow.

$$Fr = \frac{u}{\sqrt{gh}} = \frac{\frac{Q_{MD}}{hB_{ch}}}{\sqrt{gh}} = \frac{\frac{1960}{4.95*260}}{\sqrt{9.81*4.95}} = 0.22 < 1 \tag{B.1}$$

B.2. FIT TO BRESSE METHOD

A fit to the Bresse method is used to estimate backwater levels behind the weirs, see Equations B.2 till B.4. Equation B.2 describes the equilibrium flow depth in the river Waal that serves as input for Equation B.3 that describes the half length. The half length is defined as distance from the disturbance (WLC) to the position upstream of the disturbance were the difference in water level between normal flow depth and actual flow depth is halved with respect to the same difference at the location of the disturbance. The half length ($L_{\frac{1}{2}}$) and equilibrium depth (d_e) are both required to compute the water depth under the backwater curve in Equation B.4.

$$d_e = \left(\frac{\frac{2}{3}Q_{Lobith}}{B_{ch}^2 C_{ch}^2 i_b}\right)^{\frac{1}{3}} \tag{B.2}$$

$$L_{\frac{1}{2}} = 0.24\frac{d_e}{i_b}\left(\frac{d_0}{d_e}\right)^{\frac{4}{3}} \tag{B.3}$$

$$d(s) = d_e + (d_0 - d_e)2^{\frac{-(s-s_0)}{L_{\frac{1}{2}}}} \tag{B.4}$$

For channel width (B_{ch}) 260 m, Chézy coefficient (C_{ch}) 40 $m^{1/2}/s$ and average bed slope (i_b) 1E-4 the equilibrium depths as in Table B.1 were found. The average depth on the river Waal (d_{actual}) as in Table B.1 is computed from Figure 3.6 and is added for reference. The depth in front of the weirs (d_0) is set such that the depth over the the entire upstream reach till the Pannerdense Kop is at minimum at the water level corresponding to a discharge of 1960 m^3/s in a free flowing river Waal.

$\mathbf{Q_{Lobith}}$ m^3/s	$\mathbf{d_e}$ *m*	$\mathbf{d_{actual}}$ *m*
700	2.7	2.8
1020	3.5	3.4
1400	4.3	4.1
1600	4.7	4.5

Table B.1: Computed equilibrium depths and depths as computed from betrekkingslijnen 2018 and KBN 2018 bed level.

B

C

DETERMINATION OF NUMBER OF LOCK CHAMBERS AND THEIR DIMENSIONS

C.1. VOLKERAK LOCKS

In order to come to a reasonable initial estimate for the dimensions of the lock chambers and number of lock chambers, a comparison is made between the annual traffic intensity at the Volkerak locks and traffic intensity at the river Waal. The Volkerak locks are the connection between Hollands Diep and the Volkerak. The locks are on an important route that connects the Port of Antwerp to Germany (via the river Waal) and Rotterdam. The locks can transfer vessels of maximum CEMT-class VIb. Meaning that the 6 barge pushed convoys (largest vessels on the Waal) are not able to pass. The traffic intensity comparison is shown in Figure C.1.

Figure C.1 shows the difference in intensities between five blocks at the river Waal and the Volkerak locks. The intensities at the Volkerak locks show good correspondence with the intensities at the river Waal. This indicates that the number of locks and the dimensions of the Volkerak locks can be used as a reasonable first estimate of the proposed WLC's in the river Waal.

The Volkerak complex houses three lock chambers for commercial vessels. The western and middle lock are 308.9 m in effective length (length that can be taken by vessels) and the eastern lock 331.5 m. The locks are 24.1 m wide. The intensity at the Volkerak lock is expected to reach its maximum capacity in 2025-2027 (RijkswaterstaatWVL, 2021b).

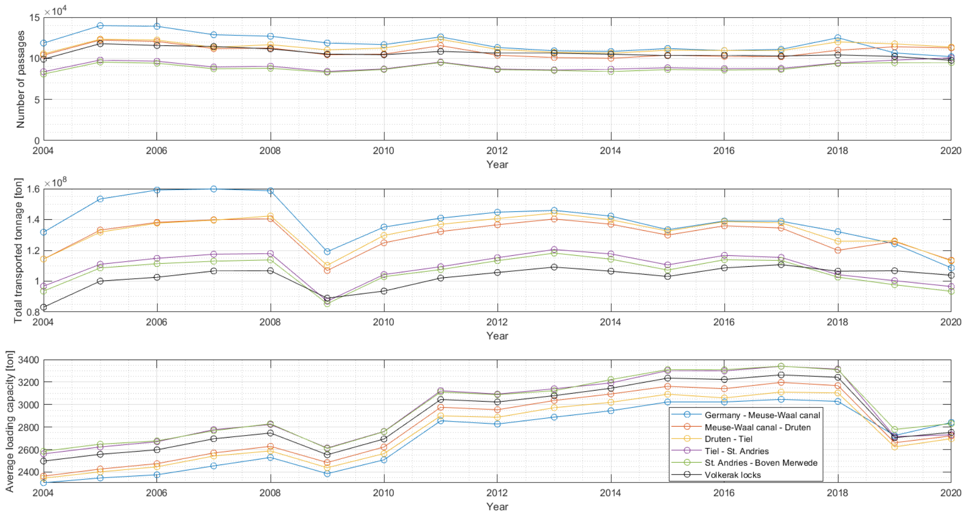

Figure C.1: Comparison intensities Waal-Volkerak locks; top panel) number of annual passages, middle panel) total annual transported tonnage, bottom panel) average vessel loading capacity

C.2. LOCKING CHAMBER DIMENSIONS

Reasoning behind the chamber dimensions in Table 4.1 is listed below:

- **Chamber ID 1**: The width of this locking chamber is 25 m, which is equal to the width of the new build locking chamber in the Princes Beatrix locking complex in the Lekkanaal. The chamber allows for two M8 vessels leveling side by side and one 2-wide push tow convoy. The length is 330 m and is chosen such that three M8 vessels can enter the lock in line simultaneously. The length allows for one 4-barge push tow convoy and a M8 vessel in line as well.
- **Chamber ID 2**:The width of this chamber is 28.4 m, which allows for a M8 and M12 vessel to level side by side. Furthermore, the space to manoeuvre has increased as well, with respect to chamber ID 1. The length of this chamber is 330 m and equal to the length of chamber ID 1.
- **Chamber ID 3**: The width of this chamber is 25 m and is equal to the width of chamber ID 1 for reasons mentioned under chamber ID 1. The length of this chamber is 245 m, which allows for levelling one M8 and M9 vessel in line.

- **Chamber ID 4**: Chamber width is 28.4 m for reasons mentioned under chamber ID 2. Chamber length is 245 m for reasons mentioned under chamber ID 3.
- **Chamber ID 5**: The width of the chamber is 25 m for reasons mentioned under chamber ID 1. The length of the chamber is 305 m, which allows for levelling one M12 vessel and two M6 vessels in line.
- **Chamber ID 6**: The width of the chamber 28.4 m for reasons mentioned under chamber ID 2. The length of the chamber is 305 m for reasons mentioned under chamber ID 5.
- **Chamber ID 7**: The width of this chamber is 34.2 m, which allows for levelling a 4-barge push tow convoy and a M8 or M9 vessel side by side. The width of the chamber also implicates that three M8 or M9 vessel can level side by side. However, this introduces mooring problems for the vessel that is in the middle. The length of the chamber is 305 m for reasons mentioned under chamber ID 5.
- **Chamber ID 8**: The width of the chamber is 25 m for reasons mentioned under chamber ID 1. The length of the chamber is 390 m, which allows for two 4-barge push tow convoys to level in line.

D

IVS FLEET ANALYSIS

D.1. INTRODUCTION

The fleet analysis is performed to gain insight in the fleets that are passing the WLC's and to extract data that serves as input for the SIVAK III traffic simulations. The analysis is a follow up on the multi-annual analysis performed in Appendix A. The analysis is performed for both WLC's for the period 7 January 2019 till 30 June 2019 based on IVS data, unless stated differently. The data is provided by *Rijkswaterstaat*.

D.2. FLEET COMPOSITION

D.2.1. FLEET MIX

The fleet mixes describe the composition of the fleets that navigate on the river Waal. Figure D.1 shows the fleet mix that has passed the location of WLC G11W3 and G11W5 as recorded from January 2019 till June 2019. Note that the vessel types are classified according the RWS classification system. For the definitions of the class codes is referred to Appendix A.1.

From Figure D.1 is observed that the M8 class dominates in terms of number of passages. roughly 8500 passages in eastern direction and almost 9400 passages in western direction are recorded at location G11W3. At location G11W5 these numbers are roughly 6800 and 8200 respectively. M6 and M9 vessels are also very commonly found on the river Waal. For most of the classes the number of passages in western direction is larger than in eastern direction. This is in line with the multi-annual trend in Figure A.2. Exceptions are found in the push-tow classes, 'no code' class and 'non commercial' class.

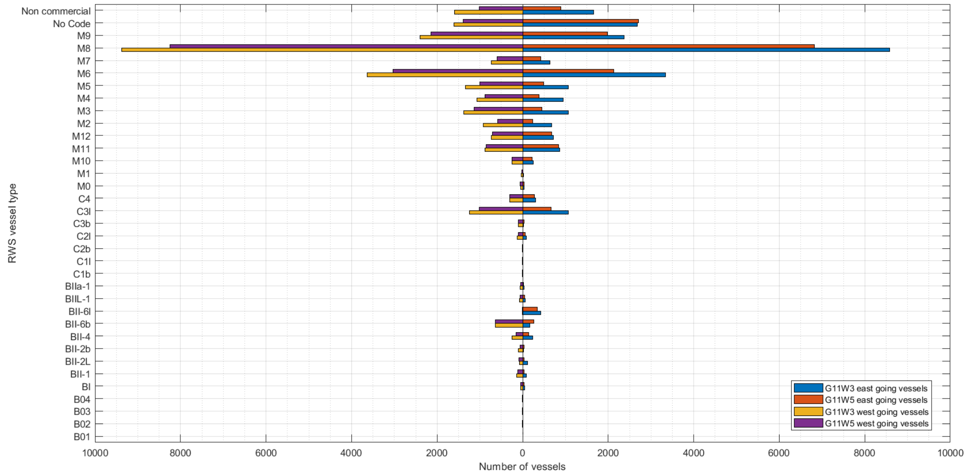

Figure D.1: Commercial fleet mixes at locations G11W3 and G11W5

Currently, six barge Push-tow units navigate in upstream direction (eastern direction) in two-wide formation and return in three-wide formation. Push-tow units are not allowed to navigate in upstream direction in the three wide formation ("Rijnvaartpolitiereglement Artikel 11.02", 2018). The 'non commercial' class is broken down in other vessel types in Figure D.2 upper panel. From this figure is concluded that the passenger vessels dominate in numbers in both directions at both locations.

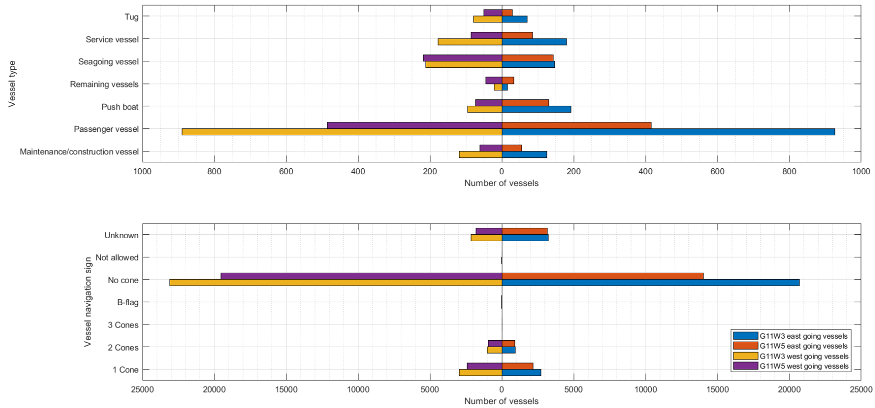

Figure D.2: Upper panel: Non-commercial fleet mixes at locations G11W3 and G11W5; **Lower panel:** Number of vessels sailing with a certain sign

The lower panel in Figure D.2 presents the number of vessels that navigate with a certain sign. Note that the y-axis is on a logarithmic scale. 1 Cone indicates that the vessel transports combustible cargo, 2 cones indicates transport of toxic cargo and 3 cones indicates the presence of explosive cargo. B-flag refers to seagoing vessels navigating with dangerous cargo. The larger portion of the vessels sails without a sign (0 cones). Meaning that no dangerous cargo is on board. Vessels navigating with 1 or more cones are subject to additional safety regulations when locking ("Rijnvaartpolitiereglement Artikel 6.28", 2018).

D.2.2. Six barge push-tow units

Six barge push tow units are allowed to navigate on the river Waal under certain circumstances ("Rijnvaartpolitiereglement Artikel 11.02", 2018). One of the conditions is that the water level, measured at Lobith, is between 8.50 m + NAP and 13.50 m + NAP. This translates to discharges of respectively 1604 m^3/s and 6098 m^3/s according to the Betrekkingslijnen 2018 (Van der Veen & Agtersloot, 2019). The WLC's are operational for discharges of 1600 m^3/s and lower, meaning that six barge push-tow units do not have to be able to pass the WLC's under the current regulations. The 6-barge push tow convoys are excluded from the fleet and replaced by 4-barge push tow convoys. This also implies that the 3 wide formation is not taken into account in establishing the chamber widths. The number of excluded 6-barge push tow convoys is multiplied by 1.5 and added to the number of 4-barge push tow convoys. The correction is included in final representation of the fleet mix in Figure D.15.

D.2.3. 'No code' class

The 'no code' class is found in Figure D.1 and contains vessel registrations that are marked as a commercial vessel but do not carry an RWS classification code and no other data on the vessel. The difference in the number of registrations without data in eastern and western direction at both locations is remarkable. In eastern direction at location G11W3, 2678 commercial vessels registrations do not contain any data. This number is substantially lower in western direction (1606). These figures are 2712 and 1386 respectively, for location G11W5. No clear reason was found for the difference in number of passages without data attached to them.

The portion of the 'no code' class is substantial and considered too large to ignore in the SIVAK III simulations. Therefore the vessels in the 'no code' class are redistributed over the M1 to M8 classes. For the redistribution is assumed that all vessels that should have reported their route, did report their route to an IVS-post. Based on this assumption and the regulations on IVS-use ("Artikel 2 Regeling communicatie en afmetingen rijksbinnenwateren", 2021), can be concluded that all vessels in the 'no code' class do have a length shorter than 110 m. This corresponds with the lengths of the vessels found in RWS-classes M1 till M8. The redistribution of the 'no code' class is kept equal to the distribution of the registered M1 to M8 classes. The distributions for east-going and west-going vessels for both locations are plot in Figure D.3. The correction is included in final representation of the fleet mix in Figure D.15.

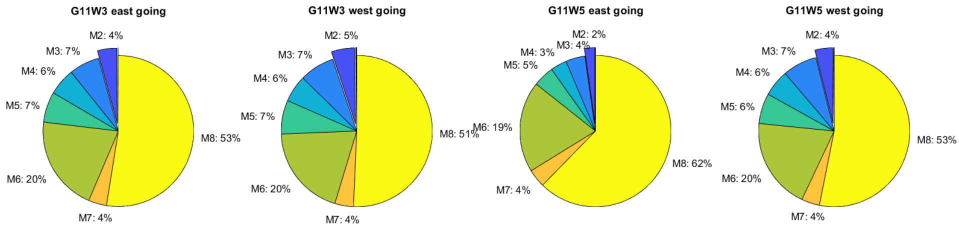

Figure D.3: Distribution of M1 to M8 vessels going in eastern- and western direction at locations G11W3 and G11W5

D.2.4. LOADED VS UNLOADED

For the traffic simulations it is of importance to know the percentage of vessels that is loaded and unloaded, as it affects the draught of a vessel, which affects the locking and passage times. Figure D.4 presents the percentage of loaded vessels per direction and vessel type at locations G11W3 and G11W5. The percentage of loaded vessels navigating in eastern direction at G11W3 is 76% and 80% at G11W5. These percentages are about 15-20% lower for vessels navigating in western direction (59% at both locations). Vessel classes without a bar in Figure D.4 were not observed in the respective period.

D.2.5. LOAD FACTOR

The load factor is defined as the weight of the cargo being transported divided by the load capacity of the respective vessel. SIVAK III uses the load factor as a measure to compute the draught of a vessel. Figure D.5 presents the average load factor per vessel class for loaded vessels only. Load factors roughly vary between 0.6 and 0.8 for most of the vessel classes and variations per direction per class are minor. Vessel classes without a bar in Figure D.4 were not observed in the respective period.

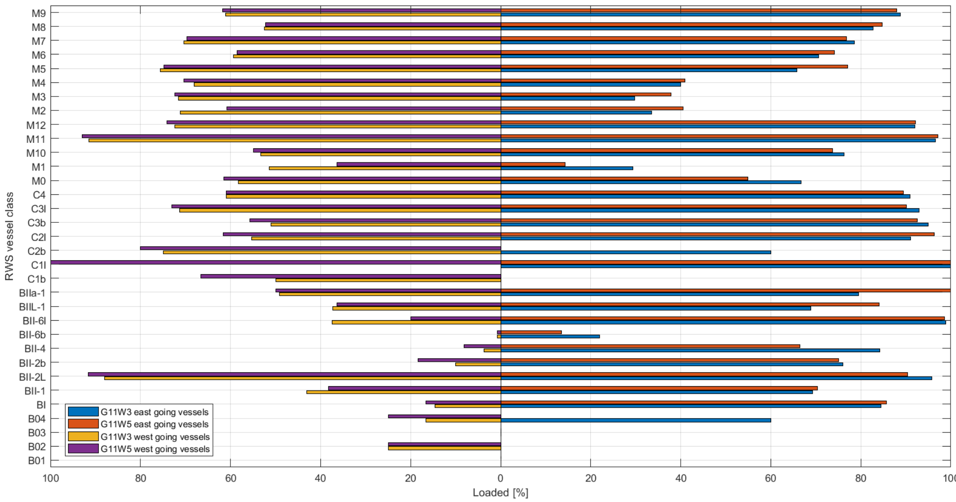

Figure D.4: Percentage of vessels that is loaded at location G11W3 and G11W5

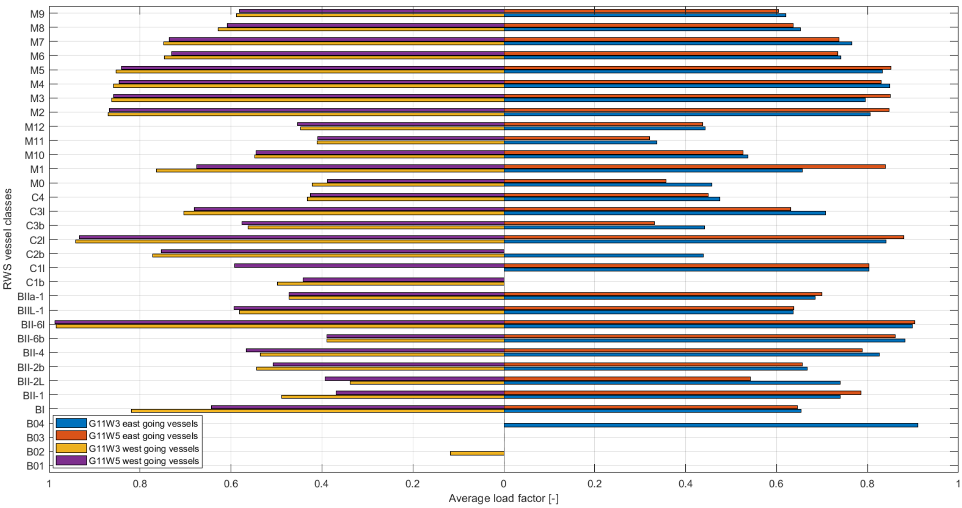

Figure D.5: Average load factor per vessel class at location G11W3 and G11W5

D.2.6. Recreational vessels

The number of recreational vessels is poorly represented in the data, as only 39 recreational vessels are recorded in the first half of 2019 at both locations combined. Possible reasons are the absence is that recreational vessel do not have to report their route to IVS posts and vessels shorter than 20 m do not have to use an AIS transponder. This means that there is not clear view on the number of recreational vessel that navigate on the river Waal.

It is expected that the river Waal is not a popular waterway for recreational vessels due to the generally high intensity of the much larger commercial vessels. Recent figures on recreational vessel passages on the river Waal were not found in literature. In 2010 a total number of recreational vessel passages at Beuningen was estimated at 9000 per year based on various counting campaigns and recorded passages at lock Weurt (Nieuwhof et al., 2010). By looking at the total number of passages at the locks that give access to the river Waal (see Figure D.6); lock Weurt, lock Sint Andries and the Prins Bernhard locks, a rather strong decrease in of 37% was found between 2010 and 2020. Reducing the estimate of 9000 vessels in 2010 by 37% results in an estimate of 5670 recreational vessels per year in 2020.

The majority of the vessels are expected to be motorised vessels, as the river Waal has height limitations due to several bridges crossing, which makes sailing with sailing boats unattractive. Furthermore is assumed that 50% of the vessel sails in upstream direction and the other 50% in downstream direction.

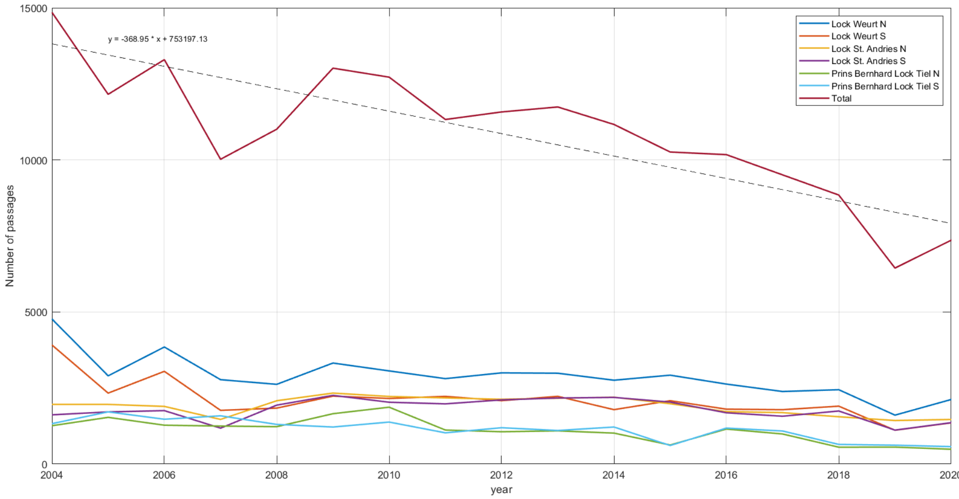

Figure D.6: Annual number of passages of recreational vessels at the locks that give access to the river Waal (Annual figures taken from Netwerkmanagement Informatie Systeem (NIS), Rijkswaterstaat)

D.3. ARRIVAL PATTERNS

D.3.1. GENERAL PATTERN

The moment of arrival of a vessel at the one of the WLC's is more likely to occur during day than during night. This example follows from the arrival patterns that are distilled from the IVS data. An arrival pattern indicates the traffic intensity at a WLC over a certain time period. Arrival patterns on different timescales are considered in this section. In Figure D.7 is shown the daily number of passages at locations G11W3 and G11W5 for both directions from January till June 2019. The plot includes all vessels, commercial and non-commercial.

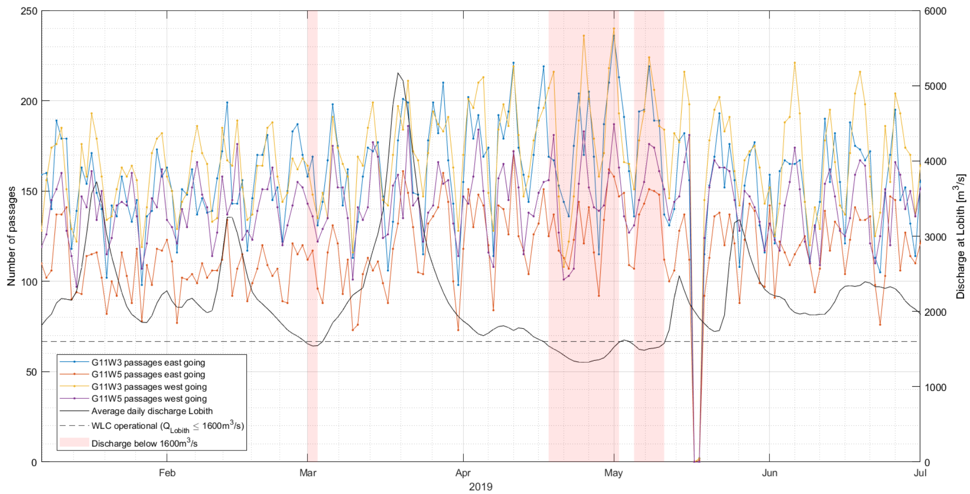

Figure D.7: Total number of daily passages at locations G11W3 and G11W5

The numbers of passages show a similar recurring pattern. The recurring pattering is on a weekly scale. Peak intensities occur during weekdays and traffic intensity appears to be at a minimum in the weekends. The maximum number of vessels passing in one day in one direction is 240 (G11W3 west going) and the minimum 73 (G11W5 east going). The pattern is looked at in more detail in the following sections. The start of an increase in number of passages is observed in March. This increase is assigned to the introduction of IVSNext as discussed in Section 4.5.4, but a slight increase as a consequence of a reduced discharge is not excluded. The figure also shows the missing data at the 17th and 18th of May as discussed in Section 4.5.4.

D.3.2. WEEKLY PATTERNS

Figure D.8 shows the total number of weekly passages for both directions at WLC G11W3 and G11W5 for the commercial fleet only. The number passages per week appears to be pretty constant, varying from roughly 1700 to 1900 passages per week. After week 10 a slight increase is observed in the number of weekly passages. Again, the increase is assigned to the introduction of IVSNext. The dip in week 19 is due to the missing data on the 17th and 18th of May.

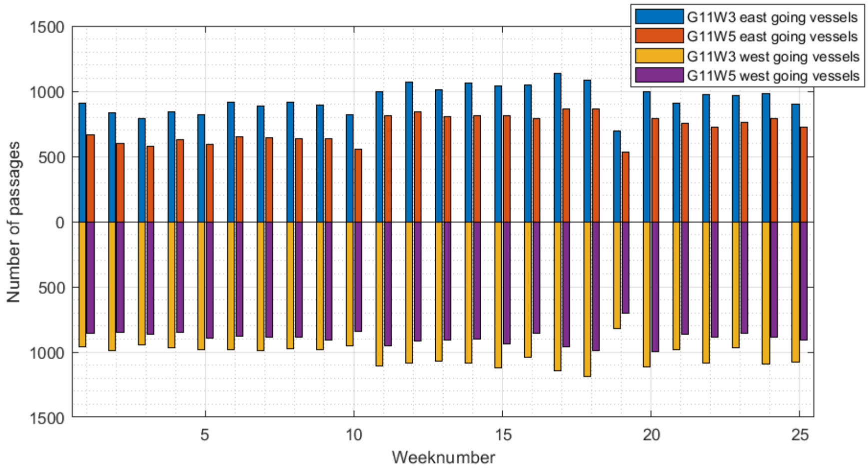

Figure D.8: Total number of east- and west-going commercial vessels at locations G11W3 and G11W5

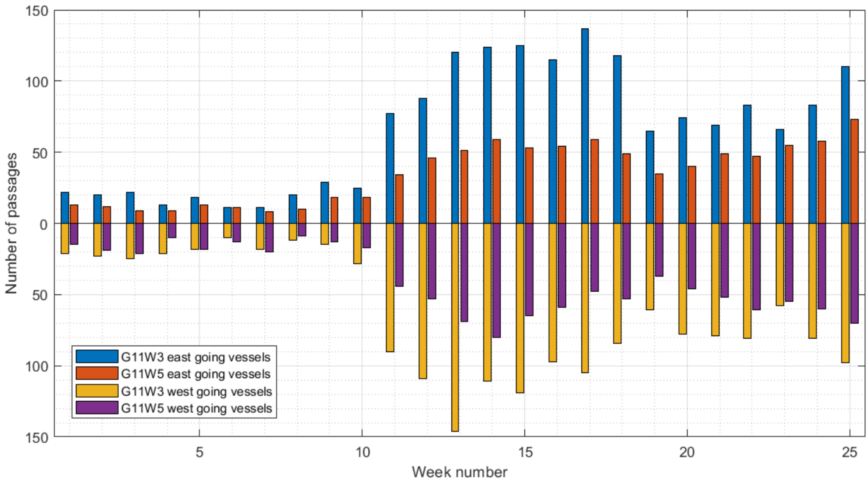

Figure D.9: Total number of east- and west-going non-commercial vessels at locations G11W3 and G11W5

Figure D.9 shows the weekly number of non-commercial vessel passages. This pattern is less constant than the pattern corresponding to the commercial fleet. A substantial increase in number of passages occurs in week 11 (again a consequence of the introduction of IVSNext). But the increase may also be enhanced by start of the spring season. In Section D.2 was found that the largest portion of the non-commercial fleet consists of passenger vessels. It is likely that in the spring season the intensity of passenger vessels increases, due to better weather conditions and the presence of tourists.

D.3.3. DAILY PATTERNS

In this section is looked into the arrival pattern on a daily scale. Figures D.10 and D.11 show the average day intensity for one week for respectively commercial vessel and non-commercial vessels. For the commercial vessels a clear peak is observed on Wednesday (east going vessels) and Thursday (west going vessels) and minimum are found in the weekend. Only slight deviations in east- and west-going intensities are found for location G11W3. The difference between east- and west going vessels at location G11W5 is substantial.

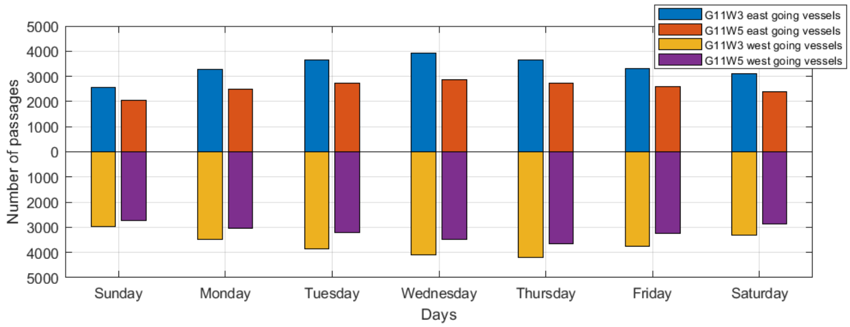

Figure D.10: Total number of commercial fleet passages per day for locations G11W3 and G11W5

For the non-commercial fleet a less distinctive pattern was found. Peak intensities occur during Mondays, Wednesdays and Fridays for the east going fleets. For the west going fleets a peak is found at Thursday. Furthermore is concluded from Figure D.11 that the intensity over the week is quite uniform (18 to 19 vessels per day on average). Only slight deviations in east- and west-going intensities are found.

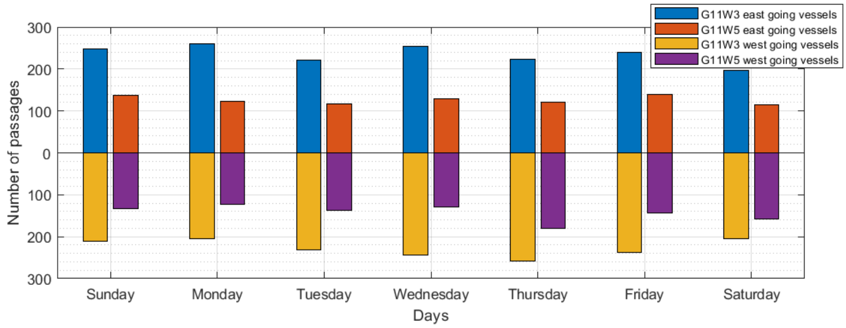

Figure D.11: Total number of non-commercial fleet passages per day for locations G11W3 and G11W5

D

D.3.4. HOURLY PATTERNS

This final section on arrival patterns considers the hourly intensities per day. In Figures D.12 and D.13 is presented the total number of commercial and non-commercial vessels respectively passing per hour of the day. For the east going at location G11W3 vessels three peaks are observed around 08:00, 13:00h and 17:00h. For location G11W5 two peak around 07:00h and 16:00h. The intensity peak for the west going vessel is around 13:00-14:00 and thus shows one peak. Lowest traffic intensities are found during night time between 24:00h and 05:00h.

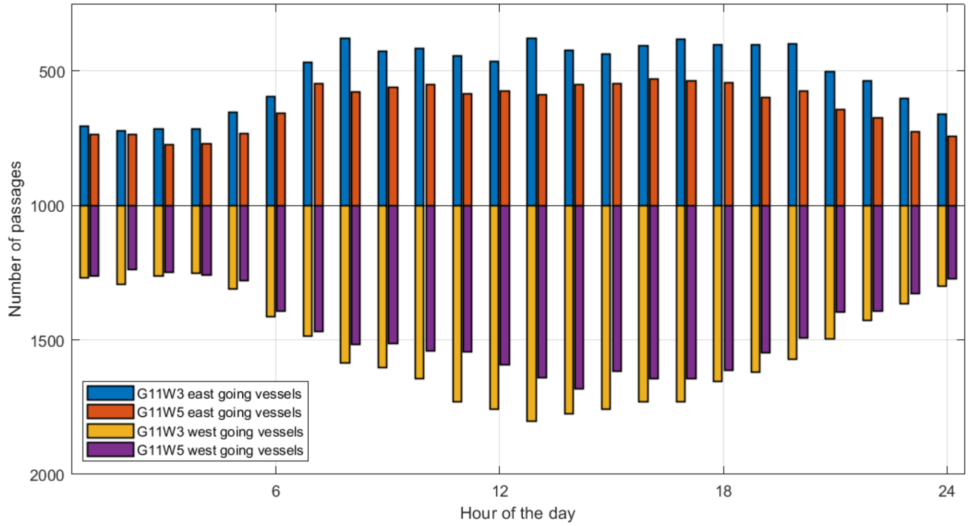

Figure D.12: Total number of commercial fleet passages per hour for locations G11W3 and G11W5

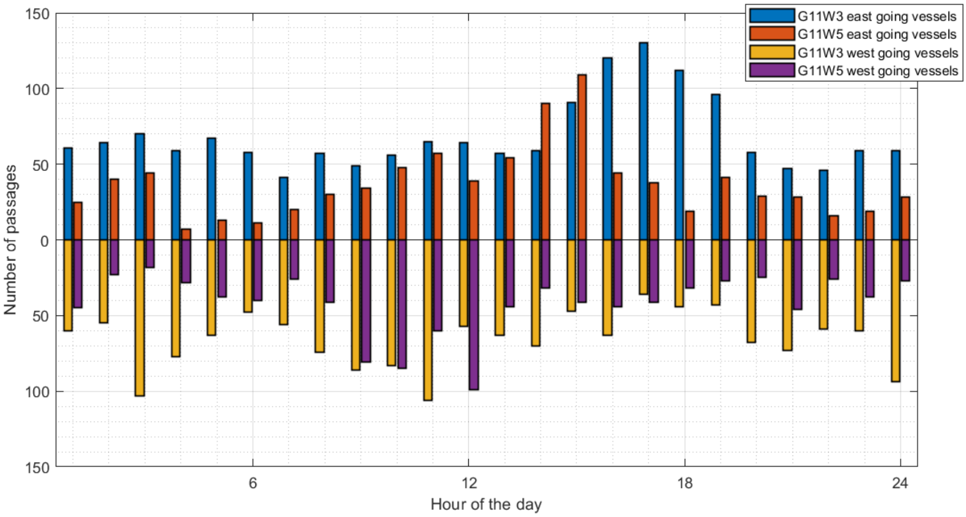

Figure D.13: Total number of non-commercial fleet passages per hour for locations G11W3 and G11W5

For the non-commercial fleet different patterns are found. It is notable that no clear reduction in vessel intensity was found during night time. Peak intensities for east going vessels occur in the afternoon around 15:00h to 18:00h. The pattern of G11W3 seems shifted toward the right with respect to the pattern at G11W5. This could be possible as the same vessel pass location G11W3 first and a few hours later G11W5. Peak intensities for west going vessels are spread around the day and night(!). A clear peak was found around noon at locations G11W3 and G11W5. Remarkable intensity peaks are found at location G11W3 during night at 24:00h and 03:00h. These peaks mainly consist of passing passenger vessels. About 77% of the non-commercial vessels that navigates between 00:00h and 06:00h is classified as passenger vessel.

D.3.5. 17TH AND 18TH OF MAY

From Figure D.7 becomes clear that only a hand full of vessels is registered on Friday 17th and Saturday 18th of May. No reason was found to assume that there were no vessels passing the locations of the WLC's. Therefore linear interpolation, between one week before and after the respective dates, was applied to fill in the gaps on the 17th and 18th of May. This is conducted for both locations and travel directions. The correction is shown in Figure D.14 for location G11W3 for east going vessels only. The distribution of vessel types is assumed to be equal to the distribution of the registered vessels over the entire period.

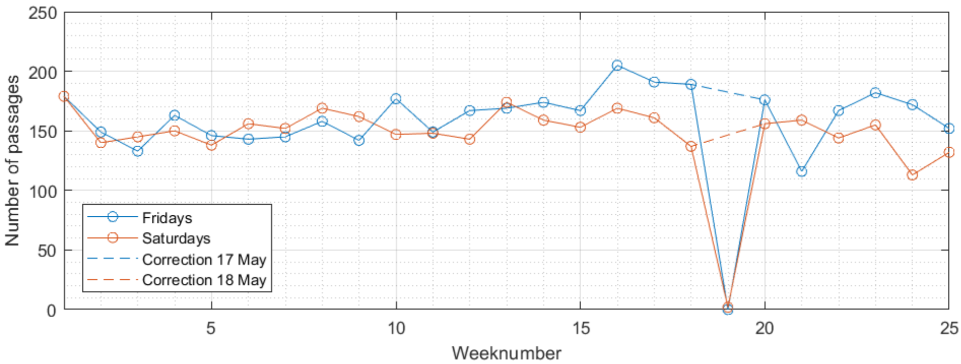

Figure D.14: Corrections for the missing data on the 17th and 18th of May for location G11W3 east going vessels only

D

D.4. DATA CORRECTIONS

This section summarises the corrections made on the data. The data was corrected on three aspects:

1. Replacement of 6-barge push tow units by 4-barge push tow units;
2. 'No code' registrations without data are redistributed;
3. Missing registrations on the 17th and 18th of May.

The 6-barge push tow units are excluded from the fleets and replaced by 4-barge push tow units. It is assumed that a 6-barge push tow unit has 1.5 times the load capacity of a 4 barge push tow unit. This makes that the removed 6-barge pushed tow units are replaced by 4-barge push tow units multiplied by 1.5.

Commercial vessel registrations without data attached to the registration are redistributed over vessel classes M1 till M8. The redistribution is kept equal to the distribution of the M1 to M8 vessels that are registered.

Finally, to include the missing registration on the 17th and 18th of may, linear interpolation was applied between the same day one week earlier and later than the respective date.

These three corrections have led to the following fleet mix (see Figure D.15). Note that the fleet mix is now given in average number of vessels per week per vessel type. The data is presented in table format in Table D.1.

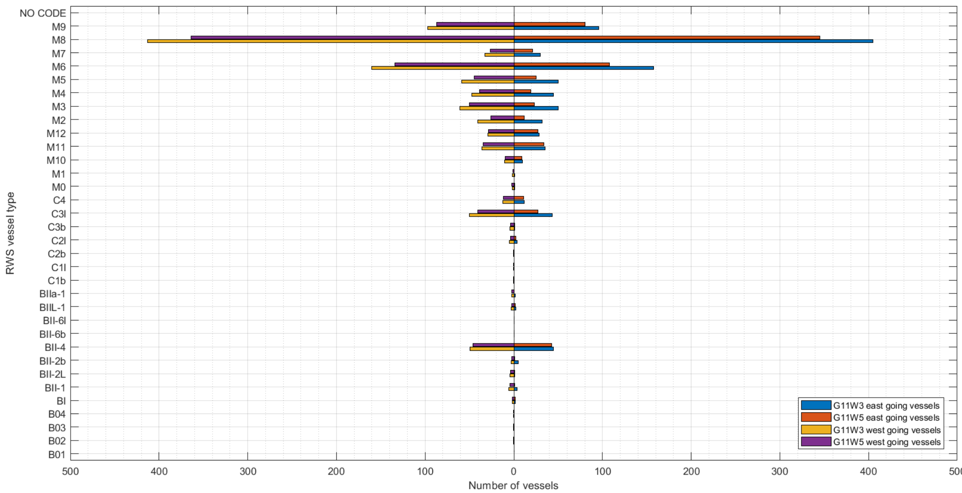

Figure D.15: Final fleet mix after corrections in average number of vessels per week

	G11W3		G11W5	
RWS vessel class	**east-going**	**west-going**	**east-going**	**west-going**
BI	1.82	1.95	1.42	1.95
BII-1	3.56	5.55	1.09	4.46
BII-2b	4.82	3.04	1.13	2.43
BII-2L	1.01	4.05	1.26	3.36
BII-4	44.97	49.26	42.34	46.03
BII-6b	0.00	0.00	0.00	0.00
BII-6l	0.00	0.00	0.00	0.00
BIIa-1	1.58	2.39	0.65	2.03
BIIL-1	2.47	3.04	1.78	2.67
B01	0.04	0.00	0.04	0.00
B02	0.16	0.32	0.00	0.16
B03	0.08	0.08	0.04	0.16
B04	0.20	0.24	0.00	0.16
C1b	0.00	0.08	0.00	0.12
C1l	0.04	0.04	0.04	0.04
C2b	0.20	0.16	0.00	0.20
C2l	3.61	5.35	2.23	4.01
C3b	0.81	4.21	1.09	3.93
C3l	43.10	50.25	26.92	40.97
C4	12.03	12.36	11.19	12.04
M0	1.22	1.95	1.26	2.63
M1	0.81	1.54	0.35	0.97
M10	9.88	10.25	8.96	9.89
M11	35.36	35.82	33.93	34.77
M12	28.88	29.50	27.48	28.37
M2	31.96	40.57	11.99	25.78
M3	50.15	60.95	22.96	50.28
M4	44.76	47.05	19.27	38.80
M5	50.35	58.80	24.94	44.41
M6	157.66	160.31	107.58	133.89
M7	29.98	32.54	21.40	26.53
M8	404.65	413.11	345.06	363.84
M9	95.93	97.18	80.46	87.04
Passenger vessel (bicycle cruise)	0.52	0.60	0.28	0.96
Passenger vessel small	0.12	0.20	0.08	0.48
Passenger vessel modern cruise	21.48	21.04	8.48	9.56
Passenger vessel older cruise	12.40	13.04	3.16	5.80
tug boat	2.84	3.16	1.20	2.00
Seagoing vessel, L<=90 m	5.60	7.96	5.40	8.16
Seagoing vessel, 90 <L<=130	0.28	0.52	0.32	0.56
Totals per direction per complex	1105.35	1178.47	815.78	999.45
Totals per complex		2283.82		1815.23

Table D.1: Final fleet mix after corrections in average number of vessels per week

D.5. FLEET'S RESPONSE TO DISCHARGE VARIATIONS

The response of the fleet to discharge variations at Lobith for 2019 is illustrated in this section. This section is written to substantiate the decision to use the IVS data of the first half of 2019 only.

D.5.1. INTENSITY

Figure D.16 shows number of commercial vessel passages for 2019 on a weekly resolution. Weekly totals are given for data with and without 'no code' vessel registrations. The same figure also shows the daily average discharge at Lobith. Note that no 'no code' vessels were recorded prior to March 2019. Periods for which the discharge is below 1600 m^3/s are shaded in red. Not that this would be the same period for which the WLC's would be operational.

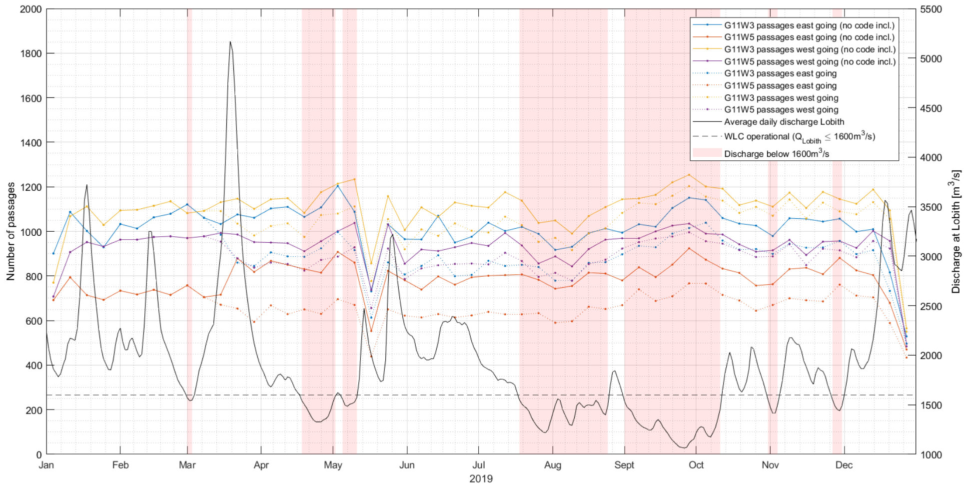

Figure D.16: Weekly number of commercial vessel passages at locations G11W3 and G11W5 for 2019 and average daily discharge at Lobith

The introduction of IVSNext and the largest discharge peak (approximately 5100 m^3/s) in 2019 occur at the same moment in time. From Figure D.16 is observed that the number of vessels increases during this peak when considering the lines that include 'no code' registrations, whilst a decrease in number of vessels is expected (see Section 1.3). However, it is not possible to conclude that the intensity did really increase as the 'no code' vessel were not recorded prior to March. A decrease in intensity is found when considering the lines that do not include the 'no code' vessels. This seems the more likely trend that occurred. No pronounced changes in intensity were found in the two peaks (3200 and 3700 m^3/s) prior to the largest discharge peak.

The first period larger than one week of discharge below 1600 m^3/s occurs in final two weeks of April. An increase in vessel intensity of about 15% is observed at both locations in both directions. Two longer periods of discharge below 1600 m^3/s between July 15 and October 15. The first period is characterised by a slight decrease in intensity (5-15%), which is likely to be due to summer holidays. The second period is characterised by an increase (10-25%) in intensity, which is expected to be due to four week period with discharges between roughly 1050-1600 m^3/s. Based on these observations is concluded that the fleet navigating on the Waal between January and July 2019 is hardly affected by the discharge at Lobith.

D

D.5.2. Load factor

The load factor can be considered sensitive to discharge variations on the river Waal. This is illustrated by means of box plots in Figure D.17. The box plots illustrate the variations in load factor per week. The weekly discharge at Lobith is given in the same figure. The data used for the figure contains all loaded commercial vessels passing location G11W3. Vessel with a load factor larger than 1 and lower than 0.01 are excluded from the data.

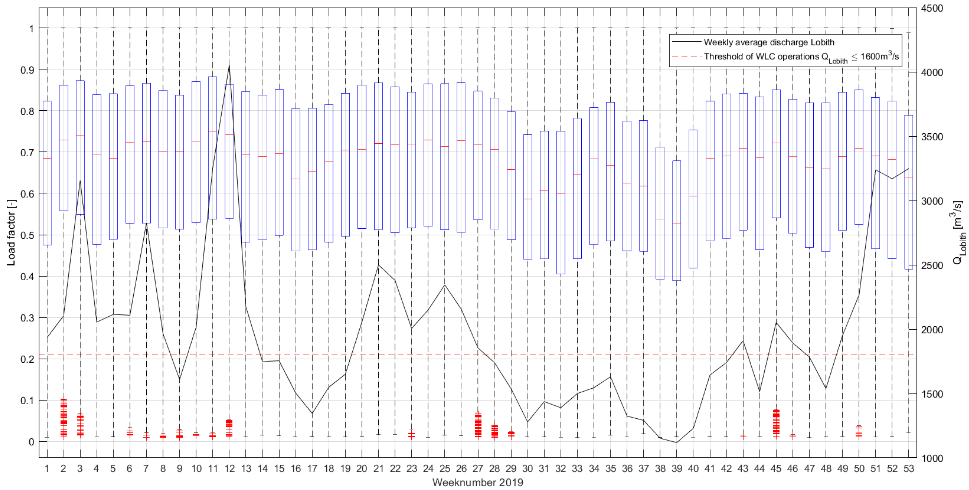

Figure D.17

For Figure D.17 is concluded that the median (and also the 25th and 75th percentile) follow the same trend as the discharge at Lobith. The load factor increase as the discharge increases, and decreases when the discharge decrease. The maximum median load factor (0.75) is recorded in week 11, during the largest discharge peak (4000 m^3/s). However similar median load factors (0.73 and 0.72) are reached at much lower discharges (2150 and 2000 m^3/s) in respectively weeks 24 and 45. This observation indicates that all vessels can navigate fully loaded for discharge around 2000 m^3/s at Lobith, as load factors do not further increase for larger discharges.

D.5.3. DRAUGHT

The draught of of a vessel is also dependent on the discharge in Lobith, however is already considered extensively in Section 3.4.

E

FLEET COMPOSITIONS FOR FUTURE SCENARIOS

E.1. VOLKERAK LOCKS AND RIVER WAAL LOCKS COMPARED

Figures E.1 and E.1 illustrate the differences in fleet share per RWS-vessel class for the future fleet mixes used in the SIVAK III simulations.

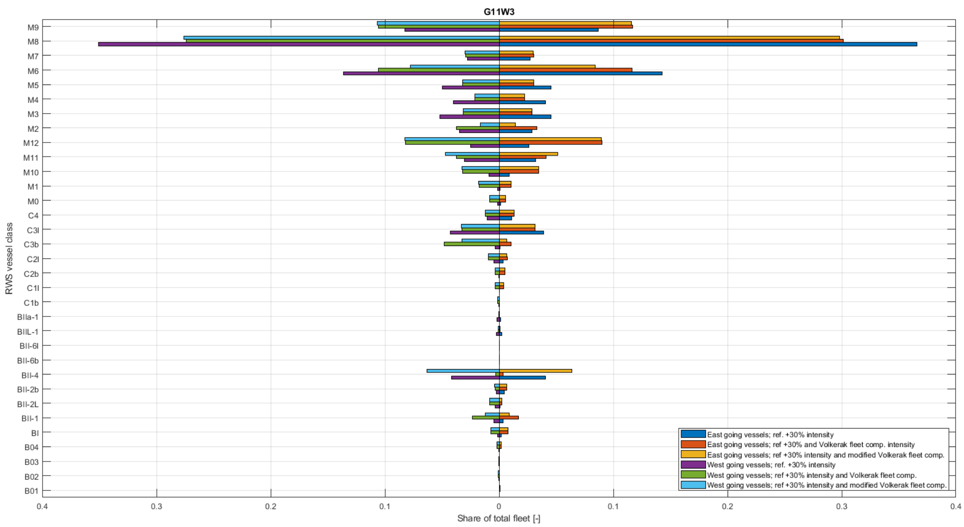

Figure E.1: Fleet mixes for lock complex G11W3

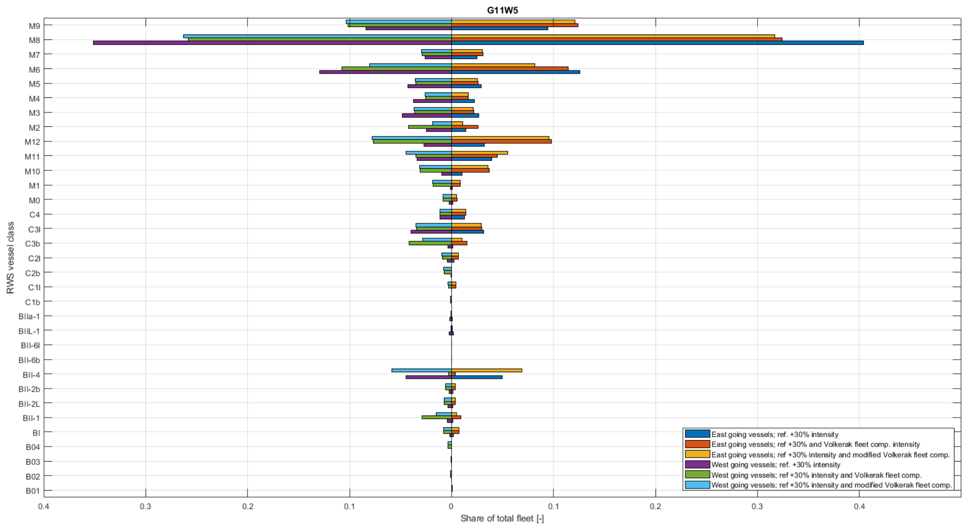

Figure E.2: Fleet mixes for lock complex G11W5

E

E.2. SCENARIO OVERVIEW

	Lock complex	Run time	Parameter	Value	Value background
Reference scenarios	G11W3	4 weeks	reference case	-	-
	G11W3	25weeks	reference case	-	-
	G11W5	4 weeks	reference case	-	-
	G11W5	25 weeks	reference case	-	-
Future scenarios	G11W3	4 weeks	total intensity	+10%	WLO2040L
	G11W3	4 weeks	total intensity	+20%	WLO2040H
	G11W3	4 weeks	total intensity	+30%	extrapolation WLO2040H
	G11W3	4 weeks	intensity + fleetmix	+30% intensity + volkerak fleetmix 2050H	WLO2050H
	G11W3	4 weeks	intensity + fleetmix	+30% intensity + modified volkerak mix	Modified WLO2050H
	G11W3	25 weeks	total intensity	+10%	WLO2040L
	G11W3	25 weeks	total intensity	+20%	WLO2040H
	G11W3	25 weeks	total intensity	+30%	extrapolation WLO2040H
	G11W3	25 weeks	intensity + fleetmix	+30% intensity + volkerak fleetmix 2050H	WLO2050H
	G11W3	25 weeks	intensity + fleetmix	+30% intensity + modified volkerak mix	Modified WLO2050H
	G11W5	4 weeks	total intensity	+10%	WLO2040L
	G11W5	4 weeks	total intensity	+20%	WLO2040H
	G11W5	4 weeks	total intensity	+30%	extrapolation WLO2040H
	G11W5	4 weeks	intensity + fleetmix	+30% intensity + volkerak fleetmix 2050H	WLO2050H
	G11W5	4 weeks	intensity + fleetmix	+30% intensity + modified volkerak mix	Modified WLO2050H
	G11W5	25 weeks	total intensity	+10%	WLO2040L
	G11W5	25 weeks	total intensity	+20%	WLO2040H
	G11W5	25 weeks	total intensity	+30%	extrapolation WLO2040H
	G11W5	25 weeks	intensity + fleetmix	+30% intensity + volkerak fleetmix 2050H	WLO2050H

	G11W5	25 weeks	intensity + fleetmix	+30% intensity + modified volkerak mix	Modified WLO2050H
	G11W5	4 weeks	fleet mix	addition of recreational fleet	estimate
	G11W3	4 weeks	leveling time	8 min	assumption
	G11W3	4 weeks	leveling time	10 min	assumption
	G11W3	4 weeks	leveling time	15 min	assumption
	G11W3	25 weeks	leveling time	8 min	assumption
	G11W3	25 weeks	leveling time	10min	assumption
	G11W3	25 weeks	leveling time	15min	assumption
	G11W5	4 weeks	leveling time	8 min	assumption
	G11W5	4 weeks	leveling time	10 min	assumption
Sensitivity scenarios	G11W5	4 weeks	leveling time	15min	assumption
	G11W5	25 weeks	leveling time	8 min	assumption
	G11W5	25 weeks	leveling time	10min	assumption
	G11W5	25 weeks	leveling time	15 min	assumption
	G11W3	4 weeks	detection length	500 m	assumption
	G11W3	4 weeks	detection length	1500 m	assumption
	G11W3	4 weeks	detection length	2000 m	assumption
	G11W3	25 weeks	detection length	500 m	assumption
	G11W3	25 weeks	detection length	1500 m	assumption
	G11W3	25 weeks	detection length	2000 m	assumption

Table E.1: Overview simulated scenarios in SIVAK III

E.3. NUMBER OF REPLICATIONS

Two scenarios are tested for the four consecutive busiest weeks and corresponding fleets (as in 2019). The simulations are repeated 150 times and after which the average waiting time per replication is registered by a blue dot in Figures E.3 and E.4. The red line in the same figures represents the average waiting time that is computed after every replication. After approximately 15 to 20 replications the average waiting time has converged to 72.5 minutes for the scenario with three lock chambers. The scenario with four lock chambers converges to an average waiting time of 15.5 minutes after approximately 30 replications.

Based on the results in Figure E.4 is decided to repeat all simulations five times. The error in average waiting will be in the order of 0.1 minutes for the scenario with four locks. This is considered acceptable. The error for the scenario with three lock chambers is in the order of 5 minutes. The difference in error can be explained based on the extremes. These will be larger for relative small lock complexes as the average waiting time increases for larger intensity/ capacity ratios.

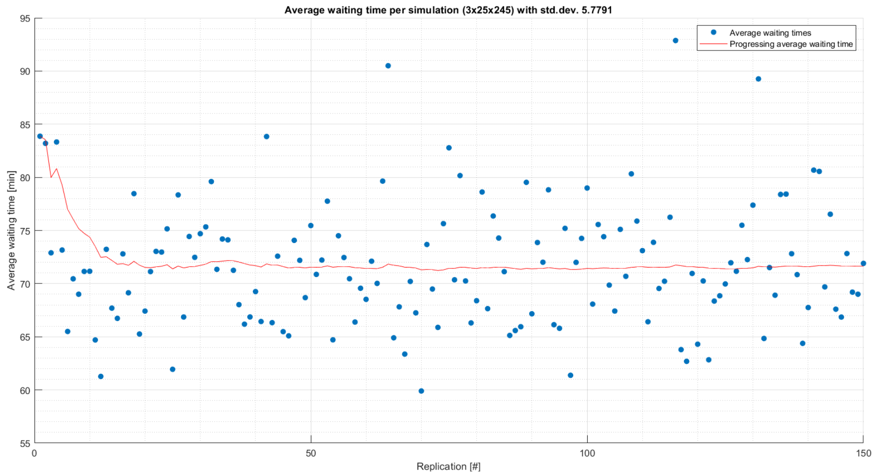

Figure E.3: Variation in average waiting time (over four weeks of simulation time) for scenario with three lock chambers (25x245m)

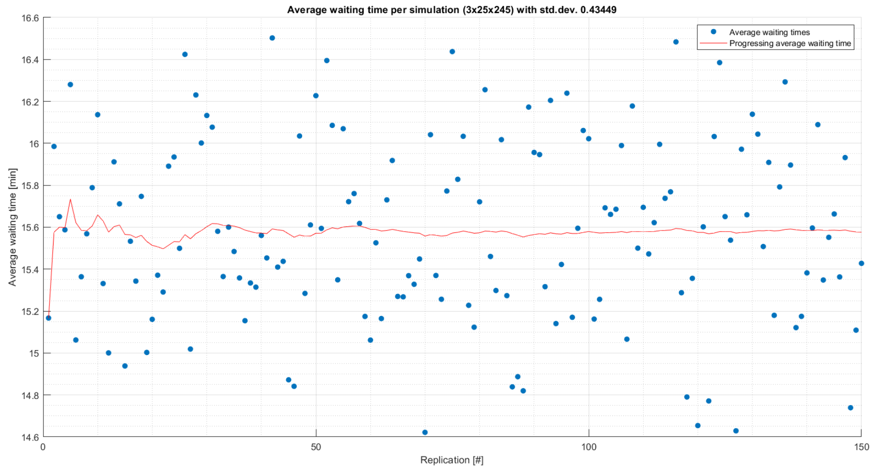

Figure E.4: Variation in average waiting time (over four weeks of simulation time) for scenario with four lock chambers (25x330m)

E.4. VESSEL GENERATION VERIFICATION

In this section is verified whether number and pattern of vessels that are generated in SIVAK III match the data as observed. The same scenario with four lock chambers (25x330m) is used again for verification. The data in the resulting generation log is aggregated on three time intervals, hourly, daily and weekly. The outputs are then compared to the raw data. The results are presented in Figures E.5 till E.7.

Note that in data of the 17th and 18th of May are missing in the raw data. This is clearly visible in Figures E.5 till E.7. In general the correspondence between the original and generated data is quite good. On a weekly scale deviations are in the order of 10 vessels, with a maximum deviation of 73 vessels in week 20 and a minimum of 10 vessels in week 10 (see Figure E.5). The generated daily pattern matches the raw data quite well too. Generally the the number of vessels per day is slightly larger in the simulation than in the raw IVS data. However there are a few exceptions that appear to compensate for this overbalance. the 24th and 25th of May and the 1st of June show exceptionally high peaks that do not fit the pattern well. These peaks are not captured in SIVAK III, as the arrival pattern is based on a weekly average that is enhanced with an intensity factor to include weekly variations only.

Figure E.7 illustrates the difference between the number of registered vessels in the IVS data and the generated number of vessels in SIVAK III per hour. The day to day variations and day and night variations are clearly visible for both. No major deviations were found between both curves, with the exception of the earlier mentioned dates.

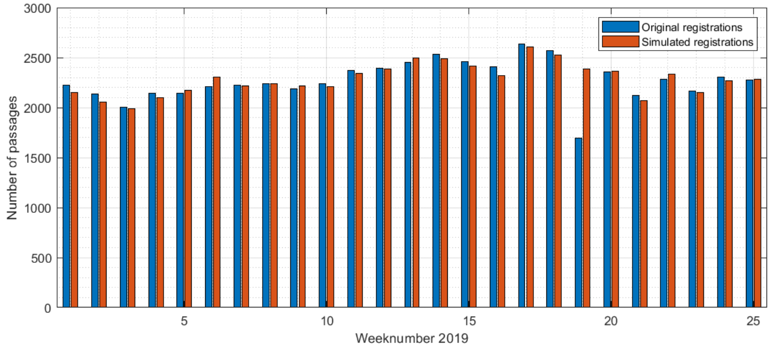

Figure E.5: Comparison between original IVS vessel registrations and vessel generation in SIVAK for the four busiest weeks

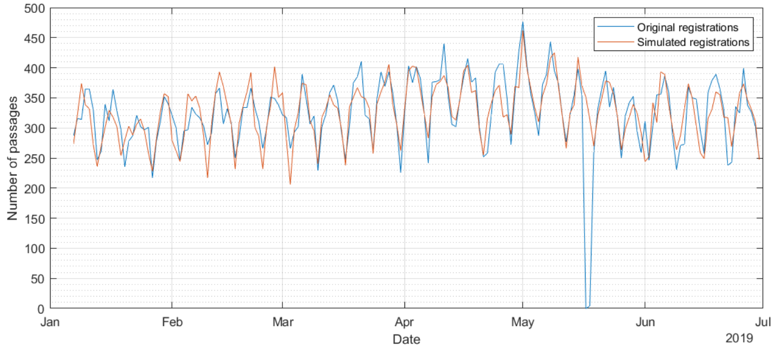

Figure E.6: Comparison between original IVS vessel registrations and vessel generation in SIVAK III for the four busiest weeks

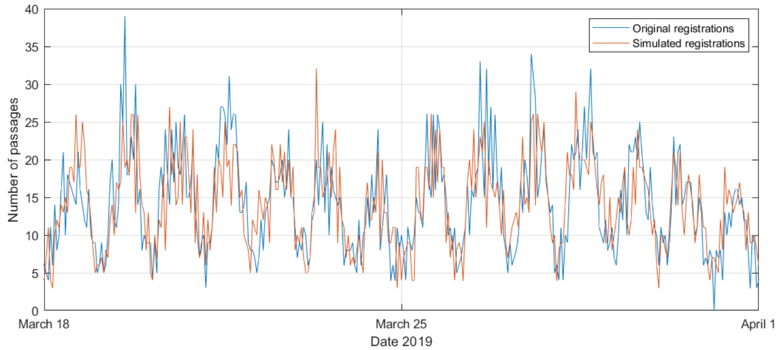

Figure E.7: Comparison between original IVS vessel registrations and vessel generation in SIVAK III for the four busiest weeks

E

F

FUTURE SCENARIOS LOCK COMPLEX G11W5

Figures F.1 till F.4 present the performance of the model variants in future fleet scenarios regarding the waiting time and service level -criterion.

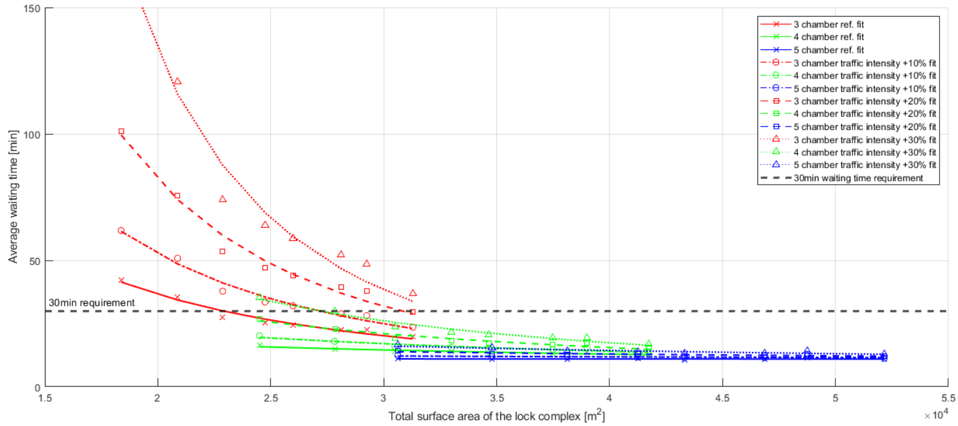

Figure F.1: Average waiting time for all model variants for varying vessel traffic intensities for complex G11W5

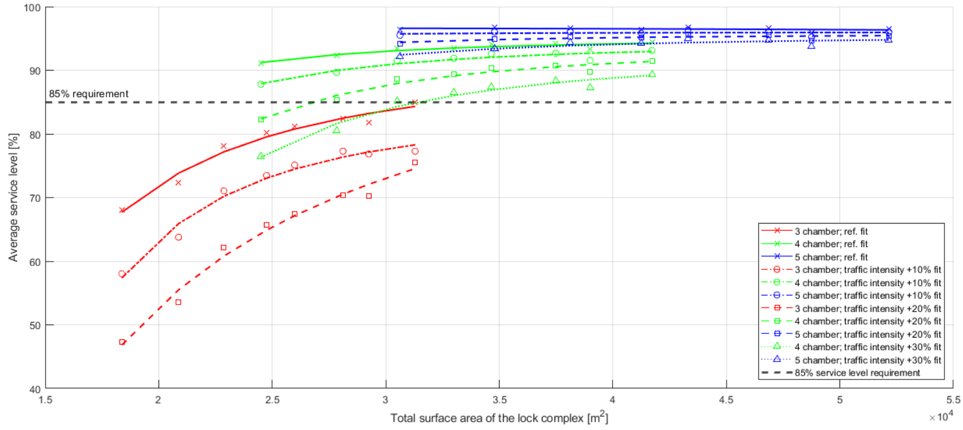

Figure F.2: Average service level for all model variants for varying vessel traffic intensities for complex G11W5

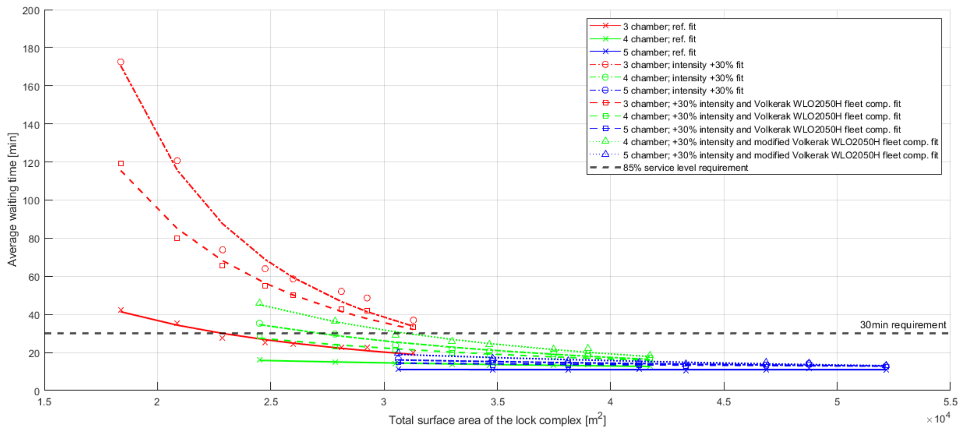

Figure F.3: Average waiting time for all model variants for varying fleet compositions and increased traffic intensity for complex G11W5

F

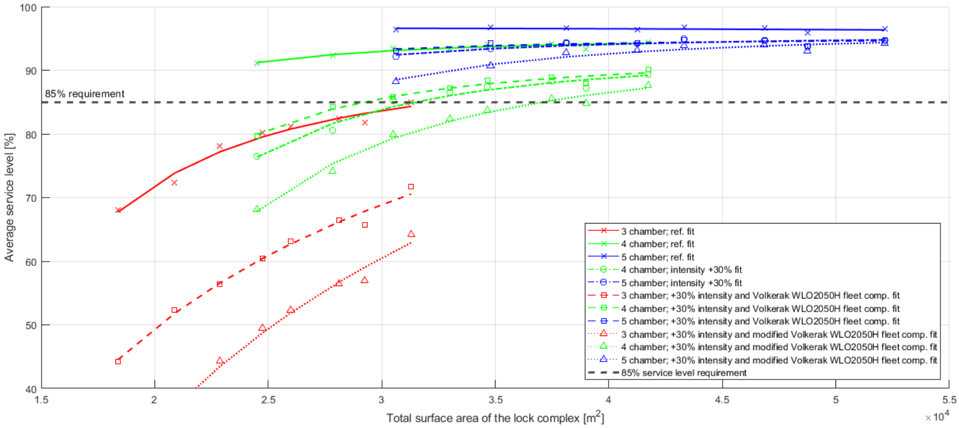

Figure F.4: Average service level for all model variants for varying fleet compositions and increased traffic intensity for complex G11W5

F

G

SENSITIVITY ANALYSIS

G.1. SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to verify on the robustness of the model variants. The performances of the model variants is analysed in terms of waiting time and service level under the following varying parameters:

- Varying lock parameters
  - Varying levelling times
  - Varying detection length
- Inclusion of recreational fleets

G.1.1. VARYING LOCK PARAMETERS

levelling time; the time required to fill and empty the lock chamber generally takes over 50% of the total time required for half a locking cycle (Molenaar & e.a., 2020). Therefore optimisation in levelling time is considered most effective in the reduction of average waiting time and passing time. Levelling times of 8, 10 and 15 minutes are considered next to the reference scenario. In addition, performances of the lock complexes are tested for detection lengths of 500 m, 1500 m and 2000 m.

G.1.2. INCLUSION OF RECREATIONAL VESSELS

Recreational vessels are poorly represented in IVS data on the river Waal. The data only shows 39 recreational vessels passing both lock locations. This is not a realistic number as in 2010 the number of recreational vessels passing *Beuningen* along the river Waal was estimated at 9000 passages, based on various counting campaigns (Nieuwhof et al., 2010).

An estimate of the number of recreational vessels navigating on the river Waal was made by looking at the trend in annual intensity at the locks of Weurt and Sint Andries and the Prins Bernhard locks that give access to the river Waal (see also Figure 3.4 for the locations of these locks). The number of recreational vessel passages has reduced by 37% Between 2010 and 2020 for the three locks combined. The total size of the recreational fleet is estimated at 5670 by reducing the estimated fleet of 9000 vessels as estimated in 2010 by 37%.

Furthermore was assumed that 50% of the vessels navigates in eastern direction and 50% navigates in western direction. The arrival patterns and seasonality factors are taken from simulations performed for the Volkerak locks in the context of the Integral Mobility Analysis (RijkswaterstaatWVL, 2021b). Recreational vessels are mixed with commercial vessels in the locking process. It is assumed that all recreational vessels do pass both lock complexes (G11W3 and G11W5) at the river Waal, which may be conservative. Vessels may for example take route via the locks at Sint-Andries or Prins Bernhard locks and pass only one lock complex.

G

G.2. SIVAK III RESULTS

G.2.1. IMPACT OF INCLUSION OF RECREATIONAL FLEETS

The impact of inclusion of the recreational fleet as described in Section G.1.2 is minor as illustrated in G.1. For model variants with 3 chambers the average waiting time increases with 1 to 2 minutes with respect to the reference scenario. Average waiting times increase with 30 seconds to 1 minute for model variants with 4 lock chambers and with less than 30 seconds for model variants with 5 lock chambers. Inclusion of a recreational fleet is not further considered due to the minor impact on waiting times, especially for model variants with 4 or 5 lock chambers.

Effects of inclusion of the recreational fleet are only tested for the normative period (4 consecutive busiest weeks) for lock complex G11W5. Because the share of the recreational fleet is larger than at lock complex G11W3, thus impact on average waiting time largest for G11W5. Note that the intensity of recreational fleets is strongly related to the seasons and that the peak intensities of commercial- and recreational fleets not necessarily coincide as assumed in this scenario.

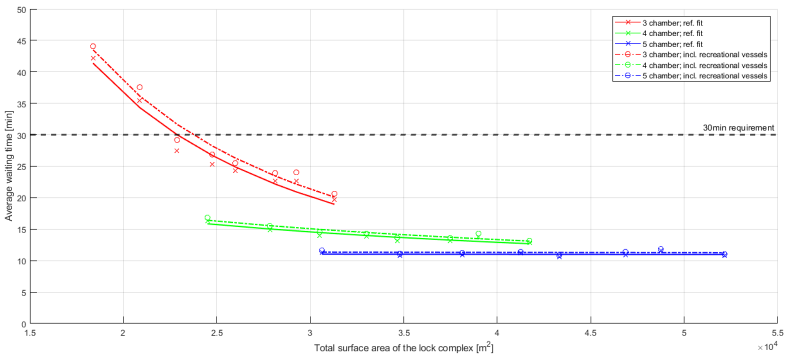

Figure G.1: Average waiting time for all the considered model variants at lock complex G11W5 over 4 weeks (normative period commercial fleet)

G.2.2. IMPACT OF LEVELLING TIME

The impact of levelling time on the average waiting time and service level is substantial as illustrated in Figures G.2 till G.5 for lock complexes G11W3 and G11W5. Effects of the reduction are most pronounced for the model variants with 3 lock chambers and least pronounced for the model variants with 5 lock chambers. However the reduction is most interesting for the model variants with 4 lock chambers, because the reductions to 10 and 8 minutes allow for the use of smaller locks chambers.

Complex G11W3 (downstream lock complex) required 4 lock chambers of dimensions 305x25 m in the reference scenario. A levelling time of 8 and 10 minutes allows for a model variant with 4 lock chambers with dimensions 245x25 m. Table G.1 summarises the minimum required number of locks and corresponding dimensions for reduced levelling times. The most right column illustrates that the surface area of the locks can be reduced by 17-33% if the levelling time is reduced from 12 min to 8 or 10 min.

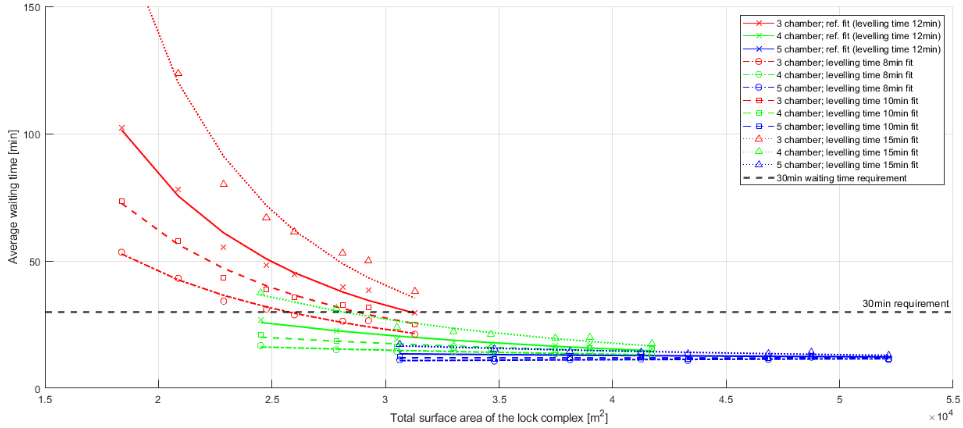

Figure G.2: Average waiting time for the different model variants for varying levelling times at lock complex G11W3

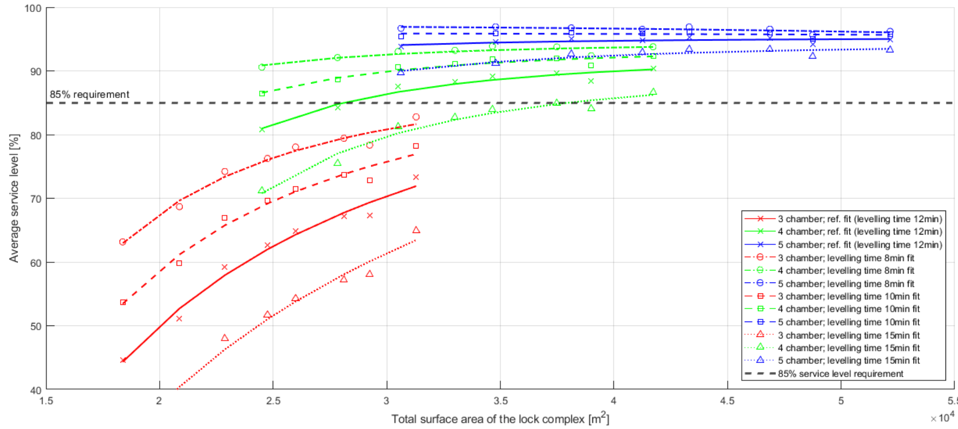

Figure G.3: Service level for the different model variants for varying levelling times at lock complex G11W3

G

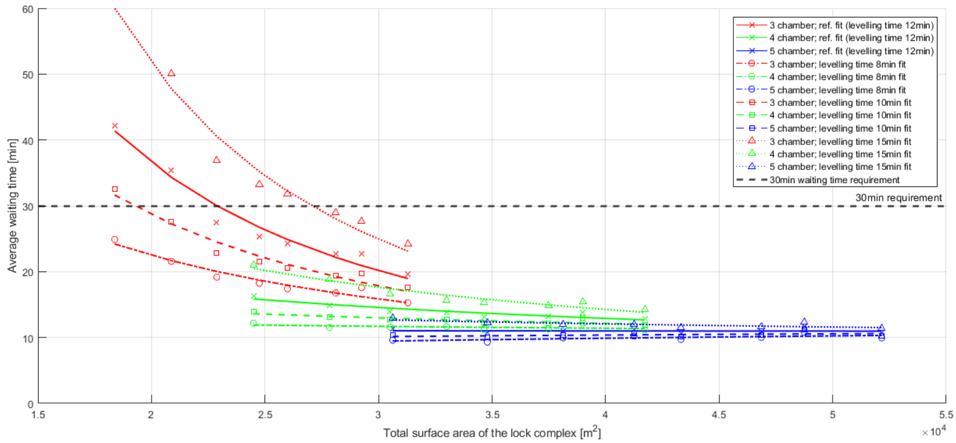

Figure G.4: Average waiting time for the different model variants for varying levelling times at complex G11W5

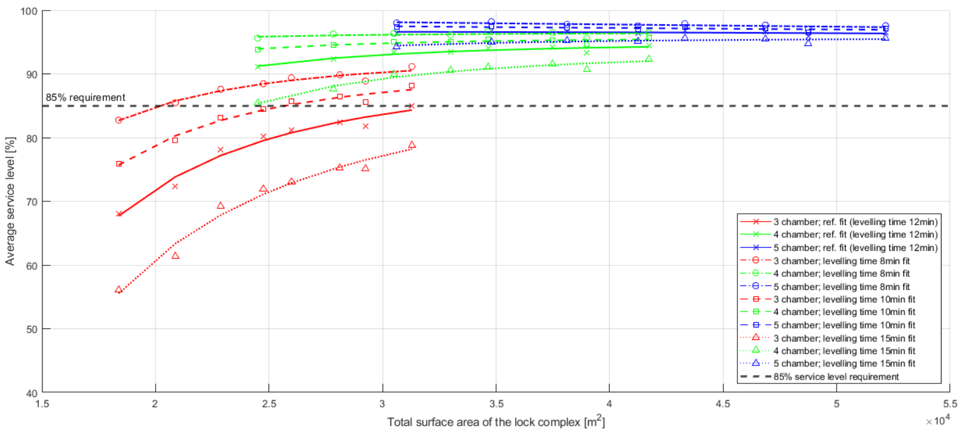

Figure G.5: Average service level for the different model variants for varying levelling times at complex G11W5

G

complex	scenario	values	chambers	length	width	avg. waiting time	avg. service level	A_{surf} reduction
	[-]	*[min]*	*[-]*	*[m]*	*[m]*	*[min]*	*[%]*	*[%]*
G11W3	levelling time	8	4	245	25	16.8	90.6	20
G11W3	levelling time	10	4	245	25	21.1	86.4	20
G11W5	levelling time	8	3	245	28.4	21.6	85.5	33
G11W5	levelling time	10	3	305	28.4	20.6	85.7	17

Table G.1: Minimum required number of lock chambers with minimum dimensions that meet the requirements under the considered reduced levelling times for lock both lock complexes.

G.2.3. IMPACT DETECTION LENGTH

The impact of variations in detection length is verified for four different lengths including the reference length; 500 m, 1000 m, 1500 m and 2000 m. The impact on the waiting time and service level is verified by running the simulations with all model variants for 4 weeks and 25 weeks for lock complex G11W3 only. Figure G.6 shows the impact of different detection lengths on the average waiting time and Figure G.7 illustrates the effect on service level.

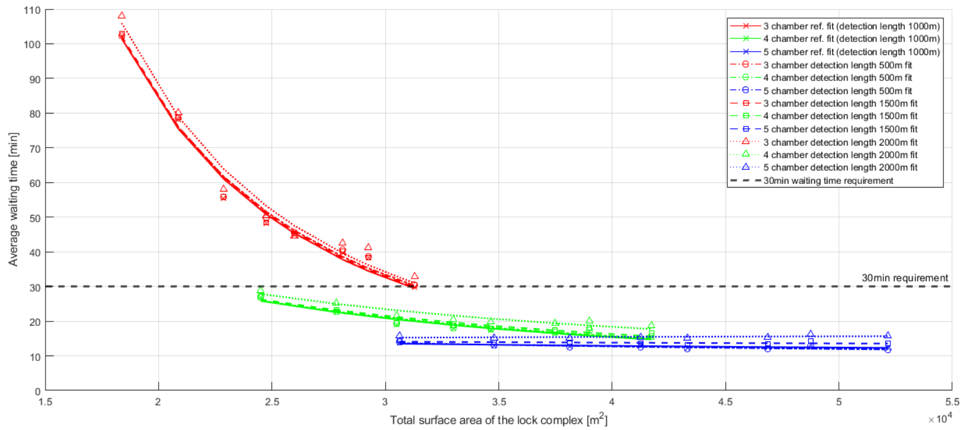

Figure G.6: Average waiting time for varying detection lengths and model variants at lock complex G11W3

A shorter detection length (500 m) than the detection length used in the reference scenario (1000 m) results in very slight deviations, in the order of seconds, in average waiting time for all model variants. A detection length of 500 m appears to reduce the waiting time for model variants with 5 chambers and relative large surface areas (see also Figure G.6). In all other model variants the average waiting time increases.

Increasing the detection length to 1500 m results in an increase in waiting time, in the order of 1 minute for all model variants. By increasing the detection length to 2000 m the average waiting time increases further for all model variants. The average increase in waiting time is about 160 seconds with respect to the reference scenario. Based on these observations is concluded that 1000 m detection length is a reasonable choice to minimise average waiting time for lock complex G11W5 (downstream).

The effects on service level are similar. A detection length of 500 m results in a decrease in service level for model variants with 3 or 4 chambers and an increase for model variants with 5 chambers. Deviations with respect to the reference scenario are in the order of 1%. Increasing the detection length to 1500 m or 2000 m results in a decrease of service level for all model variants in the order of 1-5%. Based on these observations is again concluded that 1000 m detection length is a reasonable choice to maximise the service level.

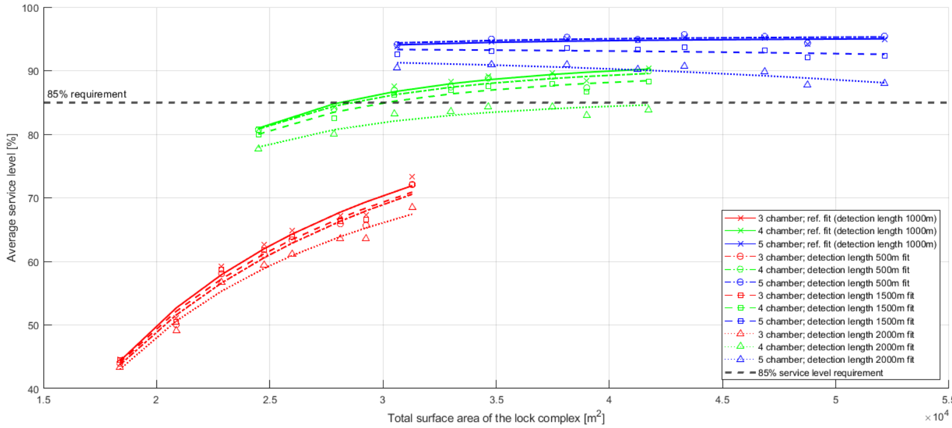

Figure G.7: Average service level for varying detection lengths for model variants at lock complex G11W3

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