Towards Risk-based Prioritisation of Primary Navigation Locks

As an improvement to the existing method used for scheduling renovation work

A. (Arno) Kemper

Technische Universiteit Delft

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by

A. (Arno) Kemper
Student ID: 4017927

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Thesis committee:	Prof. dr. ir. S. N. Jonkman,	Delft University of Technology
	ir. M. van den Boomen,	Delft University of Technology
	Dr. ing. M. Z. Voorendt,	Delft University of Technology
	ir. S. G. van den Berg,	Rijkswaterstaat
	ir. M. B. M. Harmsen,	Rijkswaterstaat

Student's contact: kemper.ao@gmail.com

Rijkswaterstaat
Ministry of Infrastructure and Water Management

Preface

This MSc thesis presents my graduation work in partial fulfilment of the requirements for the Master of Science degree in *Construction Management Engineering* at the *Delft University of Technology*. The topic that is considered is initiated by Rijkswaterstaat, the Dutch executive agency that is part of the Dutch Ministry of Infrastructure and Water Management. This research is started in the viewpoint of the renovation exercise of large infrastructural assets that are scheduled for the coming few decades. The author executed this research work from two perspectives. Primary navigation locks perform two main functions: flood safety and nautical transport. In this research, both functions are investigated to find out the influence of external conditions and how they affect the performance of the navigation lock. This approach is considered to assess whether or not the existing method that is used for the prioritisation of renovation work is sufficient and comprehensive.

I would like to show my gratitude towards the head of the committee, Professor Bas Jonkman (TU Delft) for his insights that guided me during the graduation period. All information and suggestions provided by my university supervisors Martine van den Boomen (TU Delft) and Mark Voorendt (TU Delft) were highly appreciated as they helped me to define the structure of this MSc thesis in a clever and consistent way. I am also very appreciative for the expertise of Jules Verlaan (TU Delft) regarding his broader economic view in this hydraulic field of work. Many thanks to Stefan van den Berg and Manon Harmsen (both Rijkswaterstaat) for their weekly guidance and inspiration as supervisors at the office in Utrecht. Last but not least, I would like to thank all the colleagues at Rijkswaterstaat who provided me with lots of information as well as the small talks we had during lunches and late afternoon drinks.

Heartfelt thanks go out to my family and friends, even if I cannot mention them all here. Special thanks to Attman, for scheduling periods of time to read the complete report, including appendices, on the consistent and proper use of the British tenses and vocabulary. Lastly, but most importantly, I am deeply grateful to my lovely wife Valerie, for unconditionally supporting and encouraging me during the major part of my study and graduation work.

Arno Kemper
Amersfoort, August 2019

Executive Summary

The operation and maintenance of most of the Dutch primary navigation locks are the responsibility of Rijkswaterstaat, the administrative agency of the Dutch Ministry of Infrastructure and Water Management. Primary navigation locks are hydraulic structures that are part of primary flood defences and serve a couple of functions. The two main functions of a navigation lock that are reviewed in this research are the nautical function (levelling vessels) and flood safety function (retaining water to protect hinterland).

The portfolio of Rijkswaterstaat consists of 52 primary navigation locks that are part of the primary flood defence. All these navigation locks are assigned a safety norm together with the adjacent water-retaining bodies. For both main functions, norms and acts are defined that prescribe a certain level of performance. Rijkswaterstaat is responsible that all its primary navigation locks do meet the safety or nautical requirements. The norms regarding flood safety are derived from the probability and impact of flooding that affect the hinterland. For the nautical performance of navigation locks, several acts prescribe requirements regarding availability and capacity of navigation locks, as part of the overall performance of the inland waterway network.

Most of the primary navigation locks are built in the first two decades of the 20th century. In principle, Rijkswaterstaat considers a functional lifetime of their navigation locks, equal to 100 years. A number of these navigation locks are technically modified to extend the functional lifetime. In the coming decades, many of these navigation locks have to be renovated in order to meet new norms or requirements. It might that not all the renovation work can be executed in the same period of time. Therefore, the works have to be scheduled and given a priority when they will be renovated. In the existing method, the ”Vervanging&Renovatie” (V&R) prioritisation, one indicator is considered that entails the remaining lifetime as a function of the design lifetime, according to the principle: ”first come, first served”. In this research, a more comprehensive prioritisation method is developed.

A risk analysis is conducted regarding the flood safety and nautical requirements of navigation locks. These requirements are derived from Dutch legislation (Water Act and Mobility Act). Given the requirements for the flood safety and nautical function, three drivers are defined that affect these functions: climate change, intensity growth, and ageing of material. For these drivers, a number of aspects are distinguished that affect either the flood safety or nautical function. For the flood safety function, the aspects piping, storage capacity and overflow capacity, are selected. These aspects are based on the potential failure mechanisms of navigation locks. For the nautical function, the aspects related to the unavailability as a result of water level fluctuations, maintenance, and technical failure as well as the intensity growth, are considered. The combination of aspects is framed in a method that can be used to assess the urgency of renovation, relative to the norms that are linked to the aspects. For each aspect, it is assessed at what moment in time the norm is exceeded. This result is compared to the existing V&R prioritisation of renovation works. Given both methods, it can be concluded whether or not the proposed moment of renovation is according to the required moment of renovation, to safeguard the nautical and flood safety functions.

To validate the proposed method of prioritisation, two case studies are conducted. One of them is the coastal Terneuzen navigation lock complex and the other one is the Prinses Beatrix navigation lock complex in the waterway Lek. For both complexes, the levelling capacity increases in the near future as result of new lock chambers. This capacity increase is considered in the assessment of the expected intensity growth. The main conclusion of the case studies is that the existing method of prioritising the renovation work of primary

navigation locks is not optimal. A number of aspects, as these are assessed in the case study, indicate that the required moment of renovation is before the moment according to the V&R prioritisation. This conclusion is based on the expected performance in the (near) future relative to the required performance that follows from legislation. Some aspects of the proposed prioritisation method show deviations of up to 40 years relative to the V&R prioritisation (e.g. technical failure). Furthermore, considering the increased levelling capacity of both navigation lock complexes, a capacity shortage is expected again in 2040. This is 15 and 30 years prior to the moment of renovation, as defined in the V&R prioritisation for the Prinses Beatrix and Terneuzen navigation lock complexes, respectively.

Apart from the assessment of the aspects based on the norms, a criticality assessment is conducted. For all aspects as defined in the prioritisation method, the effect of a ”postponed” moment of renovation is balanced with a proposed mitigation measure. This is done with the use of a modified FMECA. It is assumed that the mitigation measure reduces the likelihood of occurrence of the aspect to zero. The costs that are the result of a mitigation measure are compared with the costs of ”doing nothing”. This implies that the consequences of a postponed renovation are expressed in financial terms, in order to balance this with the mitigation measure. In this way, the results of the case studies are financially weighted, independent of whether or not they serve the nautical function or the flood safety function.

This research shows that the proposed prioritisation method for renovation works gives more insight into the priority of scheduling navigation locks for renovation than the existing V&R prioritisation.

Contents

1

Introduction

In this chapter, the functions and requirements of navigation locks in the Netherlands are explained, together with the urgency of renovation regarding the performance of these hydraulic structures in the coming decades. The chapter ends with the research objective and the method applied, together with the outline of the report.

1.1. Navigation locks in the Netherlands

The Netherlands is the second-most densely populated country in Europe and takes the 30th position in the worldwide ranking (Eurostat, 2017). One of the reasons for this phenomenon is the competitive economy of this nation; 26% of whose landmass is situated below sea level. The basis for a competitive economy can be explained by the governmental macro-economic policy and the well-designed and functional infrastructure (ANP, Business Insider Nederland, 2017). A part of the total infrastructure consists of waterways and ports, used for national and international trade. Navigation towards ports and/or via the waterways with different water levels is possible by the use of navigation locks. These navigation locks keep the waterways navigable and accessible. But they have physical limitations regarding the dimensions of vessels.

For centuries, the use of vessels in the Dutch transport sector is the preferred way of transferring a large amount of cargo. The two most important reasons for this fact are the cost-effectiveness of inland waterway transport and the presence of many waterways in the country. Numerous cities are accessible via these waterways by either sea or waterway classified vessels. Due to the geographical situation of this low-lying country, navigation locks are required to keep the waterways navigable (Vrijburcht et al., 2000). To safeguard the future performance of the navigation locks according to norms and regulations, renovation is required. The urgency of renovation follows from the (increasing) risk of failure over time, as a result of autonomous developments (climate change) and economic prosperity.

1.2. Research Motivation

Rijkswaterstaat (RWS) is the administrative agency of the Dutch Ministry of Infrastructure and Water Management. It manages the operation and maintenance of the majority of Dutch navigation locks. A part of the total number of navigation locks is situated in the main network of waterway infrastructure (Dutch: Hoofdvaarwegennetwerk, HVWN). Most of these navigation locks are constructed a century ago for a design lifetime of one hundred years (Vrijburcht et al., 2000). To safeguard the performance of the main functions of these objects, renovation is needed in the coming decades. In 2016, an inventory on navigation lock renovation is executed as part of the Replacement and Renovation programme (Dutch: Vervanging & Renovatie, V&R). As a result of this programme, Rijkswaterstaat prioritised the urgency of navigation lock renovation. The design lifetime and remaining functional lifetime form the basis for the prioritisation. This information is already used in many reports and documents (Van Erp, T.M.J., and Van Corven, T.A.W., 2017) and is defined as the starting point for the planning and execution of the renovation programme at Rijkswaterstaat. Figure 1.1 presents the locations of the navigation locks that have to be renovated. From these figures, it can be seen that the division of renovation work is not equally distributed over the years. In particular, the Maas corridor has many navigation lock complexes that have to be renovated in the coming two decades.

In this existing prioritisation, the design lifetime is used as an indicator for the expected moment of renovation. For a number of navigation locks, this design lifetime is extended to a period >100 years as a result of intermediate modifications. Other relevant aspects that affect the main functions of a navigation lock (levelling vessels and flood safety), that can influence the probability of failure of the object, are not considered. In this research, it is investigated which relevant aspects influence the performance of navigation locks. The goal is to provide the asset manager insight and knowledge about the impact of a risk-based approach on multiple aspects. This makes the actual prioritisation of renovation work more sophisticated and efficient relative to the actual procedure.

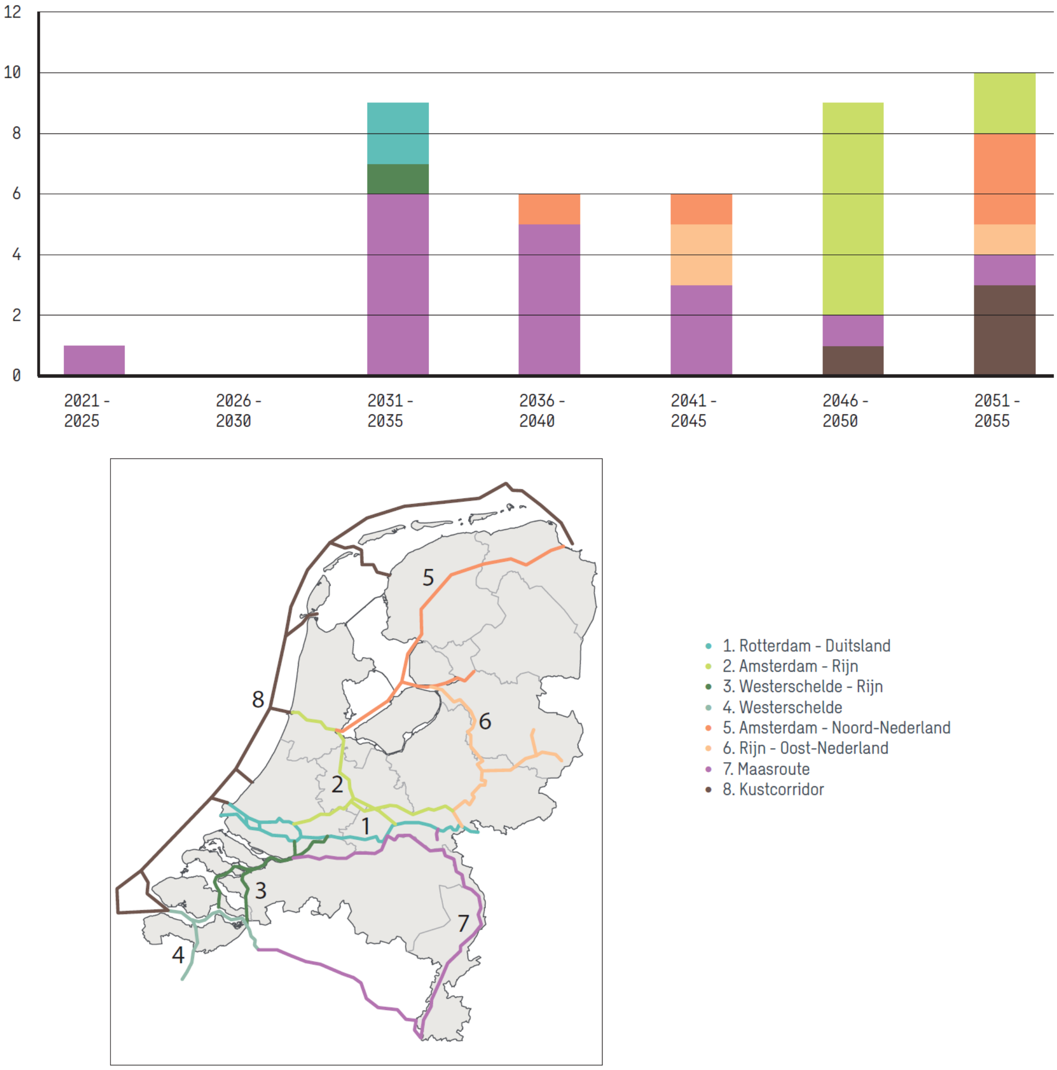


Figure 1.1: Navigation locks that have to be renovated in the coming four decades, based on ending design lifetime, divided over the HVWN corridors (source: Sluizenboekje 2017, edited)

1.3. Dutch Primary Navigation Locks

This section gives an introduction to the definition of primary navigation locks in the Netherlands. It elaborates on the main functions and the main requirements of the primary navigation locks. Throughout the report, these main functions form the foundation of the assessment.

1.3.1. Definition and functions of primary navigation locks

Primary navigation locks are part of the primary flood defence. Next to the primary navigation locks, there are regional navigation locks that are part of regional flood defences. A regional flood defence is either a ”wet or dry civil structure” that is identified in a provincial decree. The regional flood defences are in addition differentiated in four divisions (Rijkswaterstaat WVL, 2017). The primary flood defences are located along the sea coast, a major river, or lake that provide protection for areas that are highly vulnerable, as regards potential fatalities and/or economic damage (Rijkswaterstaat WVL, 2017). The reason for focusing on the primary navigation locks is related to their importance regarding flood protection and nautical function. All the primary navigation locks are managed by Rijkswaterstaat.

Primary navigation locks have two main functions. The first one is the nautical function by levelling vessels that are sailing from upstream to downstream or vice-verse. The second main function is safeguarding the flood safety of the hinterland. In this research, the aspects that are examined are related to either one or both of the main functions. Besides the main functions of primary navigation locks, there are a number of secondary functions. A hydraulic function, that gets more and more attention nowadays, is the separation of fresh inner water and the salt outer water, which should be minimised from the viewpoint of salt intrusion and the resulting ecological impact. Another secondary function is the non-nautical passage that reflects (non-)motorised traffic that can be either integrated into a multifunctional hydraulic structure (in case the gates are part of a road connection) or external (by an additional bridge that crosses the lock chamber). Facilitating the users of the navigation lock by means of control devices (lights, cables, and pipes) is another secondary function. Finally, recreation in the surrounding area of the navigation lock (e.g. a harbour that is accessible by means of that navigation lock) is a navigation lock function as well. An overview of the proposed main functions and secondary functions is presented in Figure 1.2. As stated before, the focus of this research will be on the two main functions: the nautical function and the flood safety function.

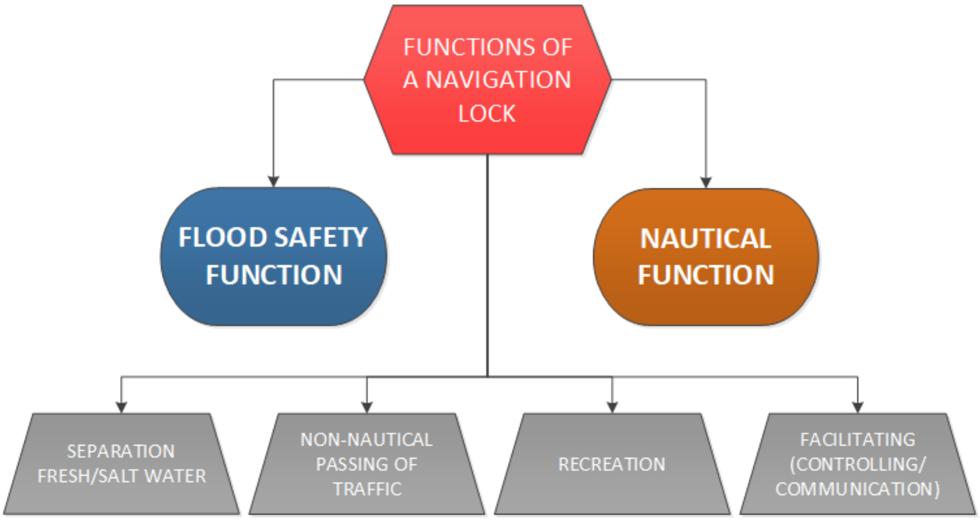


Figure 1.2: Functions of a navigation lock, the two main functions in the middle and the secondary functions at the bottom

1.3.2. Requirements of primary navigation locks

The requirements of a navigation lock are linked to the two main functions of hydraulic the structure as defined in this report: nautical and flood safety (Figure 1.2). The flood safety function can fail in case that one of the failure mechanisms occur. The guidelines for designing water-retaining hydraulic structures define five failure mechanisms (WVL Waterkeringen, 2018):

- Overflow
- Non-closure
- Piping
- Structural failure
- Failure of transition zone

The non-closure failure mechanism consists of two underlying sub-events These sub-events are: non-closure (technical or human influence) and failure due to an overload of water, as a result of exceeding the storage capacity. Therefore, the storage capacity, as a driver for potential non-closure, is assumed as an important requirement for the flood safety function. Structural failure has partial similar drivers that might result in failure (e.g. insufficient storage capacity, resulting in higher loading conditions that give failure of structural elements). Failure of the transition zone is primarily driven by erosion (WVL Waterkeringen, 2018). Summarised, the blue failure mechanisms, as defined in Figure 1.3, are considered in the method and assessed in the case studies. Nevertheless, additional research is advised to check the influence of the other failure mechanisms on the flood safety function.

The requirements for the nautical function follow from national and European mobility acts. Increasing probabilities of extreme natural boundary conditions, economic growth, and ageing of material are the main contributors that result in either unavailability or capacity shortage. The norms that are defined for the failure mechanisms are derived from the Water Act. The contribution of each failure mechanism is limited to a predefined percentage of the flooding probability norm, as defined in the WBI2017. The total contribution is often summarised in a ”failure probability budget” (*faalkansbegroting*). Legislation and risk drivers that affect the functions of navigation locks are further analysed in the next chapter.

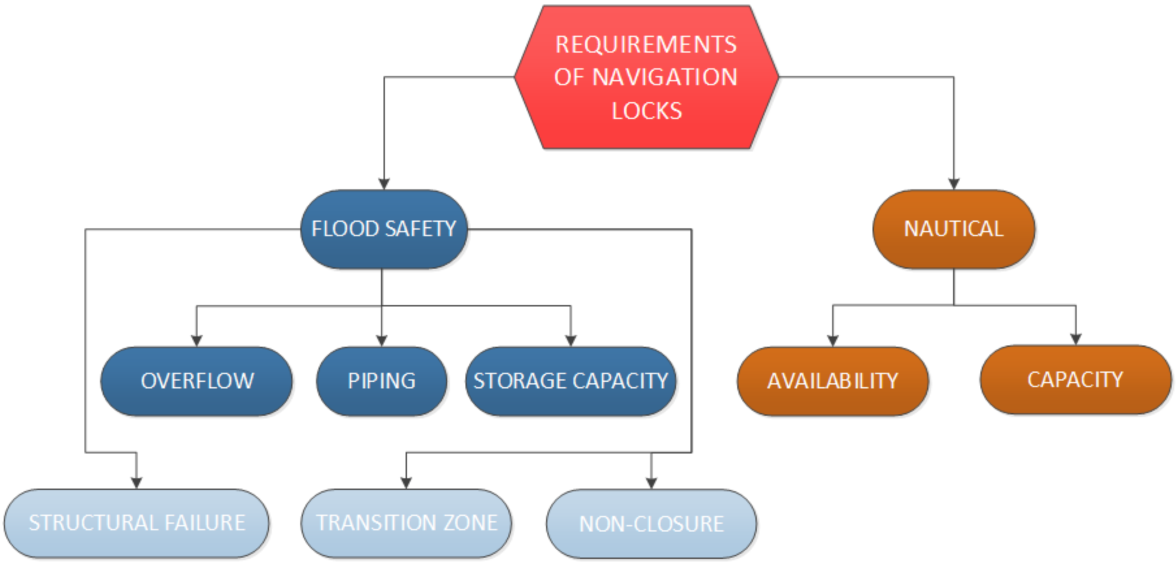


Figure 1.3: Overview of the main requirements (blue and orange) for which norms are derived that affect one of the main functions (the failure mechanisms shown in lightblue are not considered in this research)

1.4. Problem, Research Objective, and Research Method

This section outlines the problem definition of this research, the research objective, and the research method that will be followed, in order to answer the objective of the report.

1.4.1. Problem description

The majority of the Dutch primary navigation locks are constructed during the ’30s of the last century (Rijkswaterstaat, 2017). In the coming four decades, most of these navigation locks will reach the end of their functional lifetime. Rijkswaterstaat has investigated, based on the information of the V&R programme, which primary navigation locks must be renovated, based on the standard design lifetime and the remaining functional lifetime. The influence of other aspects regarding the performance of the main functions of a navigation lock is not considered. This might result in unnecessary flood safety issues or nautical hindrance/economic damage in the near future. Assessing the performance of navigation locks on multiple relevant aspects might make the existing approach for prioritising the renovation work more holistic.

Hereafter, the problem definition of the MSc thesis can be stated as:

”The present method used for the prioritisation of primary navigation locks’ renovation is only based on their design lifetime. This approach might lead to unnecessary flood risk or unnecessary nautical obstruction before the scheduled replacement.”

1.4.2. Research objective

The research objective is to determine which relevant aspects, apart from the design lifetime, give rise to the need of renovation for primary navigation locks, in order to safeguard the functional and technical performance up to the standards. The aspects will be combined which will provide the asset manager with a method for the assessment of all primary navigation locks, in order to make a substantial prioritisation of the required renovation. This method will be applied to two case studies, and is followed up by a criticality assessment. In this assessment, the outcome of the case studies with potential mitigating measures and costs are evaluated. This enables the asset manager to make decisions for renovations that are based on both performance and economic considerations.

Summarised, the research objective of this MSc thesis is defined as:

”Determine relevant aspects that are an indicator of the urgency of renovation, in order to get an insight into the nautical and flood safety performance of navigation locks over time. The relevant aspects are combined in a method that enables the asset manager to conduct risk-based and comprehensive prioritisation of renovation work.”

Existing legislation for both the flood safety and nautical function is the basis for this research. For the case studies, norms and requirements derived from legislation are used to define the performance of the navigation lock. Governance aspects, other than the legislation applicable to the two main functions, are not part of the objective.

1.4.3. Research method

The research method that is used in this report is a desk study. To obtain insights into the relevant aspects, a number of interviews will be performed with asset managers and hydraulic engineers in the field that deal with these objects in their daily work. The input from these interviews is used throughout the report. To safeguard the scientific approach, verification of the method is achieved by applying the method to two case studies. The navigation lock complexes Terneuzen (coastal navigation lock) and Prinses Beatrix (inland navigation lock) are used as cases.

Thus, verification is part of the design of a prioritisation method. The research objective is translated into five research questions:

1. What types of risk exist for navigation locks and how are these linked to legislation regarding the flood safety and nautical function of the objects?
2. Is it possible to combine legislation and requirements of primary navigation locks with risk drivers that change in the future, and can these be framed in a method to identify the urgency of a renovation?
3. What are the requirements for the flood safety function of a navigation lock, how are they affected by the boundary conditions, and how can they be assessed?
4. What are the requirements for the nautical function of a navigation lock, how are they affected by the boundary conditions, and how can they be assessed?
5. Do the case studies, that are combined with a criticality assessment, prove that risk-based prioritisation is preferred over the actual V&R prioritisation?

The answers to the research questions enable the author to formulate the answer on the research objective. The first research question is answered by investigating how the Dutch Water Act and the transport sector is regulated via norms and standards. Based on these findings, in combination with the requirements that primary navigation locks have to fulfil, it is investigated what changing boundary conditions can be expected. The next step is formulating a number of aspects, that are affected by the boundary conditions, which are given a norm or standard as found in the first research question. The method consists of the combination of all aspects that must be assessed to obtain an insight into the performance and urgency of renovation. To answer research questions three and four, the background and implication of the norms and standards for both the flood safety and nautical function are defined. The fifth research question is answered by conducting two case studies in combination with a criticality assessment, that acts as a verification of the method and demonstrates the effectiveness of a more comprehensive prioritisation method.

1.5. Outline of This Research

The report outline is in analogy with the research questions.

Chapter two of this report defines the principle of risk in civil engineering and how it is related to legislation applicable to navigation locks. The boundary conditions, that have an influence on the requirements, are defined and aspects are derived from them. Given the aspects, a preliminary prioritisation method is developed for which norms have to be identified in the next two chapters.

Chapters three and four focus on the requirements that are defined for the flood safety and nautical function of navigation locks. The norms that hold for the different aspects are defined, which are subsequently applied in the assessment of the case studies in chapter five.

Chapter five and six reflect on the case studies. First, the two cases are assessed on their present and future performance and reviewed with their norms. After that, the outcome is reviewed with the prognoses of V&R to find deviations in the renovation year.

In chapter seven, the results of the case studies are used in a criticality assessment. This assessment balances the costs that result from norm exceedance relative to the costs that follow from the application of mitigation measures.

2

Risk and Prioritisation

This chapter reflects on the principle of risk relative to the two main functions of a navigation lock. After reading this chapter, the risk-based method that is considered for a comprehensive prioritisation becomes clearer. Furthermore, an investigation of prioritisation aspects is proposed as they follow from the risk analyses and the requirements navigation locks should meet.

2.1. Risk Assessment in Civil Engineering

In almost all activities in life, a certain level of risk is involved. In particular, in the design and operation phase of engineering projects, risk and safety are the key concepts that must be considered (Jonkman et al., 2016). In the civil engineering industry, the following definition for risk is considered:

Risk = the probability of an undesired event multiplied by the consequences

For civil engineering works, it is common to conduct a risk analysis to identify and evaluate the risks and decide whether these are acceptable. The outcomes of this analysis are either used in the design phase of the project to decide on the system safety level or to support decision-making processes. By quantifying the risks, the safety levels can be transferred towards the technical domain. Overall, it can be stated that the scope of a risk analysis is to support decision-making for activities in which risk is involved (Jonkman et al., 2016). A framework of the steps that have to be considered can be found in Figure 2.1. The foundation of the framework that will be developed for the prioritisation of primary navigation locks is based on risk. Therefore, this chapter presents some background information of what must be considered in a proper risk analysis. From this point, a similar analysis can be followed for the prioritisation as this is based on a risk approach.

There are a number of steps that have to be considered in a risk analysis, as follows from Figure 2.1, which are briefly described here:

1. **System definition:** in this step, the scope and objectives of the analysis are set. The system can be represented in terms of physical components, users, and external environment.

2. **Qualitative analysis:** this step considers potential hazards and undesired events. Insight is gained into all possible events and their consequences. When (part of) a system does not perform its function, it is known as failure which can be reached by one or multiple failure modes. A limit state can be defined as the condition of a structure that is no longer fulfilling the design criteria (Eurocode) on either ultimate limit state (ULS)

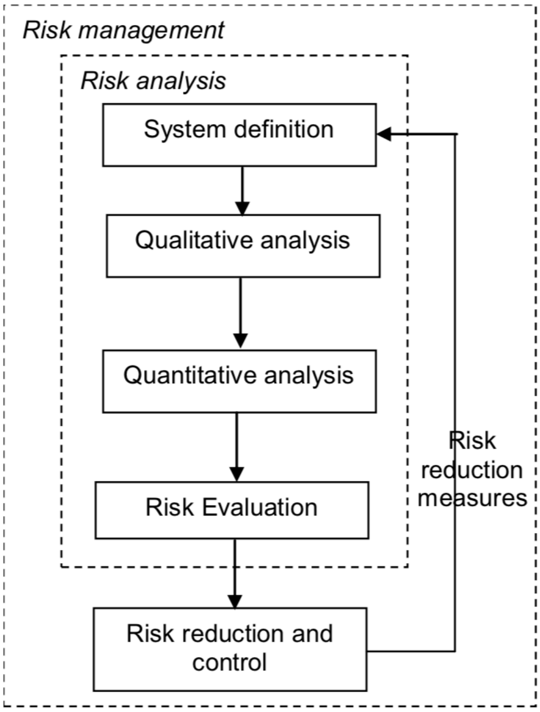


Figure 2.1: Framework of elements to be considered in risk assessment (source: CIE4130, edited)

or serviceability limit state (SLS). Tools like Failure Mode Effect and Criticality Analysis (FMECA) can be of use to systematically identify the undesired events (Chapter 7).

3. **Quantitative analysis:** This step is about defining the probabilities and consequences of the events. For each object, a particular strength and resistance function can be derived from (international) codes. A limit state function can be formulated as follows:

$$Z = R - S \tag{2.1}$$

$$P_f = P(R < S) = P(Z < 0) \tag{2.2}$$

   - R = Resistance of object
   - S = Loading of object
   - Z = Limit state function
   - P_f = Failure probability

   On the basis of this function, Figure 2.2 can be constructed in which function Z is the result of the resistance minus the strength. This limit state function forms the basis of a risk assessment and is adapted to fit the method that is developed in this report.

4. **Risk evaluation:** This evaluation phase contains the decision on the risk acceptance level and whether risk reduction measures need to be implemented. This comes with the comparison between the actual risk and the acceptable risk. Regarding the risk reduction measures, different quantitative approaches can be considered (decision-making

under uncertainties, cost-benefit analysis with economic optimisation, and safety standards).

5. **Risk reduction and risk control:** In case the risks are considered as unacceptable, several reduction measures can be opted for. It can be either on the organisational aspect or on the changes in engineering systems.

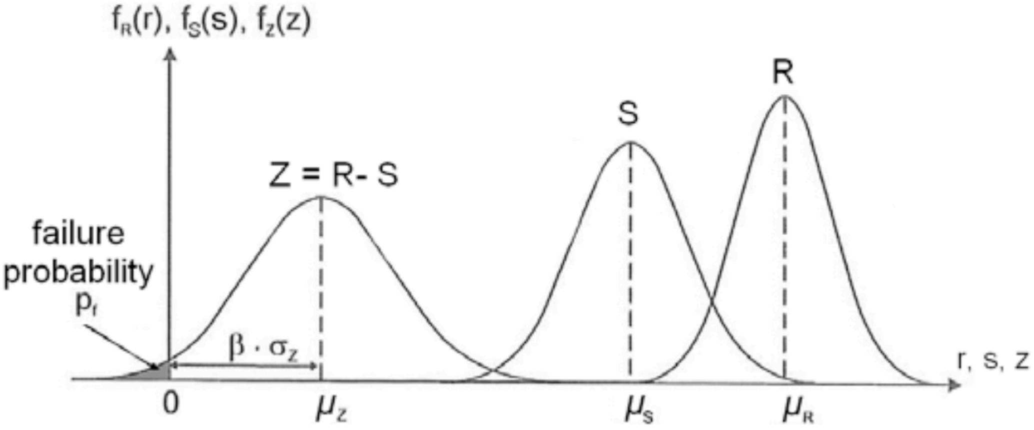


Figure 2.2: Limit state function in relation to strength and resistance distributions (source: Voorendt, 2017)

In this research, the focus is on conducting a combination of a quantitative and qualitative risk analysis. First, aspects are defined that follow from economic prosperity or changing natural boundary conditions. From that point, the aspects are used during the assessment of the case studies. The outcome of the case studies is used for a criticality assessment. In this way, the consequences of the aspects are quantified and balanced against each other. Potential mitigating measures are opted that reduce the consequences of the aspects to zero. For example, the construction of a retention basin reduce the downtime of the nautical function, due to high upstream water levels, to zero. Given the costs of the consequences of the aspects over time, relative to the costs of a mitigation measure, the asset manager is able to take a deliberate decision.

2.2. Types of Risk

There are multiple types of risk hydraulic structures are prone to. In this research, risk relative to the performance of the nautical and flood safety function is considered. In the following sections, the definition and implication of risk are described regarding flooding and nautical hindrance.

2.2.1. Flooding

In 1953, the North Sea flood resulted in 1836 fatalities and major property damage. Since that moment, plans and regulations are developed to minimise the probability of a similar future event. Under the supervision of the Dutch Ministry of Infrastructure and Water Management, a Delta Committee was founded. This committee is responsible for the national flood protection policy. Rijkswaterstaat, as a public works agency, is responsible for the implementation of the policies of the Delta Committee.

From a probabilistic point of view, the technical end-of-life phase, on which the current prioritisation of V&R is based, is founded on the exponential increase of the failure probability. In this way, failure can be defined as a state in which the system does not fulfil its functional requirements (Huibregtse et al., 2016). Altering hydraulic boundary conditions result in an increase in the probability of failure. The so-called bathtub curve is still considered for the renovation of the navigation locks. According to this principle, assuming a design lifetime of 100 years, the failure probability after 100 years is considered as unacceptable. Therefore, renovation is required to decrease the probability of failure and, therefore, reduce the risk of flooding. The navigation locks that are part of the V&R renovation programme are all located at the upper right end of the graph in Figure 2.3 (Expertise Network for Flood Protection (ENW), 2017).

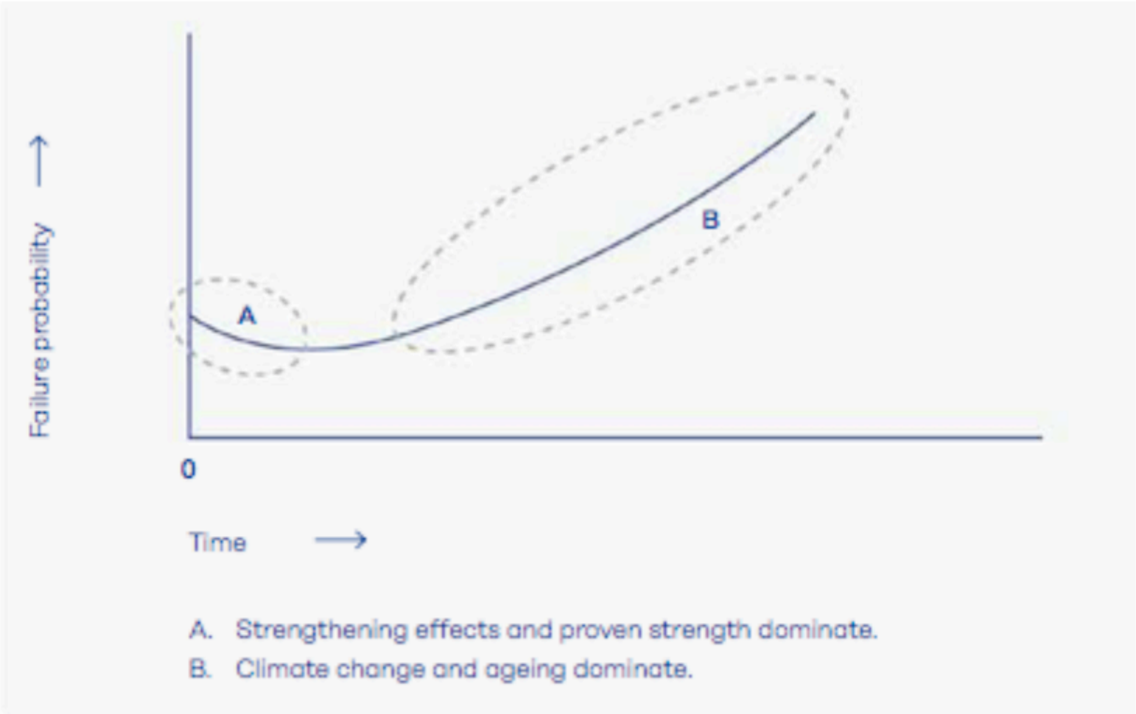


Figure 2.3: Bathtub curve with variety scattered around the average (source: ENW, 2017)

2.2.2. Nautical hindrance

The risk of nautical hindrance affects the economic position of the Netherlands. The Department of Traffic and Nautical Information (DVS) at Rijkswaterstaat uses different methods to assess the nautical performance of navigation locks. The national government defines requirements in their Mobility Act for all types of transport regarding their performance. The performance is defined in Service Level Agreements (SLA). The SLAs define a level of availability of the levelling function. This availability is based on the operational hours of a navigation lock. This is not equal to the total time per year (=8760 hours). The downtime is defined as the product of the unavailability times the total time per year (Equation 2.4). The SLA for primary navigation locks is set at 98% availability of the operational hours (OH) (Equation 2.5)

> Rijkswaterstaat calculates the availability of the nautical function in a different way than proposed in this research. It might be that an asset manager considers a low Operational Hours (OH) value, resulting in a high availability of the navigation lock, in some situations even more than 100% (Sluizenboekje, 2018). In this research, the nautical hindrance is linked to the SLA requirement for availability, to determine whether or not the navigation lock is performing its nautical function.

$$OH = operational\ hours\ = hours\ per\ year\ that\ levelling\ function\ is\ active \tag{2.3}$$

$$SLA = 98\%\ OH \tag{2.4}$$

$$Unavailability_{requirement} = 1 - SLA = 2\%\ OH \tag{2.5}$$

$$Unavailability = Number\ of\ hours\ that\ levelling\ function\ is\ interrupted \tag{2.6}$$

Example of inconsistent measuring availability

Consider a navigation lock that has 8500 operational hours (OH) per year. Assume that climate change and ageing contribute together to a total downtime of 210 hours per year. The SLA requires 98% of OH, which implies an availability for the levelling function of (0.98*8500=) 8330 hours per year. The non-operational hours are equal to (8760-8330=) 430 hours per year. According to the SLA, the unavailability is limited to a maximum downtime of (0.02*8500=) 170 hours per year. However, the non-operational hours are 430 hours per year. From this point, the availability is often defined as:

$$Availability = \frac{8760 - 210}{8330} = 1.026 = 102.6\ \% \tag{2.7}$$

Obviously, this calculated availability is inconsistent as the hours that the navigation lock is not operational (430-170 = 260 hours per year) are indirectly also considered as operational hours.

There are a number of drivers that affect the unavailability of the nautical function. This can be either related to changing natural boundary conditions or the process of ageing material.

Unavailability due to natural boundary conditions
For sea-located navigation locks, the influence of climate change by sea level rise results in more frequent and more extreme natural boundary conditions. It is expected that this frequency will increase in the future. There are limits within a navigation lock performs the nautical function. If this upper or lower limit is exceeded, the levelling function is interrupted which implies unavailability of the navigation lock. From that moment, the navigation lock only acts as a water-retaining structure. For inland navigation locks, it is mainly the discharge variety that leads to unavailability of the complex.

Unavailability due to ageing
Next to the natural boundary conditions, ageing results in a more frequent scheduled maintenance and more frequent technical failures. Both aspects result in a lesser availability of the levelling function.

Intensity growth
As a result of economic prosperity, intensity growth can be expected over time. Given the fact that the capacity of a navigation lock complex is constant, congestion can be expected in the HVWN in the future. The capacity shortage as a function of the intensity is used as an indicator to quantify the intensity growth (section 2.3).

Nautical hindrance is quantified in two ways. First is the quantification of the unavailability of the levelling function due to natural or technical boundary conditions. Second, the intensity growth is defined as a function of the capacity of the complex. Climate change, intensity growth, and ageing are defined as the main drivers.

2.3. Legislation for Dutch Navigation Locks

In the Netherlands, minimum required safety levels, formulated as minimum frequencies of which design water levels are allowed to exceed, are used in practice since 1969. Since 1996, the Flood Defence Act (Dutch: Wet op de Waterkering) was the starting point for a slightly different approach that finally resulted in the development of flood safety levels, which are regulated in the Water Act (Waterwet) since 2009. Next to the safety requirements, there are service level agreements regarding the availability and capacity as a function of the intensity of navigation locks. These three topics are clarified in the sections below.

2.3.1. The Dutch Water Act

According to the Dutch Water Act, flood probability is defined as:

> Flood probability = the probability that a water defence loses the water-retaining function with the consequence that the flood results in fatalities or substantial economic damage

From 2017 onwards, the Water Act is slightly changed. In the past, the norm prescribed the maximum hydraulic load the defence must safely bear (at ULS). Nowadays, for each object, a probabilistic approach will be used that indicates the probability that a defence is ’allowed’ to fail according to the norm (Consortium Droge Voeten door Leren, 2017). For the new assessment of the primary flood defences, these new norms will be implemented. In order to execute the assessment, a legal assessment framework (Dutch: Wettelijk Beoordelingsinstrumentarium, WBI) is being developed.

2.3.2. Assessment Framework Legislation (WBI2017)

Since 2017, a new legal assessment framework is introduced which derives from the ’Safe Delta in 2050’ plan that is defined in the Delta Programme 2018 (Deltacommissie, 2017). The legal assessment framework prescribes regulations for assessing the primary flood defences. Asset managers of primary flood defences should review whether their assets meet the safety standards as laid down in the Dutch Water Act. Since 2017, new safety standards (Dutch: Veiligheidsnormering) came into force, evolving out of the VNK2 approach that was used before (Rijkswaterstaat WVL, 2017). An overview of the legal assessment framework is depicted in Figure 2.4. The effect of this new WBI assessment will affect the need for renovating hydraulic structures as a number of the objects do have to meet new safety standards.

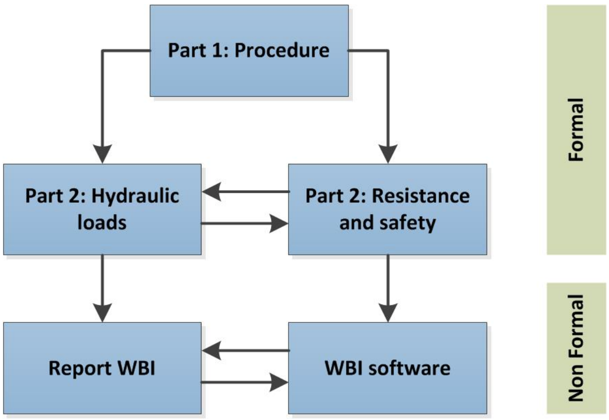


Figure 2.4: Overview of the WBI2017 system

2.3.3. Nautical requirements

Potential shortage of capacity as a result of increasing intensity of navigation lock usage can be preliminary used as a selection criterion to consider a renovation. This intensity/capacity (I/C) ratio is a measure for potential congestion issues in the (near) future that can influence other navigation locks in the corridor as well (cascade effect). An impression of this I/C ratio as a function of transit time for an arbitrary navigation lock is depicted in Figure 2.5. Dutch regulations prescribe a maximum limit I/C_{max}=0.5 as an indicator for capacity shortage (Koedijk and van der Sluijs, 2017). The waiting time exponentially increases from the moment that I/C is 0.5, as a result of increasing numbers of delay vessels. These delay vessels are defined as vessels that will not be levelled in the upcoming levelling process cycle. An additional levelling process cycle takes on average 45 minutes. The average total waiting time is, therefore, often exceeded, based on the NoMo (Mobility Act) norm of 30 minutes.

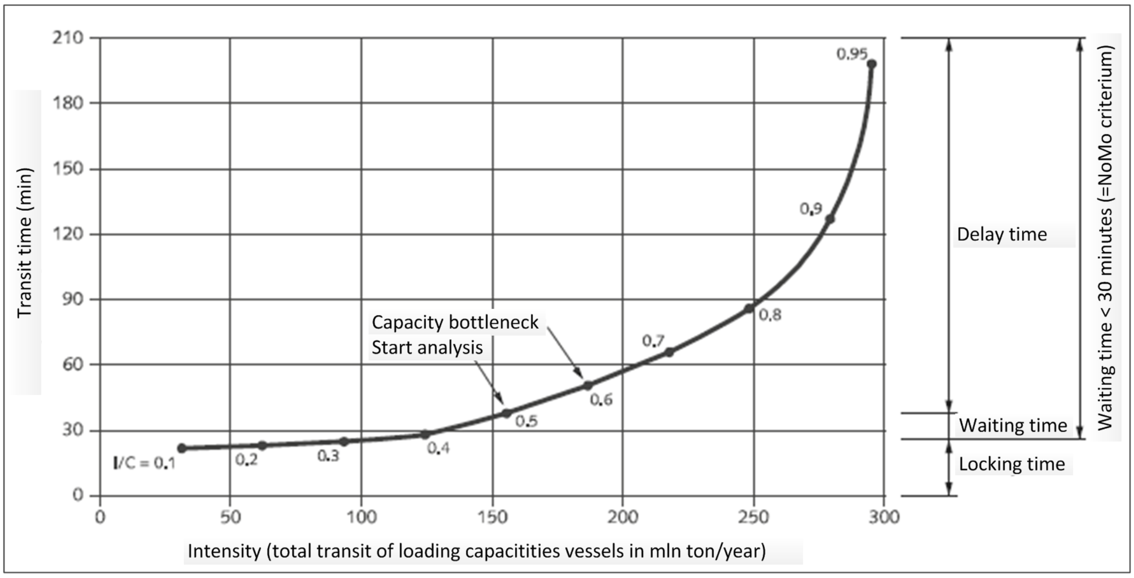


Figure 2.5: I/C ratio as a function of the transit time (source: Richtlijnen Vaarwegen 2017, edited)

Reliability of the total travel time is of importance for the nautical industry, in particular for liner services. Scheduling these services is based on the probability of higher transit times at navigation locks. Dutch policy prescribes a 90% value of the transit time as a reference for the reliability of a navigation lock (Koedijk and van der Sluijs, 2017). This value is an indicator in which 90% of the total number of vessels can transfer the navigation lock within the denoted transit time. This number is dependent on the I/C ratio; the larger this ratio, the longer the transit time (Table 2.1).

Table 2.1: Reliability of transit time at navigation locks, time in minutes (source: Richtlijnen Vaarwegen 2017)

I/C ratio	**Average $T_{transit}$**	**90%-value rel. to average $T_{transit}$**	**90%-value of $T_{transit}$**
0.3	25	1.5	38
0.4	30	1.6	48
0.5	45	1.7	77
0.6	60	1.8	108
0.7	80	1.9	152
0.8	125	2.0	250
0.9	235	2.1	494

2.4. Risk Drivers

There are a number of drivers that will change in the future, which affect the functions of a primary navigation lock. In Section 2.2, it is stated that risk in this research is related to one or both of the main functions of navigation locks: nautical and flood safety. For this reason, the risk drivers selected here follow from the impact they have on the performance of one of the main functions. Each driver contains a few aspects that will be given a norm or a requirement, and are used in the assessment of the two case studies. Definitions of the aspects are defined in Section 2.4.4.

The focus of this research is based on the two main functions of primary navigation locks: the nautical function and the flood safety function. The aspects related to flood safety are presented in blue (I-III) and will be assessed on the legislation of the Water Act. The nautical aspects (IV-XII) are indicated in orange and are assessed on the requirements of the Mobility Act.

2.4.1. Climate change

In this research, the effect of climate change due to sea level rise and discharge variety is considered. Based on the two main functions of a primary navigation lock, a number of aspects are distinguished. The blue aspects (I-III) are assessed on the flood safety function, and the orange aspects (IV-XI) on the nautical function.

- **I Piping**
- **II Storage capacity**
- **III Overflow resistance**
- **IV Unavailability due to high upstream water level**
- **V Unavailability due to low upstream water level**
- **VI Unavailability due to high downstream water level**
- **VII Unavailability due to low downstream water level**

2.4.2. Intensity and capacity

For the intensity as a function of the capacity, the I/C ratio is used (section 2.3.3). The intensity of nautical traffic is a function of the number of vessels with their corresponding length. Based on previous research, two different moments of time are defined after which the aspects are named:

- **VIII I/C economy 2015**
- **IX I/C economy 2040**

2.4.3. Ageing

Ageing is an important driver that affects the unavailability as a result of scheduled maintenance and technical failure. Therefore, these two aspects are defined in the method.

- **X Unavailability due to scheduled maintenance**
- **XI Unavailability due to technical failure**

2.4.4. Explanation of aspects

Each aspect that is used in one of the risk drivers in the previous section, is clarified below. The downstream water level for coastal navigation locks is located at the sea side of the complex. The unavailability of this type of navigation lock, due to downstream water level conditions, is driven by the semi-diurnal tidal character of the North Sea.

(I) **Piping**
Piping is the process in which water flows under the concrete structure as a result of large water head differences. This results in the transport of soil material that affects the structural integrity of the navigation lock. This process is location-dependent as soil characteristics are dominant.

(II) **Storage capacity**
The total volume of water that can be stored in the waterway behind the navigation lock, in the absence of overflow of adjacent embankments or hydraulic structures.

(III) **Overflow resistance**
The volume of water that flows over the hydraulic structure per metre width per second. This may result in erosion in the adjacent area of the navigation lock complex that hampers the structural integrity and, therefore, increases the risk of failure.

(IV) **Unavailability due to high upstream water level**
For high upstream water conditions, the levelling function will be interrupted for flood safety reasons. This affects the availability of the operational hours.

(V) **Unavailability due to low upstream water level**
For low upstream water conditions, the levelling function will be interrupted for environmental reasons (salt intrusion). This affects the availability of the operational hours.

(VI) **Unavailability due to high downstream water level**
For high downstream water conditions, the levelling function will be interrupted for flood safety reasons. This affects the availability of the operational hours.

(VII) **Unavailability due to low downstream water level**
For low downstream water conditions, the levelling function will be interrupted for flood safety reasons. This affects the availability of the operational hours.

(VIII) **I/C economy 2015**
The ratio of the intensity (the number of vessels that call at a navigation lock) as a function of the capacity (the number of vessels a navigation lock can handle) in 2015.

(IX) **I/C economy 2040**
Similar to I/C economy 2015, however the reference year is now set to 2040.

(X) **Unavailability due to scheduled maintenance**
The annual number of hours reserved for maintenance that results in a limitation of the levelling function.

(XI) **Unavailability due to technical failure**
The annual number of hours in which a technical failure occurs that results in a limitation of the levelling function.

2.5. Prioritisation Method

In the research motivation of this report (section 1.2), the urgency for prioritising renovation work is defined. Not all the renovation work can be executed at the same moment in time. Therefore, Rijkswaterstaat has to make decisions which ones are the first in line. Adequate performance of the assets' main functions is normative in the prioritisation process. The definition of prioritisation of primary navigation locks in this research is defined as:

Prioritisation = the action or process of deciding the relative importance or urgency of things

Based on the risk drivers that affect the function of a navigation lock, a risk-based prioritisation method is developed. Application of this method results in quantitative output that indicates the urgency of renovation. The aspects that follow from the drivers are assessed and reviewed on legislation and performance requirements.

The time horizon that is considered in this research is 2100. The reliability of estimations decreases over time. Therefore, a longer time horizon is considered as ineffective.

Initialising Prioritisation Method

The aspects as defined in section 2.4 affect the performance of a navigation lock. The goal of the method is to identify at what moment in time, the aspects do not meet the performance requirements. The year that this occurs, is normative for the urgency of renovation. The requirements follow from the Mobility Act or Water Act. An overview of the method is depicted in Figure 2.6. In this figure, the differences between the existing method (left side) and the proposed method (right side), used for prioritising renovation work, can be seen.

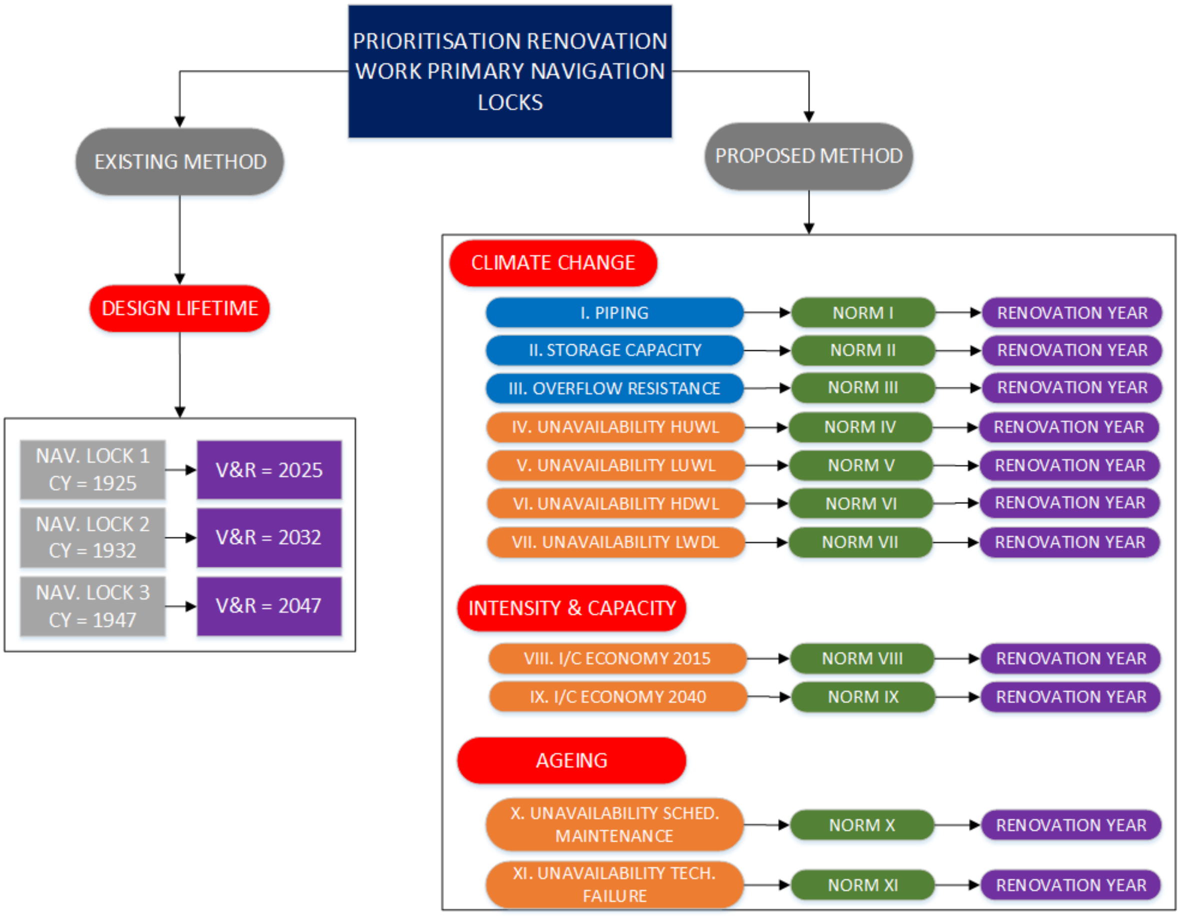


Figure 2.6: Comparison of the existing prioritisation method (left) and the proposed method (right) for the urgency of renovating navigation locks

3

Flood Safety Analysis

This chapter reflects on the second research question, focusing on the driver climate change, and how this affects the first three aspects of the prioritisation method. It gives clarification of the aspects and the assessment criteria are researched, according to the WBI2017 method.

3.1. Climate Change and National Scenarios

The effects of climate change become more and more visible. This is in line with the conclusions of studies, executed by national and international organisations. In daily life, the increase of intense rain showers results in more occurrences of local floods. On the other hand, periods of drought lead to water management issues that affect society. The impact of climate change on the flood safety function of navigation locks results in more extreme loading conditions. This has an effect on the failure mechanisms of a hydraulic structure.

Variations in extreme weather conditions, ocean circulation, sea level rise, and snow/ice declination is investigated by the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change (IPCC), 2013). Based on these reports, in combination with analyses conducted in the Netherlands, a number of climate scenarios are developed. Based on these scenarios, policies are defined. The latest climate models are published in 2015, called the KNMI'14 scenarios, conducted by the Royal Netherlands Meteorological Institute (KNMI). These scenarios are an update of the 2006-issued models (KNMI'06) and are illustrated in Figure 3.1.

The four scenarios (Figure 3.1) are based on the global temperature rise and the changes in air circulation pattern. The global temperature rise is defined as either Moderate (G) or Hot (W). The air circulation pattern can have a low (L) or high (H) value. Together, they span a total of four possible scenarios. The four possible scenarios are considered for two different time horizons: in 2050 and 2100. In this research, the W_H scenario is considered for the case studies.

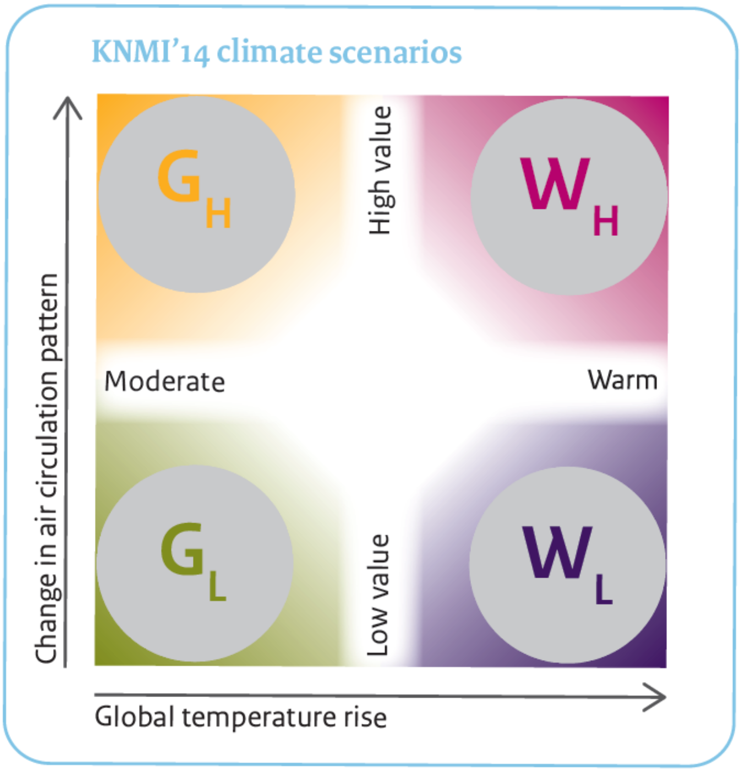


Figure 3.1: Four new scenarios for future climate change in the Netherlands (source: KNMI)

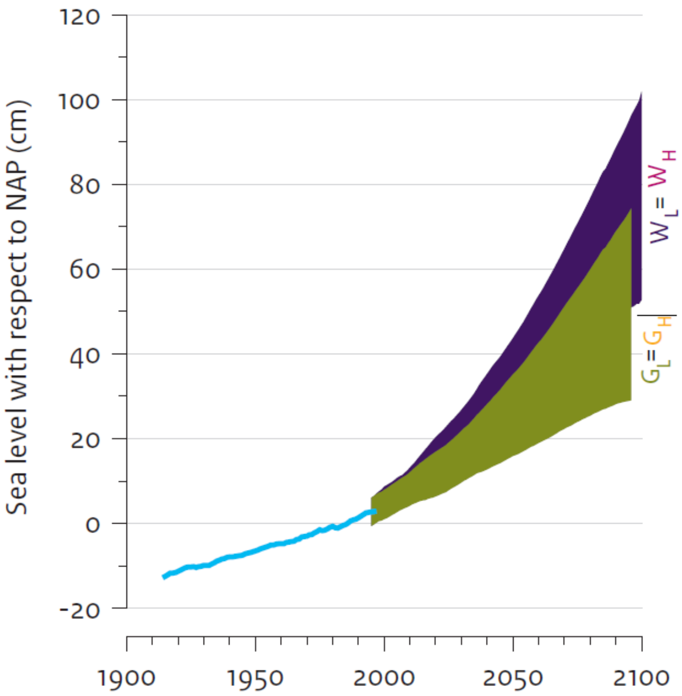


Figure 3.2: Observed sea level rise in blue and prognosis for sea lever rise (source: KNMI)

Sea level rise

The expected sea level rise along the Dutch coast in the KNMI scenarios is based on a few parameters: ocean expansions due to salinity, temperature and mass changes, as well as effects of gravitational variety over the globe due to unequal distribution of meltwater. On the contrary, land subsidence as a result of peat compaction is not included as it varies widely and estimates are unreliable or inconsistent. In this research, the W_H=W+ climate scenario is considered. This implies a sea level rise of 0.85m at the Dutch coast in 2100 (Figure 3.2).

For the assessment of the case studies, the W+ climate scenario is considered which implies a sea level rise of 0.85m at the coast in 2100. In the case study, this value is used for the Terneuzen navigation lock complex. For the inland Prinses Beatrix navigation lock complex, the influence of sea level rise is neglected as discharge variety is dominant at the location. The influence of discharge variety is further analysed in section 4.1.

3.2. Flood Safety Aspects

The aspects that influence the flood safety function are explained in more detail in the subsequent sections. The three aspects that are considered are:

- I. Piping
- II. Storage capacity
- III. Overflow resistance

3.2.1. Piping

Erosion of soil, due to water friction, takes place when the friction level exceeds the resistance' threshold of the soil particles. The result is a stream of water consisting of a large percentage of suspended materials. If this process takes place in the subsurface, due to the presence of cavities, cracks in rocks, or other openings, an open flow-path is likely the result. This process is defined as "piping", named after the pipe-like pathways that are formed underneath hydraulic structures. The prevention of piping is a primary design consideration in hydraulic engineering, as the result of this event can have devastating consequences. Due to climate change, the frequency of large water head differences over the navigation lock is expected. This results in an increased probability of piping. The process of initiation until the presence of piping is schematised in Figure 3.3.

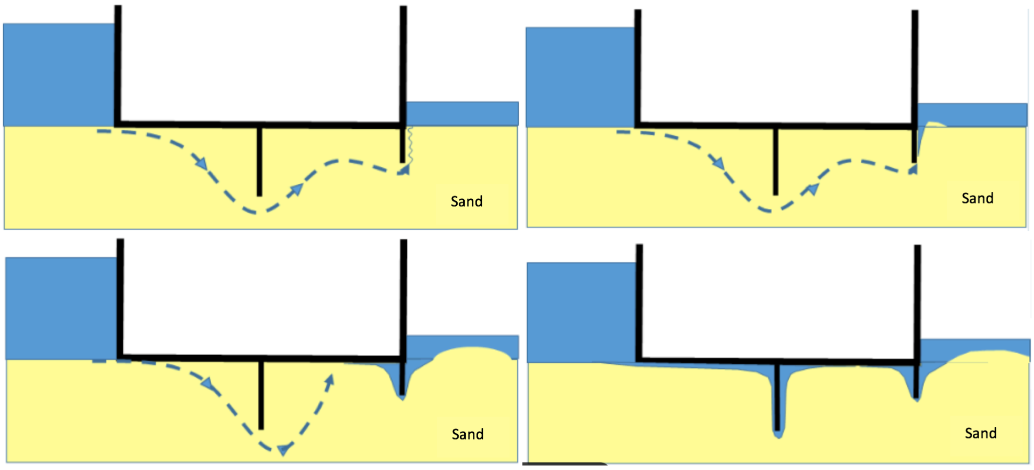


Figure 3.3: Piping mechanism (source: STOWA 2018)

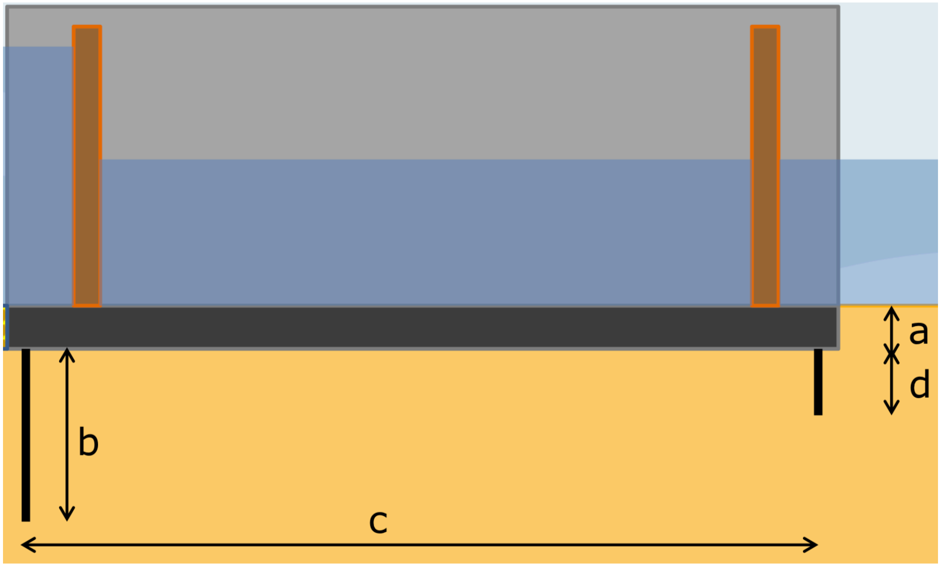


Figure 3.4: Overview of input parameters in piping calculations (source: STOWA 2018)

Whether piping will be an issue, can be calculated using the simplified Bligh/Lane design criterion. This is an empirical representation based on the dimensions of the hydraulic structure. Equations 3.1 and 3.2 present the formula to calculate the critical head difference, which is the maximum water level difference over the structure. The definitions of the letters used in Equation 3.2 are indicated in Figure 3.4.

$$\Delta H_c = \frac{L_v + \frac{L_h}{3}}{C_{w,creep}} = \frac{L_{lane}}{C_{w,creep}} \, [m] \tag{3.1}$$

$$L_{lane} = L_v + \frac{L_h}{3} = (a + 2b + 2d + a) + \frac{c}{3} \, [m] \tag{3.2}$$

- ΔH_c = Critical (maximum) head difference [m]
- L_v = Total vertical length [m]
- L_h = Total horizontal length [m]
- $C_{w,creep}$ = Scale parameter, soil dependent (sand=7, clay=2) [-]

The norm that is set for the probability of piping is expressed in Equations 3.3 and 3.4. In the WBI2017 assessment, piping is not completely embedded. It is on debate what shape factor and length factor have to be used for hydraulic structures. The WBI2017 is initially developed for embankments and not for concrete structures. Therefore, based on the new WBI2017, experts do still review piping for hydraulic structures by considering the expected vertical head difference as a function of the critical/maximum head difference according to Lane design condition (Equation 3.5).

In this research, it is assumed that a shape factor of 0.02 is applicable for both case studies. The acceptable flooding probability (P_{max}) follows from the factsheet of the trajectory the navigation lock is located in. The length factor (N) is assumed to be equal to 1. In fact, this length factor is larger than 1, which makes the result of the piping calculation conservative. Using the probabilistic Hydra-NL software package (section 3.3), the expected head difference (ΔH) is calculated given the $P_{req,dsn}$. If the ratio between the expected water level and the critical vertical head difference is smaller than 1.0, piping is not likely to occur.

$$P_{req,dsn} = \frac{P_{max} * \omega_{PIkw}}{N_{PIkw}} \tag{3.3}$$

$$N_{PIkw} = 1 + \frac{a * L_{trajectory}}{b} \tag{3.4}$$

$$\frac{\Delta H_c}{\Delta H} > 1.0 \tag{3.5}$$

- $P_{req,dsn}$ = Requirement of failure probability of an individual hydraulic structure for the failure mechanism piping [per year]
- P_{max} = Maximum acceptable flooding probability of dike trajectory [per year]
- ω_{PIkw} = Shape factor for piping (=0.02 [-])
- a = Part of trajectory prone to piping (=0.4 for Dutch ”benedenrivieren” and 0.9 for Dutch ”bovenrivieren”)
- $L_{trajectory}$ = Length of assessed trajectory [m]
- b = Length of equivalent trajectory [m]
- ΔH = Expected head difference [m]

Example
Assume a norm of 1:10,000 for a particular dike segment and a ΔH_c = 11m. The $P_{req,dsn}$ can be calculated, given the shape factor of 0.02 and a length factor of 1:

$$P_{req,dsn} = \frac{1:10,000 * 0.02}{1} = 2E - 06 \tag{3.6}$$

Assume that, given the $P_{req,dsn}$ = 2E-06, the output of the Hydra-NL calculation gives an expected water level at the downstream side of the navigation lock of NAP +7.1m. If the upstream lowest regulated water level equals NAP -0.4m, the expected head difference equals:

$$\Delta H = NAP + 7.1 - NAP - 0.4m = 7.5m \tag{3.7}$$

Based on Equation 3.5, the ratio critical head difference over the expected head difference equals:

$$\frac{11}{7.5} = 1.46 > 1.0 \tag{3.8}$$

It can be stated that piping is not expected as the ratio critical head difference over the expected head difference, given that the norm of 1:10,000 for this segment is larger than one.

3.2.2. Storage capacity

According to the analysis on the national flood risk for the Netherlands (Vergouwe, 2014), shortage of the storage capacity might result in structural failure. The principle is based on a water budget: the presence of incoming and outgoing fluxes. In case that the outflux is smaller than the influx (e.q. heavy rainfall or discharge), the capacity of the basin may be too small which will result in an increasing flooding probability. The following formulae are used to calculate the storage capacity and the acceptable level of overflow regarding the navigation lock:

$$K = A * h_{pvh} \tag{3.9}$$

- K = Storage capacity [m^3]
- A = Surface area inner waterway which is connected to the navigation lock [m^2]
- h_{pvh} = Maximum acceptable water level increase [m]

The volume of water that can overflow follows from the storage capacity as a function of the width:

$$V_b = K/B \tag{3.10}$$

- B = total width of the structure [m]
- V_b = Volume of water during high-water period per unit of length [m^3/m]

The expected overflow can be calculated on the volume of water that can overflow over the period of time that this event takes place. Due to safety reasons, this overflow is limited to 1000 L/m/s or equivalent 1 $m^3/m/s$.

$$q = V_b/t \tag{3.11}$$

- q = Maximum overflow discharge [$m^3/m/s$]
- t = period of continuous load [s]

The maximum acceptable water level increase in the waterway is limited for a number of reasons. From the nautical viewpoint, the following items are of relevance regarding this maximum water level increase:

- Reduction of vessels' air draught due to the presence of bridges
- Water management policies in the region

If the storage capacity is sufficient to store the surcharge of water during extreme conditions, it might only affect the nautical function. In that case, the effect on flood safety is considered as negligible. The aspect is not governing for the urgency of renovation.

3.2.3. Overtopping resistance

Large quantities of overtopping water can result in stability issues at the navigation lock. Furthermore, it affects the storage capacity of the complex (section 3.2.2). For the latter fact, regional water-retaining structures like embankments will face higher water levels, resulting in a higher flood risk probability of the hinterland. Besides flood safety, overflow can result in failure of actuators or other technical installations in a navigation lock complex. Increasing probabilities of technical failure result in more frequent maintenance and, consequently, an increase in the downtime. This affects the nautical function of the navigation lock.

The calculation of overtopping water is based on the schematisations of a navigation lock. The front view of the complex is defined as a vertical wall in the software Hydra-NL. This software package is based on the EurOtop Manual (The EurOtop Team, 2016) and supports the schematisation of vertical hydraulic structures.

For the calculation of the overtopping water, the navigation lock is schematised as a vertical wall in the software package Hydra-NL. A number of parameters that are used in the Hydra-NL calculations are depicted in Figure 3.5. The volumes of overtopping water at plain vertical walls, for non-impulsive conditions, can be calculated with Equation 3.12. ”The distribution of individual overtopping volumes in a sequence can be well-described by a two-parameter Weibull distribution” (The EurOtop Team, 2016) (Equation 3.14). From this point, the maximum overflow can be calculated, using Equation 3.15. In the case studies, this sequence of steps is embedded in the Hydra-NL software and results in graphs containing the expected water levels, expected wave height, and expected overflow values corresponding to a particular return period.

Literature prescribes a maximum overflow of Q=1000 L/m/s to safeguard the structural integrity of the concrete structure (Vrijburcht et al., 2000) (Equation 3.16). In this research, it is assessed whether the expected overflow volumes, as a result of climate change in the coming 100 years, will exceed the maximum acceptable overflow volume. For the calculation of the expected overflow volume, the flooding probability of the segment the navigation lock is part of is normative.

$$\frac{q}{\sqrt{g * H_{m0}^3}} = 0.054 * exp\Big[-\{\frac{2.12 * R_c}{H_{m0}}\}^{1.3}\Big] \quad (3.12)$$

$$\frac{N_{ow}}{N_w} = exp\Big[-1.21 * \{\frac{R_c}{H_{m0}}\}^2\Big] \quad (3.13)$$

$$P_v = 1 - exp\Big[-\{\frac{V}{a}\}^b\Big] \quad (3.14)$$

$$V_{max} = a * \{ln(N_{ow})\}^{\frac{1}{b}} \quad (3.15)$$

$$Q_{max,overflow} = 1000[l/m/s] \quad (3.16)$$

- g = gravitational acceleration $[m/s^2]$
- q = mean overtopping discharge $[m^3/m/s]$
- R_c = crest freeboard of structure [m]
- N_{ow} = number of overtopping waves [-]

- N_w = number of waves incident waves [-]
- P_v = probability that an individual event volume will not exceed V [-]
- V_{max} = Predicted maximum individual overtopping volume $[m^3/s]$
- a = 0.090 (Weibull shape factor) [-]
- b = 0.70 (Weibull shape factor) [-]

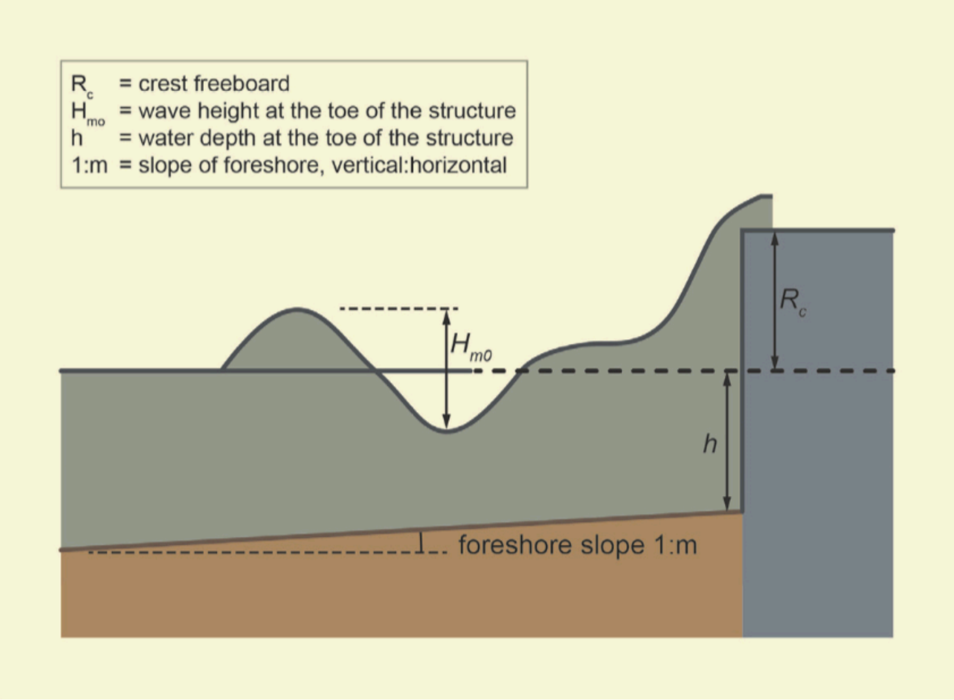


Figure 3.5: Definition sketch for assessment of overtopping at plain vertical walls (source: EurOtop Manual 2016, p.192)

4

Nautical Analysis

This chapter reflects on the third research question that defines the aspects that affect the nautical function of a navigation lock. These aspects have an impact on the unavailability or are related to the capacity of the complex.

4.1. Discharge Variety

In section 2.4, discharge variety is defined as part of climate change that has an impact on the nautical function. Four situations are defined is the result of discharge variety. The following aspects are distinguished:

- Unavailability due to high downstream water level
- Unavailability due to high upstream water level
- Unavailability due to low upstream water level
- Unavailability due to low downstream water level

4.1.1. Unavailability due to high downstream water level

At the downstream side of a navigation lock, the frequency of high water levels will increase in the future due to more extreme discharge conditions. For a number of navigation locks, this effect is amplified if they are located near the coast. In that case, sea level rise and high discharge values at the downstream side of a navigation lock will result in high water levels. Depending on the case that is reviewed, high downstream water levels affect the levelling cycle (Appendix D). The longer the levelling cycle, the lower the capacity of the navigation lock. It might be the case that the average levelling cycle decreases if more frequent high downstream water levels reduce the water head difference over the complex. Both situations also have an influence on the I/C ratio, as explained in section 4.3. Summarised, the frequency of high downstream water level events affects the availability of the navigation lock complex.

4.1.2. Unavailability due to high upstream water level

Extreme rainfall will occur more often and with higher intensities in the future. This is the main conclusion of a number of technical reports on climate change, focusing on the influence on the Netherlands (STOWA, 2015). Based on measurements, extreme rainfall events occurred 10 % more often in 2010-2015 relative to the reference period 2000-2005. Furthermore, the intensity of the rainfall events doubled in the same period.

For the Netherlands, the ”100-year dataset of De Bilt” is used since the start of measuring rainfall, which is the starting point of assessing and quantifying the extreme rainfall situations (STOWA, 2015). In this dataset, a climate trend can be observed, in particular from the eighties of the last century. Corrections are applied for both rainfall and evaporation. In Table 4.1, the rainfall characteristics are defined for 2015 and 2050. Three bins of the average frequency of occurrence periods are distinguished (10, 50, and 100 years) and different periods are defined. Based on these characteristics, it is calculated that the rainfall intensity [mm] is expected to increase with 10% in 2050 (STOWA, 2015).

This 10% increase of rainfall has an effect on the storage capacity and the availability of the levelling function. A part of the total rainfall will flow via land in the direction of the waterways, resulting in more frequent high discharge values. This leads to more frequent upstream high water levels. The geographical location of the Netherlands results in the discharge by rainfall not being the only source of water. For example, melting ice during the spring season in adjacent countries is another source. This surcharge of water drains off via the rivers Rhine and Meuse towards the Netherlands in the direction of the North Sea.

Table 4.1: Rainfall intensity [mm] with return periods of 10, 50, and 100 years (source: STOWA, edited)

Climate	**2015**			**2050**		
Return period (year)	10	50	100	10	50	100
Period = 24 hours						
2004-2014	54	71	79	57-66	75-86	84-96
2015	59	77	85	58-68	76-90	85-100
Period = 4 days						
2004-2014	80	100	109	83-93	104-116	113-127
2015	89	112	122	90-101	112-128	122-140
Period = 8 days						
2004-2014	103	124	133	105-117	127-141	136-151
2015	116	140	150	117-129	141-157	151-168

Three years ago, the research institute Deltares started with the instrument GRADE (Generator of Rainfall And Discharge Extremes), a tool that is used to estimate extreme discharge levels in either the waterway Rhine or Meuse in the Netherlands. The design flood hydrographs that are used in the current method are based on extrapolation of selected observed hydrographs to a peak value that corresponds with a return period of once in 1250 years. Shortcomings of this procedure are, among others, scaling effects and extrapolation issues, which lead to unrealistic flood hydrographs. Next to that, the effect of upstream flooding, that results in less narrow hydrographs, is not incorporated in the current method. The differences of the GRADE instrument relative to the previous ”current method” is depicted in Figure 4.1.

Based on the output of the GRADE model, the frequency of high discharge levels that result in high upstream water levels can be calculated and used to assess the impact on the availability of the navigation lock. The unavailability as a result of high upstream water level events is together with the other availability affecting aspects, reviewed relative to the SLA agreement.

> The GRADE instrument discounts for the impact of extreme rainfall in either the waterway Rhine or Meuse and indirectly for the bifurcated waterways that originate from these large waterways. Application of this instrument provides insight into the expected frequency and period of high water level events. Based on this outcome, downtime and unavailability of the levelling function of navigation locks can be calculated.

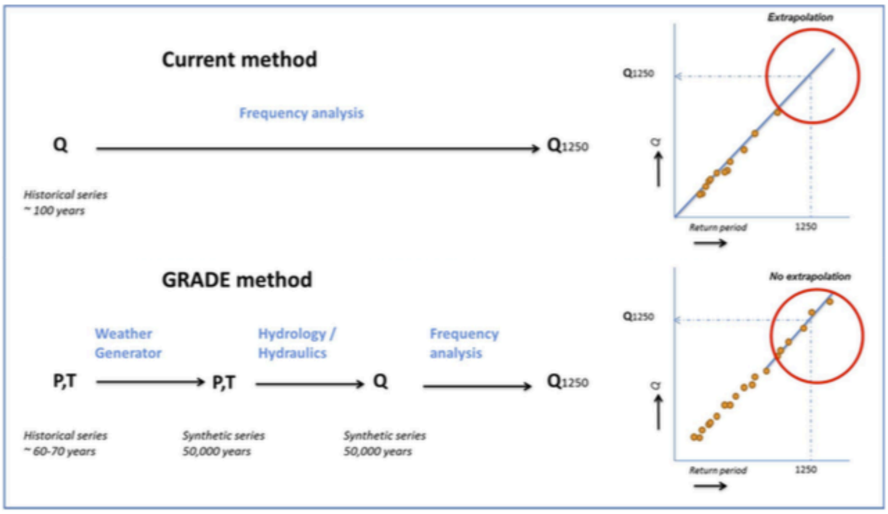


Figure 4.1: Comparison of the current method with the GRADE method (source: Deltares)

GRADE FOR WATERWAY RHINE

The maximum discharge level at Lobith (starting point of the waterway Rhine in the Netherlands) is calculated with the GRADE model. For a discharge level of 16,500 m^3/s, embankments on the traject Wesel-Lobith will overflow. This corresponds with a discharge level of 17,500 m^3/s at Lobith. Remark to this fact is that for these discharge values, embankments at Rees and Emmerich will also overflow with characteristic values up to 400 L/m/s. Therefore, an embankment failure is likely to occur (Expertise Network for Flood Protection (ENW), 2016). Nevertheless, for the Prinses Beatrix assessment, this discharge value of 17,500 m^3/s at Lobith is considered as the maximum possible discharge level at waterway Rhine (Figure 4.2).

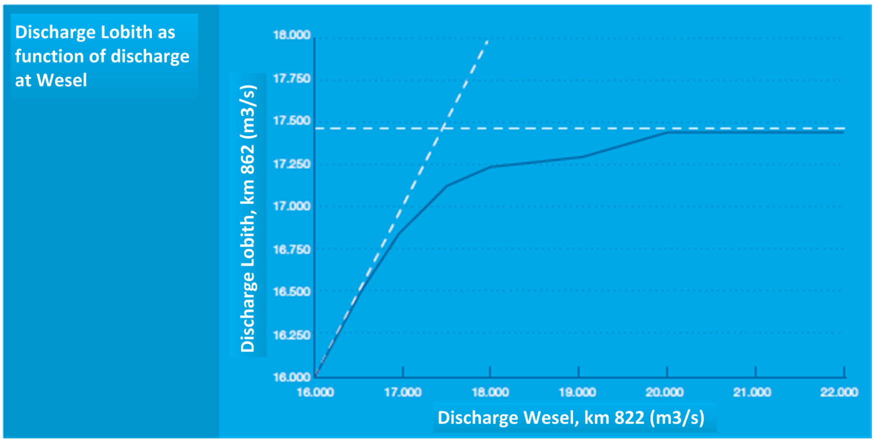


Figure 4.2: Discharge at Lobith as a function of discharge at Wesel (source: ENW, edited)

4.1.3. Unavailability due to low upstream water level

The frequency and periods of drought increase significantly in the Netherlands, in particular during the summer season. An indicator of drought is the precipitation deficit. This is the precipitation minus potential evapotranspiration. The Royal Netherlands Metrological Institute (KNMI) has researched this precipitation deficit in the Netherlands (KNMI, 2010). The four climate scenarios as defined in section 3.1 all indicate an increase of the maximum precipitation deficit (Figure 4.3). The deficit is logically largest for the W+ scenario, the one that is considered in this research. For the W+ scenario, this precipitation deficit increases from an average of 144mm per year during the past century to an average of 220mm per year around 2050 (+50%) and to more than 290mm per year around 2100 (+100%) (KNMI, 2009b).

The impact of drought indirectly results in more frequent upstream low water levels. Increasing frequency and periods of drought limit result in lower acceptable draughts of vessels. This implies that only smaller vessels can sail the waterway or larger vessels that are not completely loaded. In this way, damage to revetment is prevented. Transporting an equivalent level of cargo requires more smaller vessels and, therefore, leads to an intensity growth at the waterway. So next to lower nautical availability of the navigation lock, an intensity increase can also be expected. The intensity increase consequently results in a capacity shortage of the navigation lock. This is noticeable in the more frequent and higher intensity of congestion in the HVWN (Section 4.3).

4.1.4. Unavailability due to low downstream water level

The downstream water level, for inland navigation locks, is also affected by more frequent and longer periods of drought. It limits the availability of the levelling function for the larger vessels that sail the waterway. The application of another water level regime by the use of weirs can facilitate the nautical sector. However, this is only possible to a limited extent. For sea-located navigation locks, the ”downstream water level” is the sea-side of the complex. This water level is primarily affected by the tide, resulting in tidal levelling regimes. These tidal levelling regimes are affected by climate change and the impact is primarily the result of sea level rise. Depending on the case, this sea level rise either reduces the levelling cycle (upstream water level higher than MWL) or increases the levelling cycle (upstream water level lower than MWL). Summarised, the unavailability due to low downstream water levels driven by climate change can either positively or negatively affect the levelling function of the primary navigation lock. The exact influence is dependent on the boundary conditions of the navigation lock.

Drought, as a result of climate change, is the main source for low water level conditions that result in the unavailability of the navigation lock. As a result of climate change, droughts will occur more frequently and, therefore, the unavailability due to low downstream water level events will increase. Together with the high water level events, these aspects contribute together to the total downtime of the navigation lock.

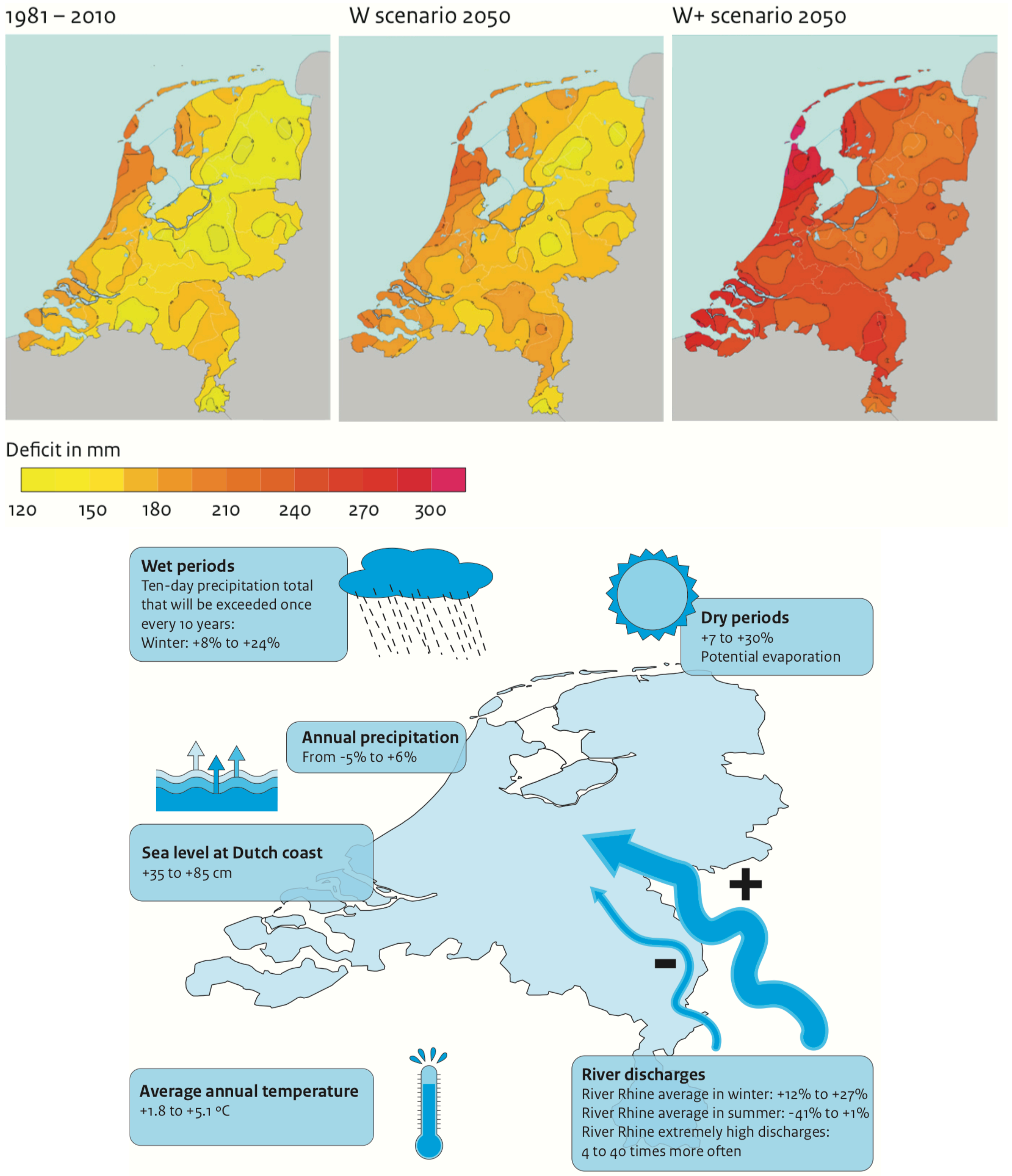


Figure 4.3: Maximum precipitation deficit for two climate scenarios (top) and contributors to the effect of climate change (bottom) (source: KNMI)

4.2. National Market and Capacity Analysis

The National Market and Capacity Analysis (NMCA) presents an overview of the national accessibility questions that affect the transport sector via road, rail, waterways, and regional public transport. The starting point for these analyses is the growth scenarios of the Dutch Environmental Assessment Agency (Planbureau voor de Leefomgeving, PBL) and the Dutch Bureau for Economic Policy Analysis (Centraal Planbureau, CPB). In the viewpoint of the report's scope, the NMCA Waterway section is of interest.

4.2.1. Developments in the inland waterway transport network

The Inland Waterway Transport (IWT) network is used more and more as a result of economic prosperity. Based on the prognoses of CPB and PBL, this intensity growth is researched for the HVWN. Figure 4.4 presents the findings of the expected intensity increase in the HVWN for two scenarios: low and high, for the target year 2050. The colour-bar indicates in yellow/red an increase of intensity and in blue a decrease of intensity, relative to the reference year 2014. The largest intensity increase is expected in the corridors Rotterdam-Antwerp and Rotterdam-Germany. On average, an intensity growth of 10% can be expected for the low scenario and 35% for the high scenario. For the low scenario, only the waterway Meuse in the province of Limburg is expected to decline. This is the result of an expected decrease in the transport of raw material (e.g. sand and gravel).

Cargo vessels are the main contributors to the intensity growth in the HVWN. Rijkswaterstaat uses the model ”BasGoed” to forecast the developments of the nautical inland transport in the Netherlands, for the target years 2030, 2040, and 2050. The effect of the increase of cargo vessels on the intensity growth is the result of studies that are named after the model ”Basisprognoses Goederenvervoer 2017” (Rijkswaterstaat WVL, 2017). In these forecasts, the recent legislation regarding acceptable carbon dioxide emissions for the inland waterway transport is taken into account. This effect is visible in the spread between the two scenarios (Figure 4.5). Furthermore, these scenarios incorporate the effect of the following relevant aspects:

- Regulations regarding modal shift that entails the mode of transport (limiting road transport in favour of train or inland waterway transport).
- Opening and closure of a number of coal-fired power plants
- New container terminals, those that are opened after the year 2014
- Increasing demand for bio-energy in favour of fossil energy

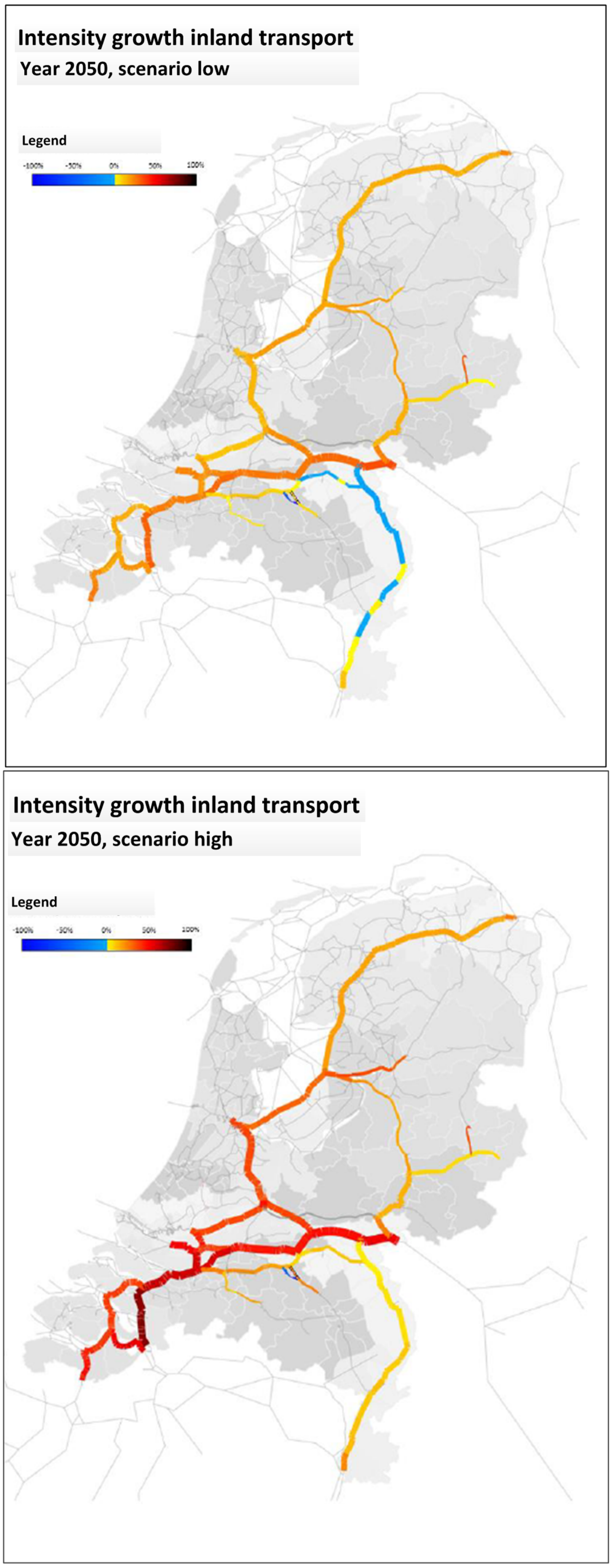


Figure 4.4: Prognosis transport volumes inland waterway transport 2014-2050, scenarios low (top) and high (bottom)

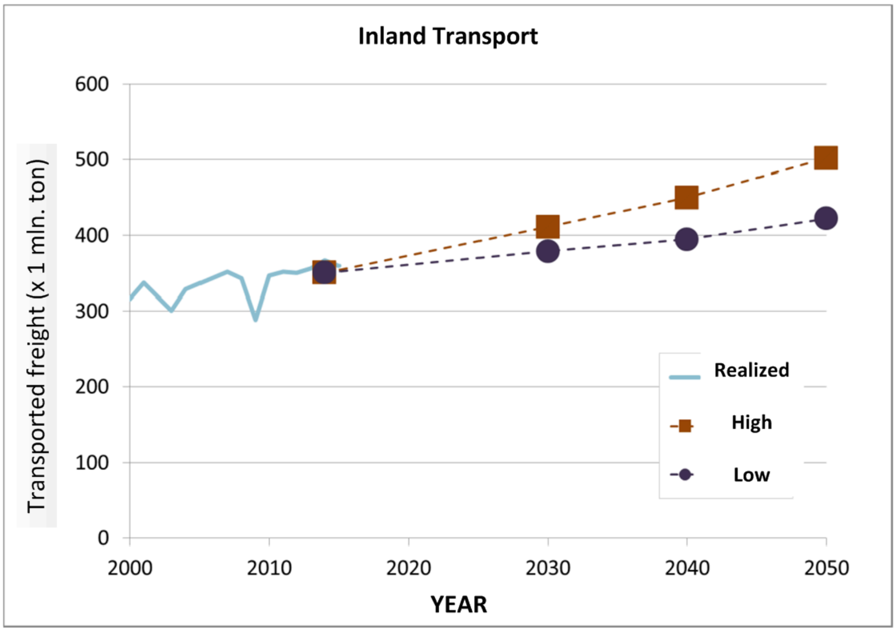


Figure 4.5: Developments of the total inland transport up to the year 2050, split between for source and destination for the two scenarios (source: NMCA Deelrapportage Vaarwegen 2017, edited)

In Table 4.2, the percentual growth or declination of inland waterway transport is indicated for four different directions. The international transport is the main driver for the IWT intensity growth, in particular due to transit vessels. This is the result of the economic situation of the Netherlands, that is more oriented towards export rather than import. This implies that more cargo is heading outside the Netherlands. This is partly the result of the geographical location of the country, that functions as a transit for adjacent countries. The fact that inland-directed transport is declining, is the result of limited economic growth together with dematerialisation.

Table 4.2: Growth inland waterway transport (tonnage) period 2014-2040

DIRECTION	**Weight (mln. ton)**	**Increase 2014-2040**		**Average annual growth 2014-2040**	
		Scenario LOW	**Scenario HIGH**	**Scenario LOW**	**Scenario HIGH**
Inland (load & unload NL)	112	-4%	10%	-0.2%	0.4%
Import (load outside NL & unload NL)	64	44%	64%	1.4%	1.9%
Export (load NL & unload outside NL)	128	6%	20%	0.2%	0.7%
Transit (load & unload outside NL)	46	26%	49%	0.9%	1.5%
TOTAL	350	13%	28%	0.5%	1.0%

Next to the cargo vessels, recreational and passenger vessels also sail in the HVWN. Demographical variations result in a gradual declination of recreational vessels up to 2050. This has a positive impact on the availability of primary navigation locks. The opposite holds for the passenger vessels; this category is expected to increase up to 55% for the high scenario in 2050. An overview of the expected growth can be found in Table 4.3.

Table 4.3: Intensity growth as a result of recreational and passenger vessels in the period 2014-2050

RECREATIONAL VESSELS							
Index 2014 = 100	2014	**Scenario HIGH**			**Scenario LOW**		
		2030	**2040**	**2050**	**2030**	**2040**	**2050**
Averaged over HVWN navigation locks	100	96	89	82	79	72	67
PASSENGER VESSELS							
Index 2014 = 100	2014	**Scenario HIGH**			**Scenario LOW**		
		2030	**2040**	**2050**	**2030**	**2040**	**2050**
Length vessel >= 110m	100	133	145	155	120	130	138
Length vessel <110m	100	100	100	100	100	100	100

The effects of the developments in the IWT network are considered during the assessment of the two case studies. The models that are used to calculate the capacity shortage, use the input from the NMCA.

4.2.2. Impact of the energy transition

As a result of the global energy transition, a decline in the transported volume of fossil fuel is expected for both the low and the high scenarios. This affects the Dutch inland transport sector, as the share cargo vessels that transport fossil fuel is equal to 13% of the total inland-waterway-transported tonnage in 2014 (Rijkswaterstaat WVL, 2017). Alternative energy sources like biofuel, solar energy, and wind energy are expected to increase significantly over the coming decades. However, estimations vary as they are based on international climate policy. The two scenarios that are developed for the impact of the energy transition incorporate an increasing volume of transported biofuel via the sea-located ports. Table 4.4 presents an overview of the percentual change as a result of the reduction of fossil fuel. Table 4.5 presents the growth of the inland waterway transport excluding and including the effect of a reduction of the national fossil fuel usage. The differences between the scenarios high and low, regarding their effect on the IWT, are:

- High: import of charcoal, gas, and oil reduces to zero in 2050 and 50% reduction of biofuels. This results in an 82% reduction of transported fossil fuel in 2050 and a 75% reduction of the transported tonnage.
- Low: import of charcoal, gas, and oil reduces by 23% in volume which results in a reduction of 16% in transported tonnage in 2050. The import of biofuels increases by 50% in 2050.

Table 4.4: Percentual change of transported volume as a result of a reduction in fossil fuel usage, relative to the reference year 2014

Scenario	**Effect IWT (tonnage)**		
	2030	*2040*	*2050*
High	-11 %	-16 %	-17 %
Low	-1 %	-3 %	-3 %

Table 4.5: Increase inland waterway transport, excluding and including the impact of a reduced national fossil fuel usage

Scenario	Weight 2014 (mln. tonnage)	Increase transported volume: reference year - target year					
		2014 - 2030		2014-2040		2014-2050	
		Scenario LOW	Scenario HIGH	Scenario LOW	Scenario HIGH	Scenario LOW	Scenario HIGH
Relative to CPB prognosis	350	8%	17%	13%	28%	21%	43%
Variant less fossil fuels	350	7%	5%	9%	8%	17%	19%

The influence of the energy transition for the scenarios up to 2050 is embedded in the assessment of the case studies via the aspects of intensity and capacity (section 4.3).

4.3. Intensity and Capacity

The Mobility Act (Nota Mobiliteit, NoMo) is a national traffic and transport plan, based on the Traffic and Transport Planning Policy. In 2012, the NoMo is replaced by the Infrastructure and Spatial Planning Act (Structuurvisie Infrastructuur en Ruimte, SVIR). Part of this SVIR is the criterion that is set regarding waiting times for primary navigation locks. The guidelines for inland waterways define that a navigation lock (one lock chamber) that is located in the HVWN must have an annual capacity for 10,000 vessel transits. In the moment that the intensity as a function of the capacity exceeds the I/C_{required}=0.5, waiting times of more than 30 minutes can be expected (section 2.3.3). This waiting time is considered as critical and normative for a potential capacity shortage. Therefore, the criterion of 30 minutes' waiting time or an I/C_{required} equivalent of 0.5 is defined as the requirement for a primary navigation lock.

The intensity as a function of the capacity is considered as an aspect for the urgency of renovation. In the assessment of the case studies, the information in section 4.2 is used to find the moment wherein the primary navigation lock does not fulfil this requirement. Two moments in time are considered. First, the actual performance is reviewed by verifying the existing intensity relative to the existing capacity (2015). The other moment is defined in 2040. Summarised, the NoMo and the I/C criteria that follow from the national traffic and transport plan are defined once more in Equations 4.1 and 4.2.

$$NoMo = SVIR\ criterion = 30\ minutes \tag{4.1}$$

$$I/C_{max} = 0.5 \tag{4.2}$$

4.3.1. I/C economy 2015

The intensity as a function of the capacity for the reference year is based on the IWT data retrieved over the year 2015. This data is in line with the reference reports of the CPB and PBL that used data available up to the year 2014. For both economic scenarios, the I/C ratio indicates whether the existing navigation lock complex meets the requirement of Equation 4.1 and 4.2.

4.3.2. I/C economy 2040

Similar to the I/C ratio of the reference year 2015, the intensity as a function of the capacity of the navigation lock complex can be calculated in 2040. A moment further in time results in a less accurate outcome as the economic situation is dependent on a number of parameters. The reliability of these parameters declines over time, so the economic prognoses are less reliable over time.

In the assessment of the case studies, the $I/C_{max}=0.5$, as defined in the Mobility Act, is used as an indicator to determine the urgency of renovation. A larger value results in exponentially increasing waiting times and, therefore, heavy congestion in the HVWN.

4.4. Ageing

The unavailability of the nautical function due to either scheduled maintenance or technical failure is increasing over time due to ageing. Ageing is an irreversible process of becoming older. For civil structures, this process often results in lower performance of the object. The effect of ageing regarding scheduled maintenance and technical failure is clarified below:

4.4.1. Unavailability due to scheduled maintenance

The annual unavailability as a result of scheduled maintenance is one of the aspects that will increase over time due to the ageing of the navigation lock. The more annual hours needed for scheduled maintenance, the more downtime and the less availability of the nautical function. In the viewpoint of performance, the reduced reliability of components gives rise to more maintenance. If the frequency and period needed for scheduled maintenance increase over time, the contribution of these aspects might become normative for advancing the moment of renovation.

4.4.2. Unavailability due to technical failure

Technical failures result in direct repairs of the components that fail their function. Ageing materials lead to higher probabilities of technical failures (Figure 2.3). The more technical failures, the more downtime is expected to execute repairs, and lower is the availability of the nautical function. Whether the levelling function is disrupted, depends on the type of failure and if a back-up is possible. For particular navigation lock complexes, if the levelling function of one lock chamber is interrupted, the other can (partly) take over. However, this will result in substantial delays in the HVWN. If the frequency and period needed for repairs increase over time, it might be that the share of this aspect in the total unavailability becomes normative for advancing the moment of renovation.

5

Case Studies: Prinses Beatrix and Terneuzen Navigation Lock Complexes

5.1. Prinses Beatrix Navigation Lock Complex

The Prinses Beatrix navigation lock is the largest monumental inland waterway navigation lock, located near the city of Nieuwegein, in the province of Utrecht. The navigation lock complex, consisting of two lock chambers, serves 50,000 vessels annually (2015). The Western lock chamber was opened in 1933 and the Eastern lock chamber in 1938. "Corridor 2 - Amsterdam-Rijn" (Figure 1.1) is one of the bottlenecks in the HVWN that needs capacity expansion according to the conclusions of the NMCA (section 4.2). Therefore, an additional lock chamber is constructed and operational since 2019. This third lock chamber is located at the eastern side of the existing complex (Figure 5.1).

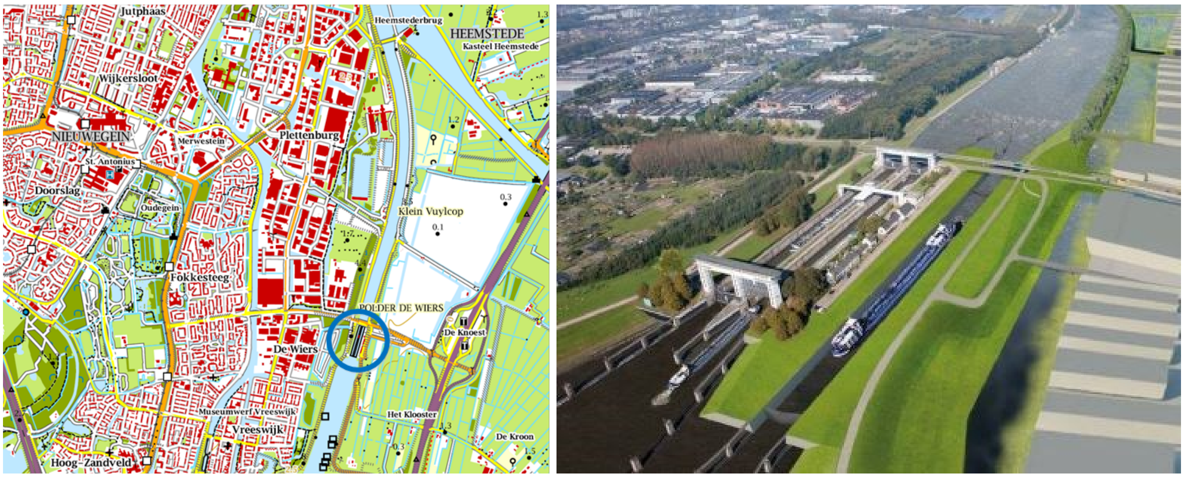


Figure 5.1: Location and artist impression of new Prinses Beatrix navigation lock complex

> All the aspects of the proposed method, as defined in section 2.5, are assessed and reviewed relative to their norm or requirement according to the Water Act or Mobility Act. For the flood safety function, a failure probability of 1% relative to the norm is applied in the criticality assessment, if the contribution to the probability of flooding is considered as negligible (for normative conditions) (WBI, 2017). For the Prinses Beatrix navigation lock, this entails a failure probability of 1% of 1:10,000 = 1E-06 per year in 2100.

5.1.1. Boundary conditions

The data of Table 5.1 is retrieved from the RINK report of Prinses Beatrix navigation lock and the Sluizenboekje (Van Erp and Van Corven, 2017). The data for the third lock chamber is not provided as this lock chamber is not considered in the V&R renovation programme (completed in 2019). Therefore, only boundary conditions of the existing Eastern and Western lock chambers are defined.

Table 5.1: Boundary conditions of Prinses Beatrix navigation lock chambers East and West, ARK = Amsterdam-Rijnkanaal

	Unit	**38F-352-01 (East)**	**38F-352-01 (West)**
Length	[m]	225	225
Width	[m]	18	18
Sailing height	[m NAP]	+8.9	+8.9
MHW_Lek	[m NAP]	+6.4	+6.4
MLW_Lek	[m NAP]	-1.15	-1.15
MWL_Lek	[m NAP]	+1.09	+1.09
Height Head_Lek	[m NAP]	+7.8	+7.8
Height Head_ARK	[m NAP]	+6.5	+6.5
MHW_ARK	[m NAP]	-0.2	-0.2
MLW_ARK	[m NAP]	-0.5	-0.5
MWL_ARK	[m NAP]	-0.4	-0.4
Max Levelling	[m NAP]	+5.9	+5.9
Min Levelling	[m NAP]	-0.6	-0.6
Sill level	[m NAP]	-4.5	-4.5
Renovation V&R	[year]	2055	2055
Discharge	[-]	through chamber	through chamber
Open annual	[hours]	8736	8736
Design vessel	[-]	CEMT Vb = M8	CEMT Vb = M8
Vessel draught	[m]	M8 = 3.5	M8 = 3.5

During the design of the hydraulic boundary conditions of the third lock chamber of the Prinses Beatrix navigation lock complex, the new legal assessment framework (WBI2017) did not exist. At that moment, a norm of 1:1,250 was considered for the existing lock chambers as well as for the extension as it was part of the dike segment 44 (Kromme Rijn). The introduction of the new WBI2017 resulted in more stringent standards that vary over the dike segment. Therefore, the hydraulic loads that are linked to the new norm, are higher as these are assessed on a 1:10,000 per year norm.

Operational conditions

The levelling function of the Prinses Beatrix navigation lock is satisfied in the range of NAP -0.60m up to NAP +5.90m in the waterway Lek. When this water level is exceeded, the levelling function is interrupted and the function water-retaining function is active. Scheduled maintenance can be executed during normal operation conditions.

New policies prescribed that the new Prinses Beatrix navigation lock chamber must level vessels up to the design high water level in the Lek waterway. The maximum water level for this new lock chamber is set at NAP +6.40m, for which the water levels in the the existing chambers East and West equal NAP +5.90m. The sill level of the new lock chamber is set at NAP -5.80m, excluding an additional 0.30m margin for translation waves.

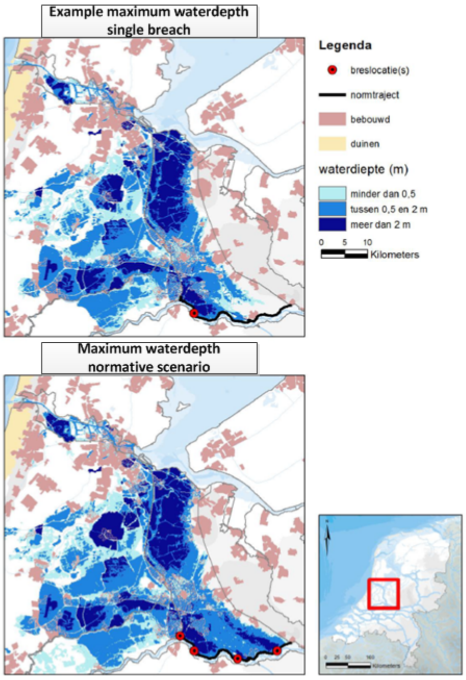
All aforementioned design water levels exclude a robustness parameter, to determine the retaining height of the hydraulic structure (Expertise Network for Flood Protection (ENW),2007). This additional safety margin is for uncertainties in high water levels and NAP-declination during the design period.

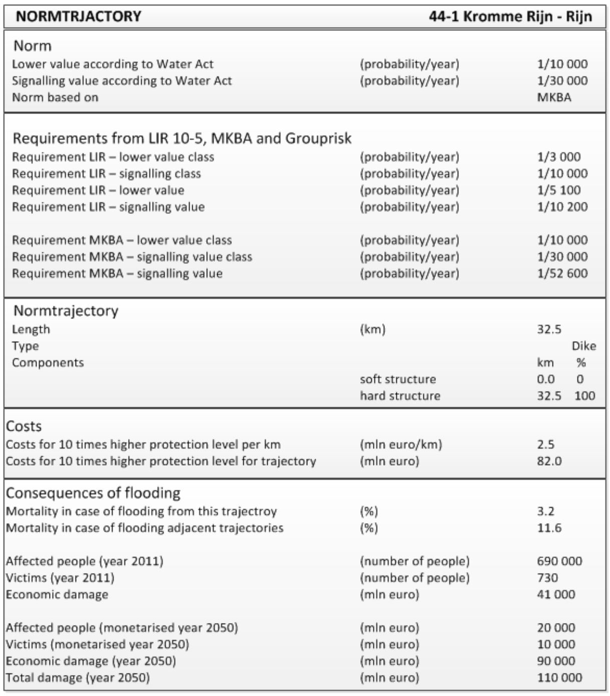
5.1.2. New standards

The Prinses Beatrix navigation lock complex is now part of segment 44-1, Kromme Rijn-Rijn (Figure 5.2). The signalling value is set at 1:30,000 per year. The lower value is set at 1:10,000 per year (new standard). This implies that segment 44-1 is now classified as highly valuable in which failure of the flood safety function results in high economic damage and causalities (Figure 5.2). Contributors that resulted in this new standard, which stem from an MKBA study, are defined below. The MKBA study is an analysis that considers the effects of potential failure on the national prosperity on both social and financial aspects.

- The upper left map presents a simulation of the maximum water depth in case of a breach during normative conditions regarding the water level
- LIR is the abbreviation of Local Individual Risk that is set at 10E-05
- Economic damage is the actual monetary damage multiplied by 1.5 that incorporates indirect losses and a risk premium

> The new standard for segment 44-1 Kromme Rijn-Rijn = 1:10,000 per year. The Prinses Beatrix navigation lock complex, that is part of this segment, has to be able to withstand hydraulic conditions that correspond with this norm. Therefore, all the aspects of the method are assessed on this new norm.





NORMTRJACTORY		44-1 Kromme Rijn - Rijn	
Norm			
Lower value according to Water Act	(probability/year)	1/10 000	
Signalling value according to Water Act	(probability/year)	1/30 000	
Norm based on		MKBA	
Requirements from LIR 10-5, MKBA and Grouprisk			
Requirement LIR – lower value class	(probability/year)	1/3 000	
Requirement LIR – signalling class	(probability/year)	1/10 000	
Requirement LIR – lower value	(probability/year)	1/5 100	
Requirement LIR – signalling value	(probability/year)	1/10 200	
Requirement MKBA – lower value class	(probability/year)	1/10 000	
Requirement MKBA – signalling value class	(probability/year)	1/30 000	
Requirement MKBA – signalling value	(probability/year)	1/52 600	
Normtrajectory			
Length	(km)	32.5	
Type			Dike
Components		km	%
	soft structure	0.0	0
	hard structure	32.5	100
Costs			
Costs for 10 times higher protection level per km	(mln euro/km)	2.5	
Costs for 10 times higher protection level for trajectory	(mln euro)	82.0	
Consequences of flooding			
Mortality in case of flooding from this trajectroy	(%)	3.2	
Mortality in case of flooding adjacent trajectories	(%)	11.6	
Affected people (year 2011)	(number of people)	690 000	
Victims (year 2011)	(number of people)	730	
Economic damage	(mln euro)	41 000	
Affected people (monetarised year 2050)	(mln euro)	20 000	
Victims (monetarised year 2050)	(mln euro)	10 000	
Economic damage (year 2050)	(mln euro)	90 000	
Total damage (year 2050)	(mln euro)	110 000	

Figure 5.2: Factsheet norm segment 44-1 Kromme Rijn - Rijn (source: Factsheets Normering Primaire Waterkeringen, edited)

5.1.3. Piping

The impact of sea level rise for the Prinses Beatrix navigation lock is negligible, as a result of the geographical location (adjacent level located at, on average, NAP +1.0m) and the presence of hydraulic structures (weirs) downstream of the waterway Lek. Rijkswaterstaat has a number of gauges at the coast and in inland waterways to measure the influence of the tide (Figure 5.3). Those inland waterway gauges are only of importance at locations where the tide is of influence. For discharge conditions of 10,000 m^3/s at Lobith, the Prinses Beatrix navigation lock complex is not influenced by sea level rise (W+ climate scenario). This is the result of the counteracting force of a high water discharge that results in a rise of the water level over potential rise due to sea level rise.

> At the Prinses Beatrix navigation lock complex, the influence of sea level rise is zero for discharge levels larger than 10,000 m^3/s at Lobith. This holds for the W+ climate scenario, implying a sea level rise of 0.85 metres at the coast in 2100.

Figure 5.3: Location of gauges at the Dutch coast and inland waterways to check the influence of tidal impact. The influence on the Prinses Beatrix navigation lock is negligible (source: Rijkswaterstaat Waterinfo)

Based on the aforementioned information, the piping aspect can be calculated for the Prinses Beatrix navigation lock. The formulae by Bligh and Lane are used to assess the piping length, combined with the input from Table 5.1. As defined in Section 3.2, the failure probability requirement of an individual hydraulic structure can be calculated (Equation 5.1). For a 1:10,000 per year norm, a shape factor of 0.02 and a length factor of 1, the failure probability requirement equals:

$$P_{req,dsn} = \frac{P_{max} * \omega_{PIkw}}{N_{PIkw}} = \frac{1:10,000 * 0.02}{1} = 2E-06\ [/year] \tag{5.1}$$

The water level that corresponds to this failure probability is calculated with the software Hydra-NL and equals NAP +7.3m at waterway Lek (Figure 5.4). Dimensions of the navigation lock are depicted in Figure 5.5. Based on this information, the piping length equals:

$$L_{lane} = L_v + \frac{L_h}{3} = 2 * 6.4 + 2 * 6 * 3.9 + 2 * 6.4 = 72.4m \tag{5.2}$$

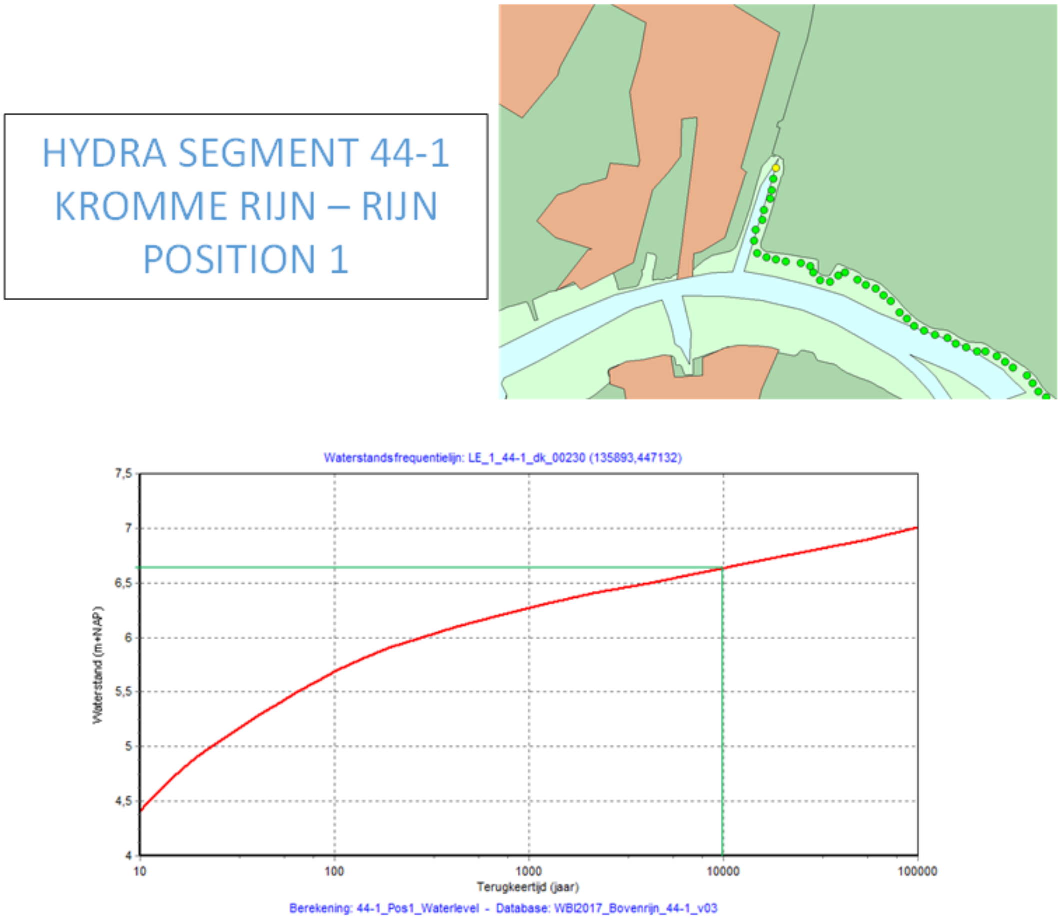


Figure 5.4: Expected water level for an average frequency of occurrence period located in front of the Prinses Beatrix navigation lock (yellow dot)

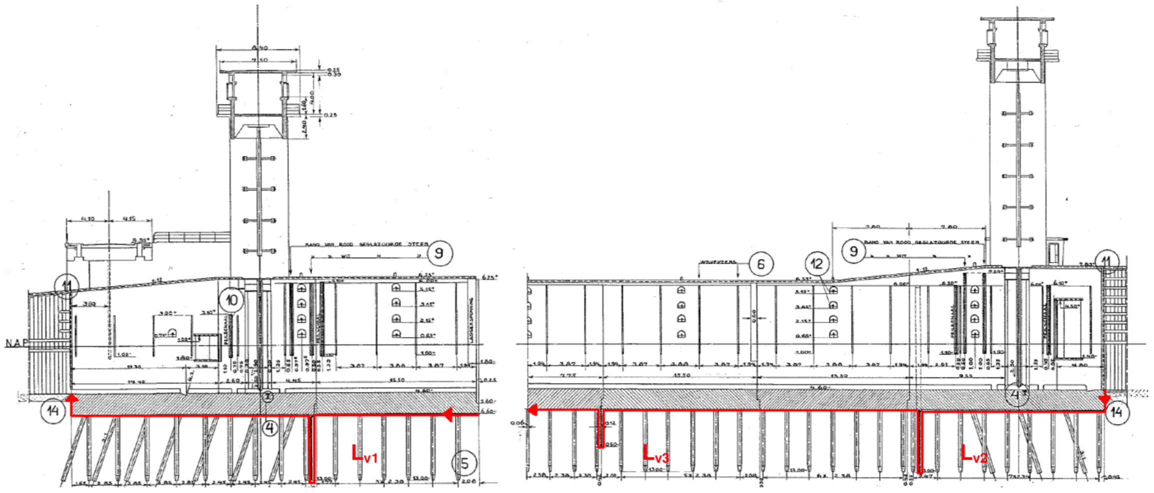


Figure 5.5: Cross-section to calculate piping length at Prinses Beatrix navigation lock (source: Rink 2011)

During construction work of the new lock chamber, loosely packed soil is removed and replaced by sand. For the calculation, it is assumed that the soil is aquiferous in the range from NAP +6.5m to NAP -20m. Therefore, a creep factor of 6 is considered. For this creep factor, the critical vertical head difference is equal to:

$$\Delta H_c = \frac{L_v + \frac{L_h}{3}}{C_{w,creep}} = \frac{L_{lane}}{C_{w,creep}} = \frac{72.4}{6} = 12.1m \tag{5.3}$$

- ΔH_c = Critical (maximum) head difference [m]
- L_v = Total vertical length [m]
- L_h = Total horizontal length [m]
- $C_{w,creep}$ = Creep factor, soil dependent (sand=7, clay=2)

The critical head difference, based on the Bligh/Lane method, equals 12.1m. The expected head difference (ΔH) is calculated based on the normative upstream and downstream water levels. For the upstream side (in the waterway ARK), the normative water level equals NAP -0.4m (regulated water level). The normative downstream water level equals NAP +7.3m. The expected head difference over the navigation lock complex equals:

$$\Delta H = H_{Lek} - H_{ARK} = NAP + 7.3m - (NAP - 0.4m) = 7.7m \tag{5.4}$$

The influence of piping is calculated based on the ratio expected head over the critical head (Equation 3.4). This gives the following ratio:

$$\frac{\Delta H_c}{\Delta H} = \frac{12.1}{7.7} = 1.57 > 1.0 \tag{5.5}$$

As a result of the large length of the navigation lock complex, in combination with the presence of seepage screens under the structure, piping will not occur for normative conditions. A safety margin of more than 50% is present (Equation 5.5). The normative conditions entail the impact of climate change and a maximum discharge level at Lobith (section 4.1.2). Therefore, the contribution to the flooding probability is considered as negligible. The failure probability of piping is estimated to be equal to 1% of the norm (1E-06 per year in 2100) (WBI, 2017).

Given the result of Equation 5.5, the contribution of piping to the flooding probability is considered as negligible. Therefore, this aspect is not normative for advancing the moment of renovation. The failure probability for piping is estimated to be equal to 1E-06 per year in 2100, based on the contribution it has on the flooding probability.

5.1.4. Storage capacity

In section 3.2.2, the principle of storage capacity relative to flood risk of the hinterland is explained. For the Prinses Beatrix navigation lock complex, the storage capacity consists of a combined basin: the ”Amsterdam Rijnkanaal (ARK)”, the ”IJ” and the waterway ”Noordzeekanaal (NZK)”. The Amsterdam-Rijnkanaal has a total length of 72 kilometres and an average width of 110m. This waterway connects via the IJ in Amsterdam with the Noordzeekanaal. On the other end, the ARK ends at the Waal close to the city of Tiel (Figure 5.6). Relevant for the storage capacity calculation is the total surface area of the adjacent basin next to the Prinses Beatrix complex. In the south, the ARK is bounded at the Prinses Irene navigation lock, close to the city *Wijk bij Duurstede*. In the northwest, the boundary is located at the IJmuiden navigation lock complex that closes off the North Sea with the Noordzeekanaal (Figure 5.6).

Figure 5.6: Location of Noordzeekanaal and Amsterdam Rijnkanaal, different scales (source: RWS Beeldbank)

The relevant waterway characteristics of the ARK, the NZK, and the IJ are summarised in Table 5.2. The surface area that has to be considered, to calculate the storage capacity, equals:

$$A_{ARK+IJ+NZK} = 58,000 * 110 + 21,000 * 270 + 10,000 * 300 = 15.05km^2 \tag{5.6}$$

In section 3.2.2, it is defined that the maximum acceptable water level increase is limited for a number of reasons. The waterboard that is responsible for the three waterways (Waternet), has a water regulation policy that prescribes a maximum deviation of 10 centimetres relative to the reference water level (Kanaalpeil, KP). For this reason, the KP can increase with a maximum of 5 centimetres over the total surface area (neglecting backwater effects and translatory waves that might take place). Using the output of Equation 5.6, the storage capacity of the ”combined basin” equals (Equation 5.7):

Table 5.2: Waterway characteristics of ARK, NZK, and IJ

	[m]
Total length ARK	72,000
Reduced length ARK	58,000
Length NZK	21,000
Length IJ	10,000
Width ARK	110
Width NZK	270
Width IJ	300

$$K = A * h_{pvh} = 15.05 * 10^6 * 0.05 = 752,500\ m^3 \tag{5.7}$$

- K = Storage capacity $[m^3]$
- A = Surface area waterway $[m^2]$
- h_{pvh} = Maximum increase in water level (ARK) [m]

Based on the output of Hydra-NL, the combination of expected overflow and overtopping, for an average frequency of occurrence of 1:10,000 per year, is presented in Figure 5.7. Given these figures, it is concluded that overflow at the Prinses Beatrix navigation lock is not expected and will, therefore, not result in a shortage of storage capacity. A remark to this conclusion is that high discharge levels are limited due to the ”Lek ontzien” policy that is valid up to 2050. Therefore, in the viewpoint of the long term vision of the renovation programme, it might be that higher discharge levels are expected in the future that do not fit the ”Lek ontzien” policy. Therefore, a quantitative analysis is elaborated that is based on the maximum overflow requirement.

The total width, including the third lock chamber, spans approximately 110m. Furthermore, literature prescribes a maximum overflow requirement of a navigation lock complex that is limited to 1000 L/m/s (section 3.2.3). Based on this requirement, the time needed to fill up the storage basin, as a result of only the combination of overflow and overtopping, equals (Equation 5.7):

$$t = K/(Q_{max} * W) = \frac{752,500}{1000 * 10{-}3 * 110} = 1.89\ hours \tag{5.8}$$

- t = period that the maximum overflow takes place [s]
- W = total width of the navigation lock complex [m]
- Q_{max} = Maximum acceptable overflow [L/m/s]

This implies that for a period of 1.89 hours, 1000 L/m/s has to overflow the navigation lock complex before the storage capacity requirement is insufficient. In practice, this amount of water can only overflow for water levels higher than NAP +7.8m, which is the level of the navigation lock in the waterway Lek. Furthermore, the surrounding embankments at the Lek will first overflow. Summarised, the contribution to the flooding probability due to insufficient storage capacity is considered as negligible. Therefore, the failure probability is estimated to be equal to 1% of the norm (1E-06 per year in 2050) (WBI,2017). After 2050, this probability might increase, depending on the policy that is adopted regarding ”Lek ontzien”.

As a result of the large storage capacity, this aspect is not considered as an indicator of the urgency of renovation for the Prinses Beatrix navigation lock. The failure probability of insufficient storage capacity is estimated at 1% of the norm, which is equal to 1E-06 per year in 2050. After 2050, modifications of the policy ”Lek ontzien” might increase the failure probability of this aspect.

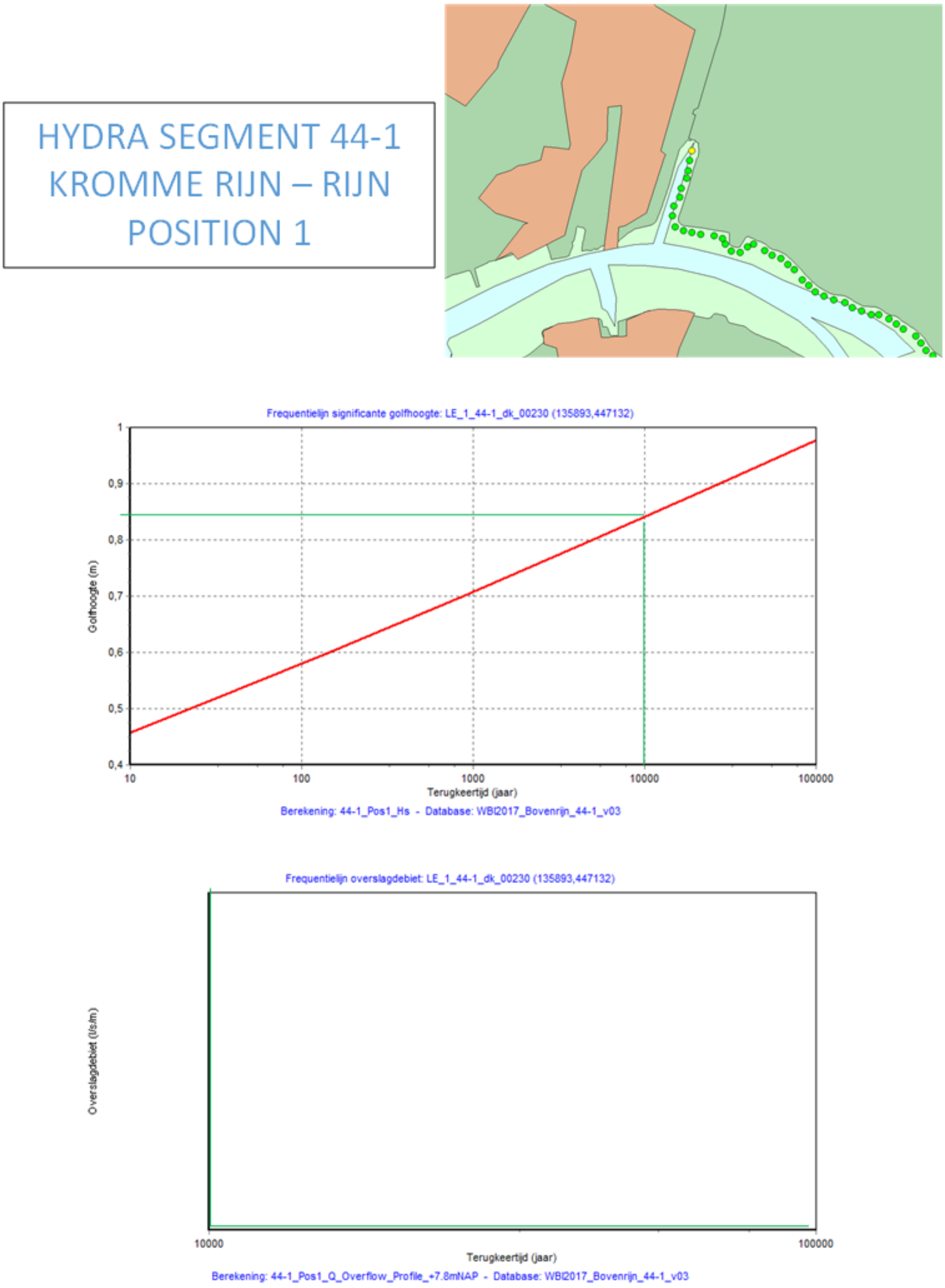


Figure 5.7: Expected wave height and overflow over the navigation lock for a given average frequency of occurrence at the Prinses Beatrix navigation lock

5.1.5. Overtopping resistance

Literature prescribes a maximum acceptable overflow capacity to safeguard the structural integrity of the hydraulic structure. Recap from section 3.2.3 gives the following maximum overflow capacity:

$$Q_{max,overflow} = 1000\ [L/m/s] \tag{5.9}$$

The impact of waves and discharge variety is calculated for a 1:10,000 per year average frequency of occurrence, to define the effect relative to the overflow resistance. For this calculation, Hydra-NL is used in which the normative conditions are used. These normative conditions are the maximum discharge levels according to the policy ”Lek ontzien” as well as a wave direction orthogonal to the navigation lock. The volume of overtopping water is calculated to check whether the overflow resistance criteria is reached over time. The result of this calculation is an expected overflow discharge that is negligible, even for an average frequency of occurrence of 1:100,000 per year. (Figure 5.7). Therefore, the failure probability is estimated again to be equal to 1% of the norm (1E-06 per year in 2050) (WBI,2017). Similar to the storage capacity, the influence of the policy ”Lek ontzien” might increase the failure probability for this aspect after 2050.

The aspect overtopping resistance is not considered as an indicator of the urgency of renovation as the expected overflow is negligible under normative conditions. The failure probability is estimated at 1% of the norm for this segment, which equals to 1E-06 per year in 2050. After 2050, modification of the policy ”Lek ontzien” might increase the failure probability again.

5.1.6. Unavailability due to high downstream water level

At the Prinses Beatrix navigation lock, the downstream side is defined as the waterway Lek side of the complex. The average discharge level in the river Rhine, that partly discharges through waterway Lek, equals 2200 m^3/s (Helpdesk Water - WVL, 2018). For discharge levels larger than 10,000 m^3/s at Lobith, the influence of the vertical tide is negligible. (Table 5.3). More frequently higher discharges are expected in the future. This results in higher discharge levels at Lobith and, depending on the interference of the ”Lek Ontzien” policy, more frequent high water levels at the Lek.

Table 5.3: Actual average water levels for a number of discharges and tides in the waterway Lek at ”Hagestein beneden” (relative to NAP)

Discharge Lobith (m^3/s)	**Average tide**		**Spring tide**		**Neap tide**	
	HW	**LW**	**HW**	**LW**	**HW**	**LW**
700	0.89	-0.48	1.01	-0.44	0.89	-0.44
1400	0.99	-0.44	1.07	-0.41	0.94	-0.40
3500	2.04	1.48	2.13	1.50	1.97	1.51
5000	2.72	2.42	2.78	2.43	2.69	2.44
6800	3.60	3.44	3.64	3.45	3.59	3.45
10000	-	-	-	-	-	-

Table 5.4: Impact on water levels due to limitation of discharges at Lobith at Vianen [metres]

	2050	2100
	Norm = 1/10,000	Norm = 1/10,000
GRADE (no limitation) [m +NAP]	6.878	7.211
GRADE (limitation at 18,000 m^3/s) [m +NAP]	6.877	7.121
GRADE (Lek Ontzien at 16,000 m^3/s) [m +NAP]	6.693	6.846
Impact (limitation at 18,000 m^3/s) [m]	-0.001	-0.100
Impact (Lek Ontzien at 16,000 m^3/s) [m]	-0.184	-0.275
Total Impact Limitation	**-0.185**	**-0.375**

Based on the research of the combined effect of tide and discharge for a norm of 1:10,000 per year, it can be concluded that water levels can be expected up to NAP +6.69m in 2050 (Table 5.4) (Deltares 2016). A remark to this is the influence of the ”Lek ontzien” policy, that results in a limitation of the maximum discharge level at the Lek (Smalle, 2016). In this research, the impact of this programme is considered as present over the period up to 2050. In section 5.1.3, it is already demonstrated that the water level at NAP +6.7m corresponds with an average frequency of occurrence of 1:10,000 per year, the norm that holds for this navigation lock complex.

The maximum downstream water level for which the levelling function is active, is limited to NAP +5.9m (Table 5.1). Based on Figure 5.4, the average frequency of occurrence that corresponds to NAP +5.9m water level equals 1:300 per year. The period of an extreme water level event (larger than NAP+5.9m) is calculated based on historical data over the last 10 years (Figure 5.8). Given the data, this period is estimated over 48 hours per event. The unavailability can be calculated based on the average frequency of occurrence of the event multiplied by the period that the event occurs. The unavailability of the levelling function due to high downstream water level conditions (HDWL) in 2020 equals:

$$Unavailability_{HDWL,2020} = F_{occurrence} * T_{event} = 1:300 * 48 = 0.16\, hours/year \tag{5.10}$$

Based on an expert review (Deltares, 2018), it is estimated that the average frequency of occurrence corresponding to a water level of NAP +5.9m, is equal to 1:100 per year in 2100. The period of the high water level event increases up to 72 hours. Therefore, the unavailability of the levelling function due to high downstream water level conditions (HDWL) in 2100 equals:

$$Unavailability_{HDWL,2100} = F_{occurrence} * T_{event} = 1:100 * 72 = 0.72\ hours/year \tag{5.11}$$

As a result of high downstream water level events, due to more frequent discharge variety, the unavailability of the levelling function is expected to be 0.16 hours/year in 2020 and will increase up to 0.72 hours/year in 2100. These low unavailability values are dependent on the ”Lek ontzien” policy. The unavailability of the levelling function can increase faster if the maximum discharge at waterway Lek will increase.

The unavailability of the levelling function due to high downstream water levels equals 0.16 hours/year in 2020 and will increase up to 0.72 hours/year in 2100.

5.1.7. Unavailability due to low downstream water level

Low water levels in the waterway Lek result in a limited maximum draught of vessels which implies less or no transport at all, depending on the type of vessel. Low water level situations in the waterway Lek are derived from a RAMS-analysis and a time-series of the water level over the last 10 years (Figure 5.8).

The lowest recorded water level in the waterway Lek is NAP -1.35m, recorded back in 1996 (Table 5.5) due to malfunction. The levelling function is interrupted at the moment that the water level on the Lek side equals NAP -0.6m for the design vessels M8. Interviews are conducted during a RAMS-analysis study in 2011 (Van den Dungen, E.L.E., 2011). The outcome of these interviews is that the unavailability of the Prinses Beatrix navigation lock for the levelling function due to low downstream water levels (LDWL) is equal to 3.84% of the operational hours (OH) in 2011 (Equation 5.12). This unavailability is based on the design vessel M8. It is assumed that the unavailability of 2011 is equal to the unavailability in 2019.

Table 5.5: Downstream low water level events (Deltares, 2011)

Event	water level [NAP]
Lowest recorded (March 12, 1996)	-1.35
OLW	-0.47

Given the data of Figure 5.8, it is calculated whether the unavailability, as defined in Equation 5.12, corresponds with the RAMS-analysis output. The data on which this figure is based, gives 0.256% of the OH, a water level of -0.6m NAP or lower in the period 2008-2018 (Equation 5.13). The reason for the difference between this outcome and the one given in the RAMS-analysis (Equation 5.12), is that the annual unavailability is considered for the design vessel M8. This implies that smaller vessels, with limited draught, might still be levelled during lower water level conditions. However, environmental reasons prevent any further levelling of vessels.

$$Unavailability_{LDWL,2011} = Unavailability * OH = 3.84\% * 8736h = 336\ hours/year \tag{5.12}$$

$$Unavailability_{LDWL,2008-2018} = Unavailability * OH = 0.256\% * 8736h = 22.4\ hours/year \tag{5.13}$$

For the capacity expansion of the Prinses Beatrix navigation lock complex, a hydraulic boundary condition study has been conducted (Meijerink,2015). In this report, it is stated that the expected unavailability for the levelling function in the period 2020-2050 is estimated to P_{unav}=2% of the OH, after the third lock chamber is operational. This implies an expected unavailability of 175 hours/year (Equation 5.14). Expert judgement (Meijerink, 2018) defines that over the period 2050-2100, the unavailability increase up to P_{unav}=4% of the OH. A remark to this statement, the exact unavailability is hard to define as the ”Lek ontzien” policy might change after 2050 (section 4.1).

$$Unavailability_{LDWL,2020-2050} = P_{unav} * operationalhours = 2\% * 8736h = 175\ hours/year \tag{5.14}$$

$$Unavailability_{LDWL,2050-2100} = P_{unav} * operationalhours = 4\% * 8736h = 350\ hours/year \tag{5.15}$$

The unavailability of the levelling function, due to low downstream water levels in 2020, equals 336 hours/year. The new lock chamber is not considered as operational in this result. In the period 2020-2050, the unavailability is expected to be 175 hours/year. In the period 2050-2100, the unavailability of the navigation lock complex increases up to 4% of the OH, which is equivalent to 350 hours/year.

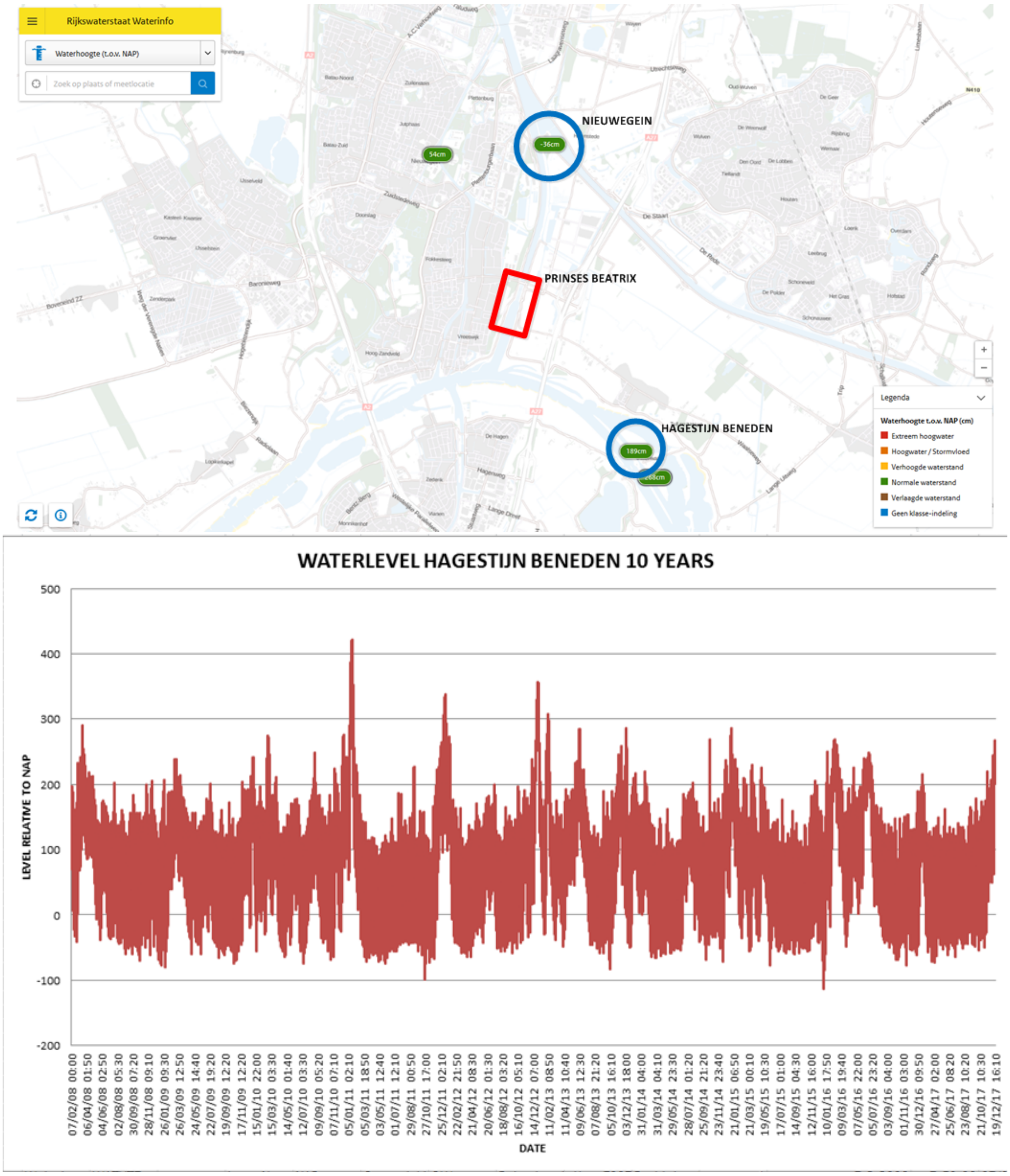


Figure 5.8: Location of measurements and water level characteristics in a 10-year period (source: Waterinfo RWS)

5.1.8. Unavailability due to high upstream water level

The location of the upstream water level is defined as the water level at the side of the Amsterdam-Rijnkanaal (ARK). In section 3.2.2, the water management policy of Waternet (waterboard) is explained, regarding water level fluctuations in the ARK. Due to this policy, the maximum water level deviation equals 0.1 metres. This means a maximum water level upset of 5cm. If higher water levels are expected, as a result of significant rainfall and runoff, discharge sluices are activated at IJmuiden, to drain off the water. Over the last 10 years, the high upstream water level (HUWL) conditions resulted in 5 events for which the nautical function was interrupted (Figure 5.9). The period of the event is assumed to be 48 hours per event. Based on research, an increase of rainfall of 9% is expected up to 2050 (STOWA, 2015) (section 4.1.2). Assuming that this rainfall is equally distributed over the country, the increase of run-off towards the ARK or NZK as well as discharged water is expected to be equal to P=9%. In the period 2050-2100, a conservative safety factor of α=1.5 is assumed (Meijerink, 2018). The unavailability of the levelling function in the periods 2020, 2020-2050, and 2050-2100, are calculated based on this information (Equations 5.16 to 5.19).

$$Downtime_{HUWL,2020} = number\ of\ events * T_{event} = 5 * 48h = 240\ hours\ in\ 10\ year \quad (5.16)$$

$$Unavailability_{HUWL,2008-2018} = \frac{Downtime}{Period\ of\ 10\ years} = \frac{240}{10} = 24\ hours/year \quad (5.17)$$

$$Unavailability_{HUWL,2020-2050} = \mathrm{P}*Unavailability_{HUWL,2008-2018} = 1.09*24 = 26.2 hours/year \quad (5.18)$$

$$Unavailability_{HUWL,2050-2100} = \alpha*Unavailability_{HUWL,2020-2050} = 1.5*26.2 = 39.3 hours/year \quad (5.19)$$

The unavailability of the levelling function equals to 24 hours/year in 2020. This unavailability will increase up to 26.2 hours/year in the period 2020-2050. In the period 2050-2100, the unavailability of the levelling function will increase up to 39.3 hours/year.

5.1.9. Unavailability due to low upstream water level

The unavailability due to low upstream water level (LUWL) conditions occurs more frequently during the summer season (section 4.1). The levelling function of the Prinses Beatrix navigation lock is interrupted for water levels lower than NAP -0.6m at the ARK. Given the data of Figure 5.9, it is calculated that the levelling function interruption equals $\mathrm{P}_{\mathrm{unav}}$ = 0.3% OH in the period 2008-2018. It is assumed that the unavailability in 2020 is equal to 0.3% as calculated in the period 2008-2018. The unavailability as a result of low upstream water level conditions in 2020 equals:

$$Unavailability_{LUWL,2020} = P_{unav} * OH = 0.3\% * 8736h = 26.2\ hours/year \quad (5.20)$$

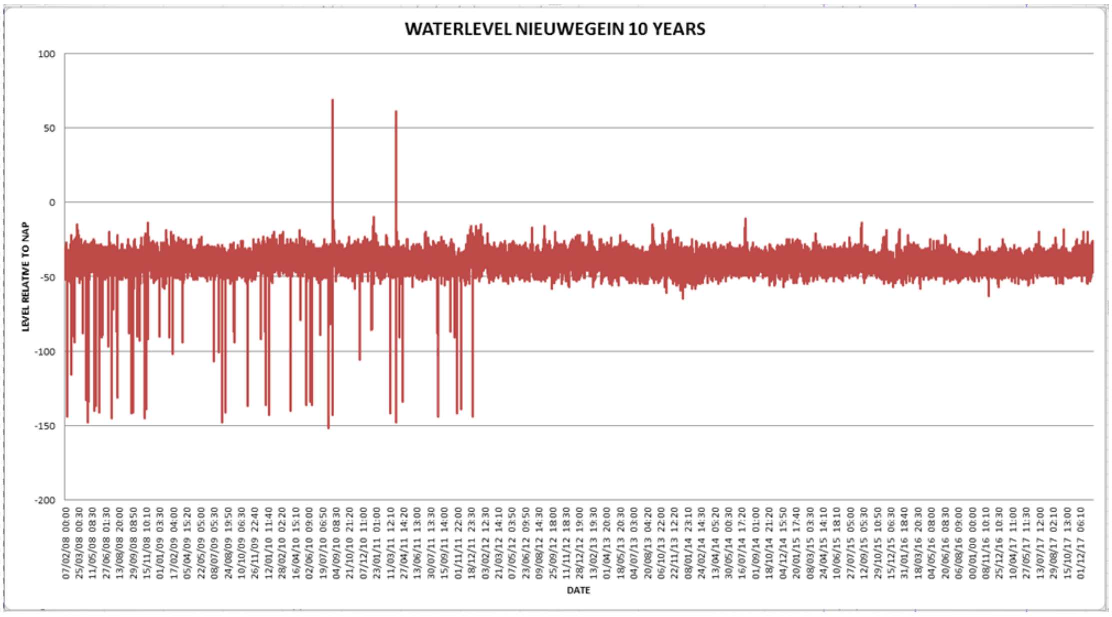


Figure 5.9: Water level characteristics in a 10-year period (source: Waterinfo RWS)

In section 4.1.3, a combination of the rainfall deficit and evaporation as a result of dry periods, based on the W+ climate scenario, is expected to rise up to an average Δ2050 = 50% in the period 2020-2050 and Δ2100 = 100% in the period 2050-2100. The results of these events are used as a parameter to determine the unavailability of the levelling function in the future. Based on these values, the expected unavailability of the Prinses Beatrix navigation lock, due to low upstream water levels, is calculated for the periods 2020-2050 and 2050-2100 in Equations 5.21 and 5.22.

$$Unavailability_{LUWL,2020-2050} = \Delta 2050 * Unavailability_{LUWL,2020} = 1.5*26.2h = 39.3 hours/year \tag{5.21}$$

$$Unavailability_{LUWL,2050-2100} = \Delta 2100 * Unavailability_{LUWL,2020} = 2.0*26.2 = 52.4 hours/year \tag{5.22}$$

The unavailability of the levelling function due to low upstream water levels in 2020 is equal to 26.2 hours/year. In the period 2020-2050, this unavailability increases up to 39.3 hours/year. The unavailability increases up to 52.4 hours/year in the period 2050-2100.

5.1.10. Intensity/Capacity economy 2015

In 2014, the Department of Traffic and Nautical Information at Rijkswaterstaat, (Dienst Verkeer en Scheepvaart, (DVS)", conducted research focussing on the development of the nautical sector in the coming 30 years. In this research, the scenarios as defined in section 4.2, are used (Table 5.6 and 5.7). In this research, the effect of the capacity expansion is taken into account, from 2020 onwards. The third lock is operational since 2019.

Table 5.6: Prognosis nautical transport Prinses Beatrix navigation lock complex

	2015	**2020**	**2030**	**2040**
Total transported cargo [mln ton]	41.2	46.0	54.2	62.5
Lockages (without 3rd lock chamber) [x 1.000]	48.9	51.3	60.7	66.8
Lockages (including 3rd lock chamber) [x 1.000]	48.9	51.3	58.3	65.4

Table 5.7: Sensitivity analysis nautical transport Prinses Beatrix navigation lock complex

	Strong Europe				**Global Economy**			
	2015	**2020**	**2030**	**2040**	**2015**	**2020**	**2030**	**2040**
Total transported cargo [mln ton]	38.1	41.3	46.7	52.6	43.8	50.2	65.8	65.8
Lockages (without 3rd lock chamber) [x 1.000]	45.2	46.1	52.3	56.2	52.0	56.0	73.8	73.8
Lockages (including 3rd lock chamber) [x 1.000]	45.2	46.1	50.2	55.0	52.0	56.0	70.8	85.1
I/C (without 3rd lock chamber)	0.5	0.6	0.6	0.7	0.6	0.7	0.9	1.0
I/C (including 3rd lock chamber)	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.6

In the period 2015-2040, the number of lockages (levelling cycles) at the Prinses Beatrix navigation lock increases by almost 20% relative to the reference year 2015 (Table 5.7). This holds for both the existing situation of the two lock chambers as well as after the capacity expansion. The total transported cargo increases by 30% relative to the reference year 2015 up to 2040. The latter fact is the result of increasing cargo capacity of larger vessels.

In section 4.3, the impact of the Mobility Act is explained. This act defines that the maximum waiting time at a lock passage is limited to 30 minutes, which is equivalent to an intensity and capacity ratio of $I/C_{max} = 0.5$. Given the data of Table 5.7, it is concluded that the I/C requirement is reached, for which capacity shortage is expected. This was the trigger for expanding the capacity of the navigation lock complex.

The requirement of the $I/C_{max} = 0.5$ is reached in 2015. This implies a capacity shortage relative to the intensity. Therefore, the third lock chamber is constructed at the Prinses Beatrix complex and operational since 2019. In section 5.1.11, the effect of intensity growth up to 2040 is considered.

5.1.11. Intensity/Capacity economy 2040

The study conducted by Rijkswaterstaat's DVS in 2014, considered a period of 25 years. This limited scope, in the viewpoint of civil engineers, is due to the fact that economic uncertainties increase significantly over time (expressed in the so-called bandwidth between the different prognoses), which result in less reliable scenarios (section 4.3 and Figure 5.10). Based on the data of Table 5.7, the capacity shortage is expected in 2040, in which the capacity increase by the third lock chamber is considered. From 2040-2100, assuming an annual average economic growth of 1.4%, this I/C value will reach values>1 in 2100 which is devastating for the transport sector. A remark to this statement is that a cascading effect might be possible in the HVWN as multiple navigation lock complexes have to handle the same intensity flow.

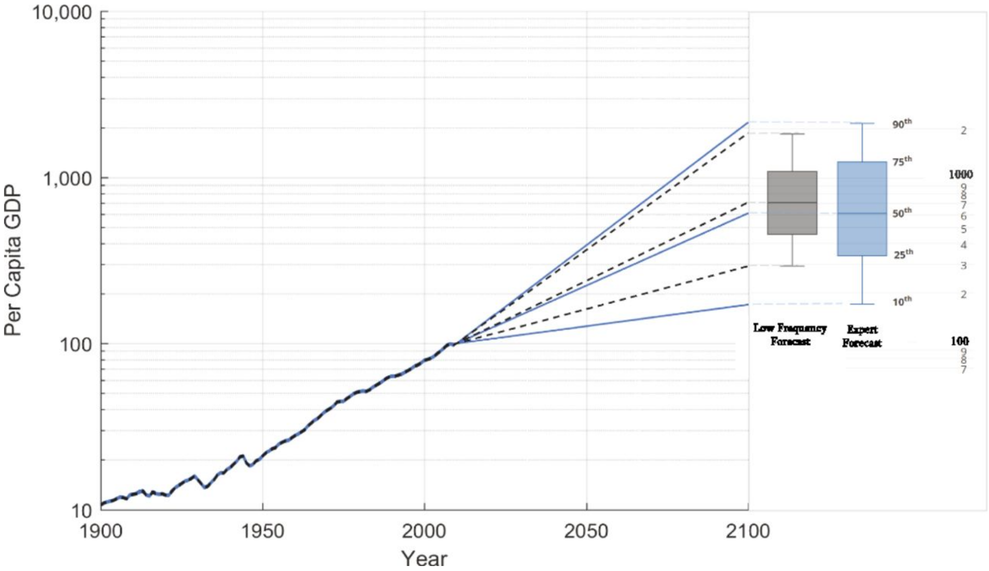


Figure 5.10: Uncertainty in the forecasts of the long-run economic growth (source: PNAS, 2018)

In the period 2040-2100, the expanded capacity of the Prinses Beatrix navigation lock complex is expected to be insufficient. The requirement of $I/C_{max} = 0.5$ is reached in 2040, in which the third lock chamber is operational.

> The intensity as a function of the capacity of the Prinses Beatrix navigation lock is exceeding the norm of $I/C_{max} = 0.5$ after 2040. In this calculation, the increased capacity, by means of a third lock chamber, is embedded. Assuming a reasonable economic growth after 2040, a capacity shortage is again the result.

5.1.12. Unavailability due to scheduled maintenance

Scheduled maintenance is in this research defined as the level of maintenance that requires planning, allocation of a significant amount of time, and a high degree of coordination between different departments to keep the performance of the navigation lock according to the standards. Ageing of material is the main driver for maintenance.

In 2011, IV-Infra conducted a RAMS analysis regarding the performance of the complex in which the water-retaining function and the levelling function were assessed (Van den Dungen, E.L.E., 2011). Scheduled maintenance is variable according to the interviews with the asset manager of the Prinses Beatrix navigation lock complex. Renovation of revetment and maintenance of the gates in not regular every year. Renovation of the revetment is executed in 2010, resulting in a downtime of 18 days. It is expected that this renovation will last for the coming 50 years. The gates are renovated in 2011 and need no maintenance in the coming 25 years. Another maintenance is expected to not affect the levelling function of the navigation lock. Based on the large interventions, the annual unavailability is equal to P_{unav}=0.226% OH (Van den Dungen, E.L.E., 2011).

$$Unavailability_{maintenance,2020} = P_{unav} * OH = 0.226\% * 8736h = 20\ hours/year \tag{5.23}$$

For the period 2020-2060, the expected increase of the unavailability is estimated based on expert judgement. The result is an expected increase in the unavailability of α = 20% relative to the unavailability in 2020. Therefore, the unavailability in the period 2020-2060 is estimated on:

$$Unavailability_{maintenance,2020-2060} = 1.2 * Unavailability_{maintenance,2020} = 1.2 * 20 = 22 hours/year \tag{5.24}$$

The unavailability due to scheduled maintenance equals 20 hours/year in 2020. In the period 2020-2060, this unavailability is expected to increase up to 22 hours/year.

5.1.13. Unavailability due to technical failure

Technical failure can have a number of causes for the Prinses Beatrix complex. In the RAMS analysis by IV-Infra, all causes for technical failure are defined. Based on this information, a subset is defined. In this subset, fire collision of vessels, human error and power shutdown have the highest contribution to the unavailability of the levelling function.

The probability of fire in one of the compartments is estimated at 2.56E-03 per year. It is assumed that the repair time is equal to two weeks or equivalent 336 hours. The unavailability as result of fire is therefore:

$$Unavailability_{techfail,fire,2020} = P_{year} * T_{repair} = 2.56E-03 * 336 = 0.86\, hours/year \quad (5.25)$$

Collision of a vessel resulting in unavailability of the levelling function is estimated at once in 35 years (best practice). It is assumed that the repair time is equal to 168 hours.

$$Unavailability_{techfail,collision,2020} = P_{year} * T_{repair} = 1/35 * 168 = 4.8\, hours/year \quad (5.26)$$

For human error, power shutdown, and ice situations, expert judgement defines an unavailability of 55 hours/year. The total unavailability of the levelling function is the sum of the aforementioned subset (Equation 5.27).

$$Unavailability_{techfail,2020} = 0.86 + 4.8 + 55 = 60.7\, hours/year \quad (5.27)$$

Ageing will increase the unavailability of the levelling function. Nevertheless, experts at Rijkswaterstaat do not expect that this increase will be more than 20% relative to the unavailability in 2020. Therefore, the unavailability for the period 2020-2060 is calculated (Equation 5.28).

$$Unavailability_{techfail,2020-2060} = 1.2 * Unavailability_{techfail,2020} = 1.2 * 60.7 = 72.8 hours/year \quad (5.28)$$

The unavailability of the levelling function due to technical failure equals 60.7 hours/year in 2020. In the period 2020-2060, the unavailability is expected to increase by 20% to be up to 72.8 hours/year.

5.1.14. Overview assessment

The assessment of piping under normative conditions results in an additional safety margin of more than 50%. The contribution to the flooding probability is therefore considered as negligible and makes this aspect not normative in the urgency of renovation. The same conclusion holds for the storage capacity. The ”combined basin” at the Northern side of the Prinses Beatrix navigation lock complex is for extreme conditions still sufficiently large. The failure of the adjacent embankments at the Lek is more likely, considering the overflow value that is used in this assessment. The overflow resistance is, for normative conditions, sufficient as expected overflow is not reaching the limit value.

The unavailability as a result of high downstream water level conditions is negligible. The influence of the ”Lek ontzien” policy is normative, as this policy prescribes maximum discharge values in the waterway Lek. The low downstream water level conditions however, give a large unavailability of the nautical function. This will increase even further over time and is, therefore, considered as normative in the urgency of renovation. The high and low upstream water level conditions give a moderate unavailability. This is the result of water management policies regulated by the waterboard (Waternet) in the ARK.

The intensity increase as a function of the capacity of the navigation lock is also normative. In 2015, the I/C ratio gave results that indicate capacity shortage starting from 2015. Since 2019, the new lock chamber is operational. However, a capacity shortage is expected again in 2040. Assuming positive economic growth, congestion in the HVWN can be expected.

Finally, the unavailability of the nautical function due to ageing is primarily driven by technical failures. The effect of scheduled maintenance on the availability is moderate. Technical failures, on the contrary, result in an unavailability that contributes to almost 35% of the SLA requirement for the unavailability of primary navigation locks in 2020.

5.2. Terneuzen Navigation Lock Complex

The Terneuzen navigation lock complex is the only barrier in the waterway ”Kanaal Gent-Terneuzen (KGT)” which connects the port of Gent (Belgium) with the Westerschelde tidal basin. The existing complex consists of three navigation lock chambers, defined as East, Middle and West respectively. The Eastern lock chamber is, together with the Western lock chamber, opened in 1966 and scheduled for renovation in 2075 according to the V&R programme. The Western lock chamber is, until the opening of the new Middle lock chamber, the largest one and scheduled for renovation in 2076. The construction of a new lock chamber (Middensluis) is now executed and replaces the existing smallest middle lock chamber, which was scheduled for renovation in 2034 according to the V&R programme (Figure 5.11). For context, the new ”Middensluis” has more or less the same dimensions as the new navigation lock complex in Panama (Central America).

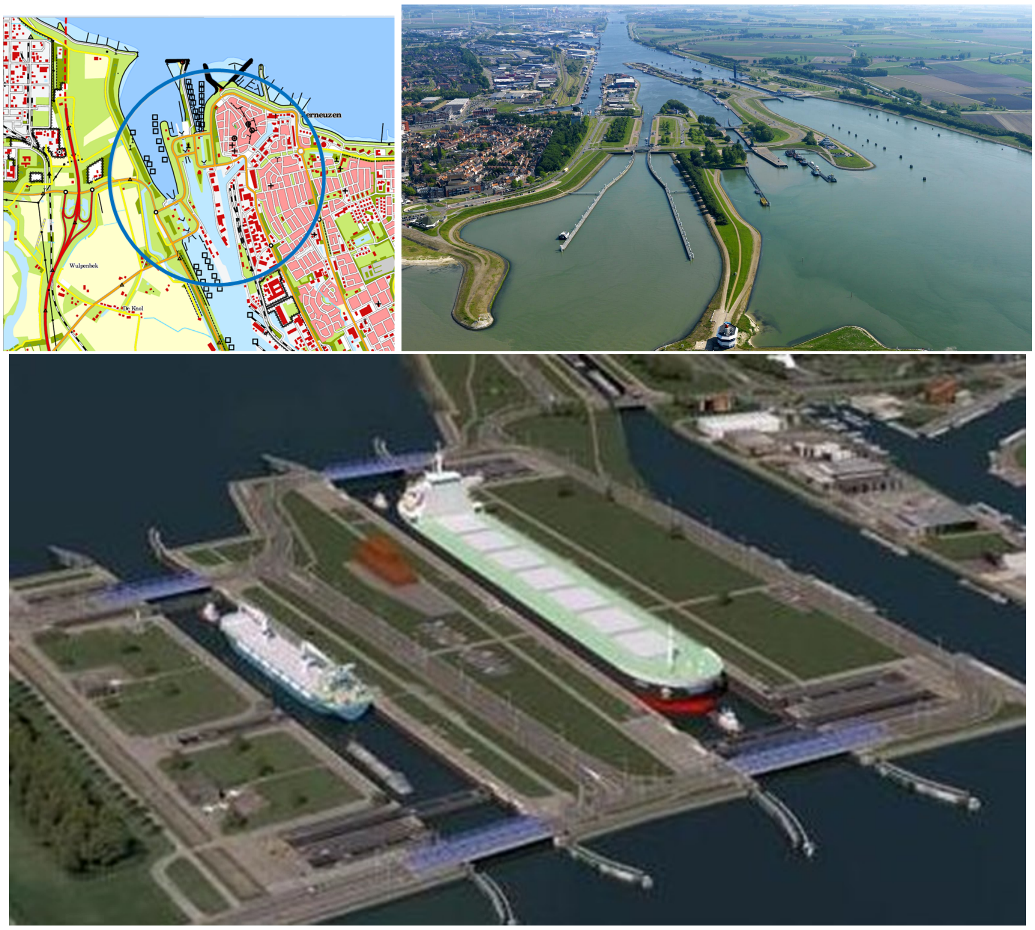


Figure 5.11: Location of the complex (upper left), an overview of existing complex (upper right), and an artist impression of the Terneuzen navigation lock complex after replacement of the Middensluis (bottom)

All the aspects of the proposed method, as defined in section 2.5, are assessed and reviewed relative to their norm or requirement according to the Water Act or Mobility Act. For the flood safety function, a failure probability of 1% relative to the norm is applied in the criticality assessment, if the contribution to the probability of flooding is considered as negligible (for normative conditions) (WBI, 2017). For the Terneuzen navigation lock complex, this entails a failure probability of 1% of 1:1,000 = 1E-05 per year in 2100.

5.2.1. Boundary conditions

The data of Table 5.8 is retrieved from the RINK reports of Terneuzen navigation lock complex and the Sluizenboekje (Van Erp and Van Corven, 2017). Not all the data for the new Middle lock chamber was available at the moment of conducting this research. As the Middle lock chamber is replaced at the moment, the assessment is focused on the existing Eastern and Western lock chamber that is scheduled for renovation in 2075 and 2076 respectively according to V&R.

Table 5.8: Boundary conditions Terneuzen navigation lock complex

	Unit	54E-001-01 (East)	54E-001-04 (Middle, old)	54E-001-01 (Middle, new)	54E-001-07 (West)
Length	[m]	258	140	427	245
Width	[m]	23.5	24	55	38
MHW_WS	[m NAP]	2.3	2.3	2.3	2.3
MLW_WS	[m NAP]	-1.9	-1.9	-1.9	-1.9
LAT_WS	[m]	-3.5	-3.5	-3.5	-3.5
Actuators	[m NAP]	3.90			6.00
Outerhead_WS	[m NAP]	6.0			6.0
MHW_KGT	[m NAP]	2.38	2.38	2.38	2.38
MLW_KGT	[m NAP]	1.88	1.88	2.38	1.88
MWL_KGT	[m NAP]	2.13	2.13	2.13	2.13
Max Levelling	[m NAP]	3.5	2.3		3.5
Min Levelling	[m NAP]	-1.2	-0.5		-3.5
Sill level	[m NAP]	-6.5		-16.5	-12.8
Draught max	[m]	4.3			12.5
Renovation V&R	[year]	2075	2034	-	2076
Discharge average	[m^3/s]	90	100		130
Design vessel	[CEMT]	VIa = M10		VIb = C4	VIb = C4
Underseepage barrier	[m NAP]	-17			-17.7

During the design period of the new Middle lock chamber, the new assessment framework (WBI2017) was not in operation. According to the new Water Act, the Terneuzen navigation lock complex is part of the dike segment 32-3 (Zeeuwsch Vlaanderen 3) for which the norm is set at 1:1,000 per year. In the remainder of the assessment, all the hydraulic load situations are derived from this norm.

Operational conditions

The levelling function of the Eastern lock chamber is performed for water levels ranging between NAP -1.20m and NAP +3.50m for the Eastern lock chamber. For the larger Western lock chamber, this range is between NAP -3.50m and NAP +3.50m as the level of the sill is more than six metres deeper than the Eastern lock chamber. For water levels that are not within this range, the levelling function is interrupted and the complex functions as a flood safety barrier.

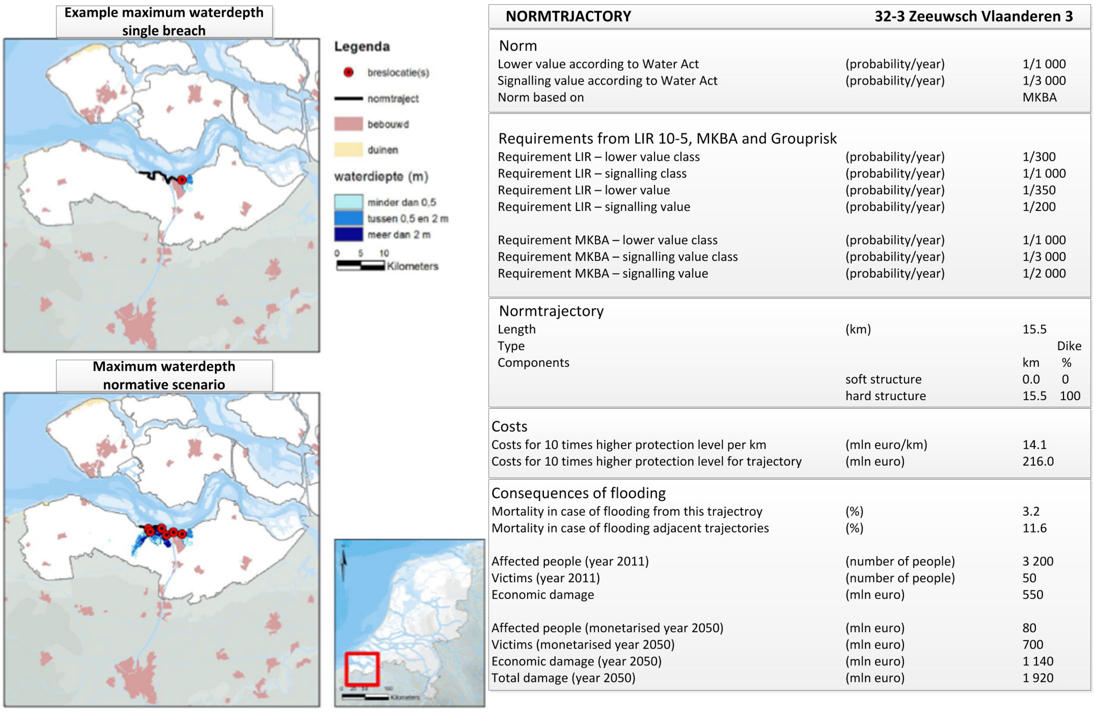
All the aforementioned design water levels exclude a robustness parameter of 0.1m (Expertise Network for Flood Protection (ENW), 2007). This additional safety margin is for uncertainties in high water levels and NAP-declination during the design period. Nevertheless, in this assessment, the extreme conditions are considered which imply maximum or minimum hydraulic boundary conditions. Therefore, the additional robustness parameter, that is in general used for designing hydraulic structures, is not additionally considered.

5.2.2. New standards

The Terneuzen navigation lock complex is since the introduction of the New Standards, part of segment 32-3, Zeeuwsch Vlaanderen 3 (Figure 5.12). According to these new regulations, a norm of 1:1,000 per year is defined for this segment. This norm implies the maximum acceptable flooding probability that is given to this segment, based on a social cost-benefit analysis (MKBA) of the protected hinterland. Compared to the Prinses Beatrix navigation lock complex, these safety norms are less strict, due to the lower expected amount of damage in this region. The definitions of the most important aspects of the table in Figure 5.12 are defined below:

- The upper left map presents a simulation of the maximum water depth in case of a breach during normative hydraulic boundary conditions
- LIR is the abbreviation of Local Individual Risk that is set at 10E-05
- Economic damage is the actual monetary damage multiplied by 1.5 that incorporates indirect losses and a risk premium

> The new standard for segment 32-3 Zeeuwsch Vlaanderen 3 = 1:1,000 per year. The Terneuzen navigation lock complex, that is part of this segment, has to be able to withstand hydraulic loads that correspond to this norm.



NORMTRJACTORY		32-3 Zeeuwsch Vlaanderen 3	
Norm			
Lower value according to Water Act	(probability/year)	1/1 000	
Signalling value according to Water Act	(probability/year)	1/3 000	
Norm based on		MKBA	
Requirements from LIR 10-5, MKBA and Grouprisk			
Requirement LIR – lower value class	(probability/year)	1/300	
Requirement LIR – signalling class	(probability/year)	1/1 000	
Requirement LIR – lower value	(probability/year)	1/350	
Requirement LIR – signalling value	(probability/year)	1/200	
Requirement MKBA – lower value class	(probability/year)	1/1 000	
Requirement MKBA – signalling value class	(probability/year)	1/3 000	
Requirement MKBA – signalling value	(probability/year)	1/2 000	
Normtrajectory			
Length	(km)	15.5	
Type			Dike
Components		km	%
	soft structure	0.0	0
	hard structure	15.5	100
Costs			
Costs for 10 times higher protection level per km	(mln euro/km)	14.1	
Costs for 10 times higher protection level for trajectory	(mln euro)	216.0	
Consequences of flooding			
Mortality in case of flooding from this trajectroy	(%)	3.2	
Mortality in case of flooding adjacent trajectories	(%)	11.6	
Affected people (year 2011)	(number of people)	3 200	
Victims (year 2011)	(number of people)	50	
Economic damage	(mln euro)	550	
Affected people (monetarised year 2050)	(mln euro)	80	
Victims (monetarised year 2050)	(mln euro)	700	
Economic damage (year 2050)	(mln euro)	1 140	
Total damage (year 2050)	(mln euro)	1 920	

Figure 5.12: Factsheet norm segment 32-3 Zeeuwsch Vlaanderen 3 (source: Factsheets Normering Primaire Waterkeringen, edited)

5.2.3. Piping

The impact of sea level rise for the Terneuzen navigation lock complex follows directly from the KNMI climate scenario. According to the W+ scenario (section 3.1), a sea level rise of 0.85m is expected for the year 2100 in front of the Terneuzen complex.

For the replacement of the new Middle lock chamber at Terneuzen, an analysis of the hydraulic boundary conditions is conducted by Rijkswaterstaat. In this report, the expected water levels for a standard of 1:4,000 per year are calculated, which is a more stringent norm than the actual 1:1,000 per year that holds for this navigation lock complex. For the norm of 1:1,000 per year, the expected water levels including sea lever rise are calculated (Table 5.9). Remark to this calculation, the V&R programme defined the renovation year for the Eastern and Western lock chamber in 2075 and 2076 respectively. Comparing the values of Table 5.9 and Table 5.8, the expected water levels with sea level rise give values that are larger than the height of the navigation lock at the Westerschelde side (NAP +6.0m).

Table 5.9: Expected water levels for W+ climate scenario for a norm of 1:1,000 per year

	2030 W+	**2070 W+**	**2100 W+**
MHW Terneuzen [m NAP]	+5.50	+5.50	+5.50
Sea level rise [m]	0.22	0.58	0.85
Error in sea level rise Scenario W+ [m]	-0.05	-0.05	-0.05
Water level with sea level rise [m NAP]	**+5.67**	**+6.03**	**+6.30**
Robustness parameter [m]	0.20	0.20	0.20
Total water level [m NAP]	**+ 5.87**	**+ 6.03**	**+ 6.50**

For the coastal-oriented Terneuzen navigation lock complex, the expected sea level rise equals 0.85m in 2100, based on the W+ climate scenario. In 2100, water levels up to NAP +6.5m can be expected, assuming the W+ climate scenario, which is higher than the height of the navigation lock at the Westerschelde side.

Based on the aforementioned information, the piping aspect is calculated for both the Eastern and the Western lock chambers. The formulae by Bligh and Lane are used to assess the piping length, combined with input from Table 5.8. The failure probability requirement of an individual hydraulic structure can be calculated (section 3.2). For a 1:1,000 per year norm, a shape factor of 0.02, and a length factor of 1, the failure probability requirement equals:

$$P_{req,dsn} = \frac{P_{max} * \omega_{PIkw}}{N_{PIkw}} = \frac{1:1,000 * 0.02}{1} = 2E-05\ [/year] \tag{5.29}$$

The water level that corresponds to this failure probability is calculated with the software Hydra-NL and equals NAP +7.6m at the Westerschelde (Figure 5.13). The execution point is indicated in yellow and located in front of the main entrance. Due to the non-similarity of both lock chambers, the remaining elaboration is executed in parallel for the Eastern and the Western lock chambers respectively.

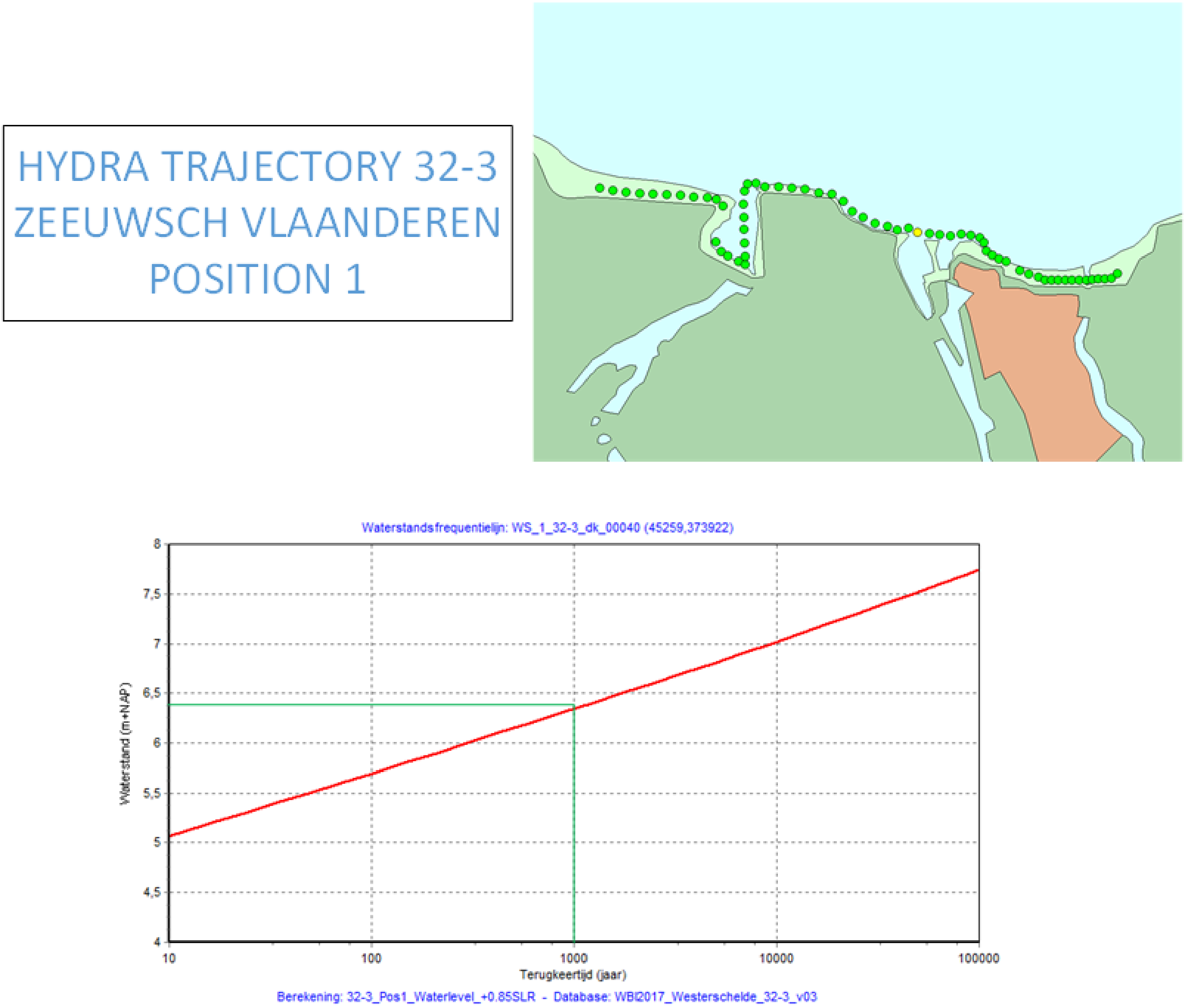


Figure 5.13: Expected water level for a given average frequency of occurrence located in front of the Terneuzen navigation lock complex

EASTERN LOCK CHAMBER

Based on the data of the Tables 5.8 and 5.10 and Figure 5.14, the piping length (assuming Lane approximation) can be calculated given Equation 5.30:

$$L_{lane} = L_v + \frac{L_h}{3} = 9.5 + 7.4 + 3.4 + 8.0 + \frac{384}{3} = 156.3m \tag{5.30}$$

Table 5.10: Parameters to determine the piping length of the Eastern navigation lock chamber at Terneuzen

Level start [m + NAP]	Level end [m + NAP]	Symbol	Value [m]
-9.6	-9.6	L_h	384
-7.5	-17.0	L_v1	9.5
-17.0	-9.6	L_v2	7.4
-9.6	-13.0	L_v3	3.4
-13.0	-5.0	L_v4	8.0
-3.5	-11.0	L_v1a	7.5
-11.0	-9.6	L_v2a	1.4
-11.0	-11.0	L_ha	16.8

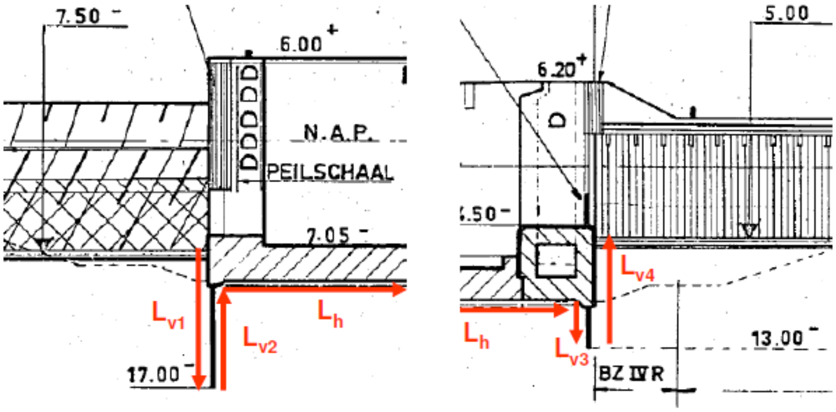


Figure 5.14: Cross-section to determine the piping length at the Terneuzen Eastern navigation lock chamber (source: Rink 2011)

The RINK study that is conducted in 2011 (Celie, 2011) for the Terneuzen navigation lock complex, gives information about the geotechnical subsoil conditions. For this particular location, it is defined that a creep factor of 8.5 has to be considered to determine the piping length. Given this creep factor, the maximum vertical head difference over the complex is defined as (Equation 5.31):

$$\Delta H_c = \frac{L_v + \frac{L_h}{3}}{C_{w,creep}} = \frac{L_{lane}}{C_{w,creep}} = \frac{156.3}{8.5} = 18.4m \tag{5.31}$$

- ΔH_c = Critical (maximum) head difference [m]
- L_v = Total vertical length [m]
- L_h = Total horizontal length [m]
- $C_{w,creep}$ = Scale parameter, soil dependent (sand=7, clay=2)

The critical head difference, based on the Bligh/Lane method, for the Eastern lock chamber, equals 18.4m. The governing conditions for which the vertical head difference over the lock chamber is maximum, hold for LAT conditions in the Westerschelde and maximum water level in the waterway ”Kanaal Gent-Terneuzen”. A remark to this is that the LAT conditions are likely to increase over time due to the impact of sea level rise, as given in Table 5.9. The expected head difference (ΔH) is calculated based on the normative upstream and downstream water level. There are two options: high upstream and low downstream water level conditions or vice versa. For the Terneuzen navigation lock, the normative situations hold for LAT at the Westerschelde (NAP -3.5m) high upstream water level at KGT (NAP +2.38m). The expected head difference over the navigation lock complex equals:

$$\Delta H = H_{KGT} - H_{Westerschelde} = NAP + 2.38m - NAP - 3.5m = 5.88m \tag{5.32}$$

The influence of piping is calculated based on the ratio of the expected head to the critical head (Equation 3.4). This gives the following result:

$$\frac{\Delta H_c}{\Delta H} = \frac{18.4}{5.88} = 3.13 >> 1.0 \tag{5.33}$$

As a result of the large length of the Eastern lock chamber, in combination with the presence of seepage screens under the structure, piping will not occur for normative conditions. Therefore, the contribution to the flooding probability is considered as negligible. The failure probability of piping is estimated to be equal to 1% of the norm (1E-05 per year in 2100) (WBI, 2017).

Given the result of Equation 5.33, the contribution of piping to the flooding probability is considered as negligible for the Eastern lock chamber. Therefore, this aspect is not normative for advancing the moment of renovation. The failure probability for piping is estimated to be equal to 1E-05 per year in 2100, based on the contribution it has on the flooding probability.

WESTERN LOCK CHAMBER

Based on the data of the Tables 5.8 and 5.11 and Figure 5.15, the piping length (assuming Lane approximation) can be calculated given Equation 5.32:

$$L_{lane} = L_v + \frac{L_h}{3} = 8.3 + 9.0 + 6.6 + 3.1 + \frac{439}{3} = 173.3m \tag{5.34}$$

Table 5.11: Parameters to determine the piping length of Western navigation lock chamber at Terneuzen

Level start [m + NAP]	Level end [m + NAP]	Symbol	Value [m]
-14.0	-22.3	L_v1	8.3
-14.3	-22.3	L_v2	9.0
-14.3	-20.9	L_v3	6.6
-17.8	-20.9	L_v4	3.1
		L_h	439

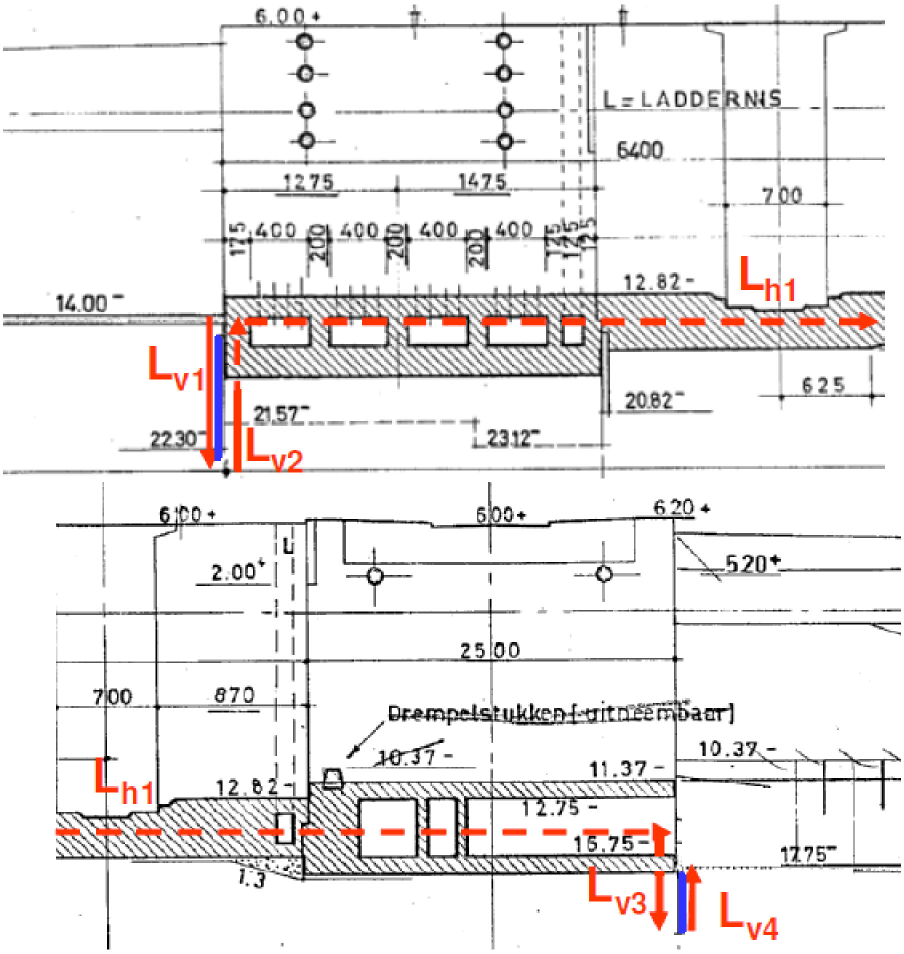


Figure 5.15: Cross-section to determine the piping length of Terneuzen Western navigation lock chamber (source: Rink 2011)

The RINK study that is conducted in 2011 (Celie, 2011) for the Terneuzen navigation lock complex, gives information about the geotechnical subsoil conditions. For this particular location, it is defined that a creep factor of 7.0 has to be considered to determine the piping length. Given this creep factor, the maximum vertical head difference over the complex is defined as (Equation 5.33):

$$\Delta H_c = \frac{L_v + \frac{L_h}{3}}{C_{w,creep}} = \frac{L_{lane}}{C_{w,creep}} = \frac{173.3}{7.0} = 24.8m \tag{5.35}$$

- ΔH_c = Critical (maximum) head difference [m]
- L_v = Total vertical length [m]
- L_h = Total horizontal length [m]
- $C_{w,creep}$ = Scale parameter, soil dependent (sand=7, clay=2)

The critical head difference, based on the Bligh/Lane method, for the Western lock chamber, equals 24.8m. The governing conditions, for which the vertical head difference over the lock chamber is maximum, hold for LAT conditions in the Westerschelde and maximum water level in the waterway ”Kanaal Gent-Terneuzen” (KGT). Similar to the Eastern lock chamber, the LAT conditions are likely to increase over time due to the impact of sea level rise, as given in Table 5.9. The expected head difference (ΔH) is calculated based on the normative upstream and downstream water levels. For the Terneuzen navigation lock, the normative situations hold for LAT in the Westerschelde (NAP -3.5m) and high upstream water level in KGT (NAP +2.38m). The expected head difference over the navigation lock complex equals:

$$\Delta H = H_{KGT} - H_{Westerschelde} = NAP + 2.38m - NAP - 3.5m = 5.88m \tag{5.36}$$

The influence of piping is calculated based on the ratio of the expected head to the critical head (Equation 3.4). This gives the following result

$$\frac{\Delta H_c}{\Delta H} = \frac{24.8}{5.88} = 4.22 >> 1.0 \tag{5.37}$$

Similar to the Eastern lock chamber, as a result of the large length of the navigation lock chamber, in combination with the presence of seepage screens under the structure, piping will not occur for normative conditions. Therefore, the contribution to the flooding probability is considered as negligible. The failure probability of piping is estimated to be equal to 1% of the norm (1E-05 per year in 2100) (WBI, 2017).

Given the result of Equation 5.37, the contribution of piping to the flooding probability is considered as negligible for the Western lock chamber. Therefore, this aspect is not normative for advancing the moment of renovation. The failure probability for piping is estimated to be equal to 1E-05 per year in 2100, based on the contribution it has on the flooding probability.

5.2.4. Storage capacity

For the Terneuzen navigation lock complex, the ”Kanaal Gent-Terneuzen” (KGT) waterway acts as a storage basin for a surcharge of water. From a flood safety point of view, the upper value of the storage capacity is of interest. The maximum storage capacity is limited as a result of water management policies and nautical reasons. According to information of Rijkswaterstaat (Vaarwegennetwerk), the total length of the waterway KGT equals 32 kilometres of which 50% is located in the Netherlands and 50% in Belgium. The waterway is bounded in the North at the Terneuzen navigation lock complex and in the south at the city of Gent (Belgium) (Figure 5.16).

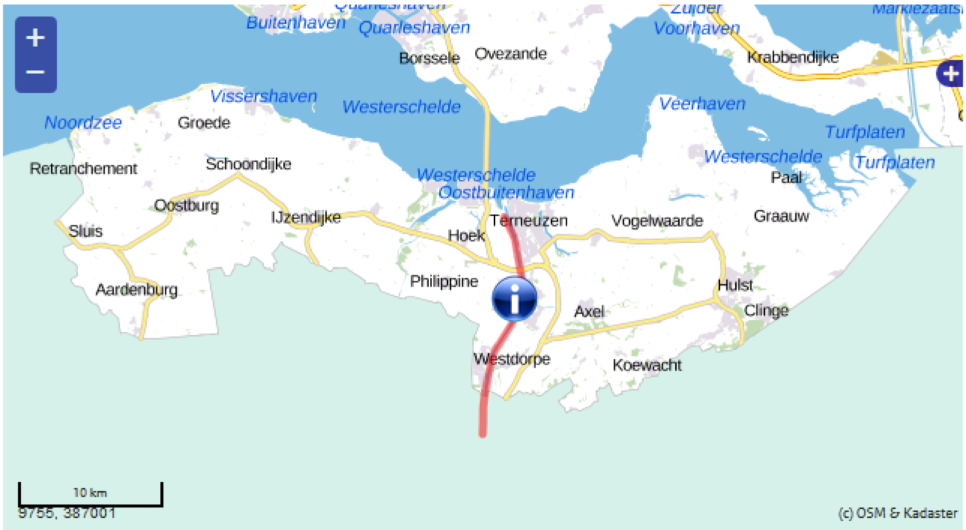


Figure 5.16: Location Kanaal Gent-Terneuzen (source: RWS Beeldbank)

The relevant waterway characteristics of the KGT are summarised in Table 5.12. The average width is 175m and the depth relative to the reference level (KP) ranges between KP -13.50m and KP -13.00m. In contrast to the Amsterdam-Rijnkanaal, this waterway is not bounded by intermediate water regulating structures. The surface area that spans the storage basin is defined in Equation 5.38:

$$A_{KGT,est} = L_{GT} * B_{avg} = 32,000 * 175 = 5.6\ km^2 \tag{5.38}$$

Prior to the expansion of the Terneuzen navigation lock complex, LievenseCSO conducted a study in which they defined the storage capacity of the waterway KGT (Pfaff-Wagenaar, 2015). In this research, they considered a surface area of the KGT as given in Equation 5.39. Rijkswaterstaat reviewed the statements of LievenseCSO and concluded that the storage capacity is 12% less (Harmsen, 2015), which implies a surface area as given in Equation 5.40.

$$A_{KGT,LSCO} = 10\ km^2 \tag{5.39}$$

$$A_{KGT,RWS} = 8.8\ km^2 \tag{5.40}$$

Table 5.12: Waterway characteristics of Kanaal Gent-Terneuzen

	[m]
Total length KGT	32,000
Average width KGT	175
Minimum depth KGT (KP)	-13.00

In the viewpoint of the flood safety function of a primary navigation lock, the remainder of this calculation is based on the minimum surface area as calculated in Equations 5.38 to 5.40.

The surface area that is considered in this research, to calculate the storage capacity, equals:

$$A_{KGT} = 5.6km^2 \tag{5.41}$$

The existing (international) water management policy at the KGT defines a maximum water level deviation of 0.25m relative to KP at NAP +2.13m. This implies that the range spans between NAP +1.88m and NAP +2.38m (Ministry of External affairs, 1987). Given this information, the storage capacity is defined in Equation 5.42:

$$K = A_{KGT} * h_{pvh} = 5.6 * 10^6 * 0.25 = 1,400,000m^3 \tag{5.42}$$

- K = Storage capacity [m^3]
- A = Surface area waterway [m^2]
- h_{pvh} = Maximum increase in water level KGT [m]

Based on the output of Hydra-NL, the expected overflow, for an average frequency of occurrence of 1:1,000 per year, is presented in Figure 5.17. Given these figures, it can be concluded that the expected overflow equals q=13 L/m/s. However, a water level of NAP +6.4m is expected for a standard of 1:1,000 per year (Figure 5.13). Given the data of Table 5.8, the height of the complex is at NAP +6.0m. This implies already a possible overflow over 0.4m height, neglecting the influence of waves. The total width of both lock chambers including platforms is estimated at:

$$W = W_{Eastern} + W_{Western} + W_{platforms} = 23.5 + 38 + 88 = 150m \tag{5.43}$$

Considering a storm in the North Sea that lasts for t=6 hours (≡21,600 seconds), it is assumed that the expected overflow is continuous over the storm period. In that case, the total expected overflow is calculated as the product of the specific overflow as result of the water level times the width of the structure times the storm period, neglecting the influence of waves (Equation 5.44):

$$V_{overflow} = \frac{q * W * w * t}{v} = \frac{0.4 * 150 * 0.1 * 21,600}{2} = 64,800m^3 \tag{5.44}$$

- q = Overflowing water [m^3/m/s]
- W = Total width for which water is overflowing [m]
- v = Velocity of overflowing water [m/s]
- w = Width of "crest" [m]
- t = Period of time of overflowing water [s]

Considering the results of Equations 5.42 and 5.44, it is assumed that the storage capacity is abundantly sufficient. Therefore, the failure probability of insufficient storage capacity is estimated at 1% of the norm (1E-05 per year) in 2100 (WBI, 2017).

As a result of the large storage capacity in the KGT, this aspect is not considered as an indicator in the urgency of renovation. The failure probability of an insufficient storage capacity is estimated at 1% of the norm, which is equal to 1E-05 per year in 2100.

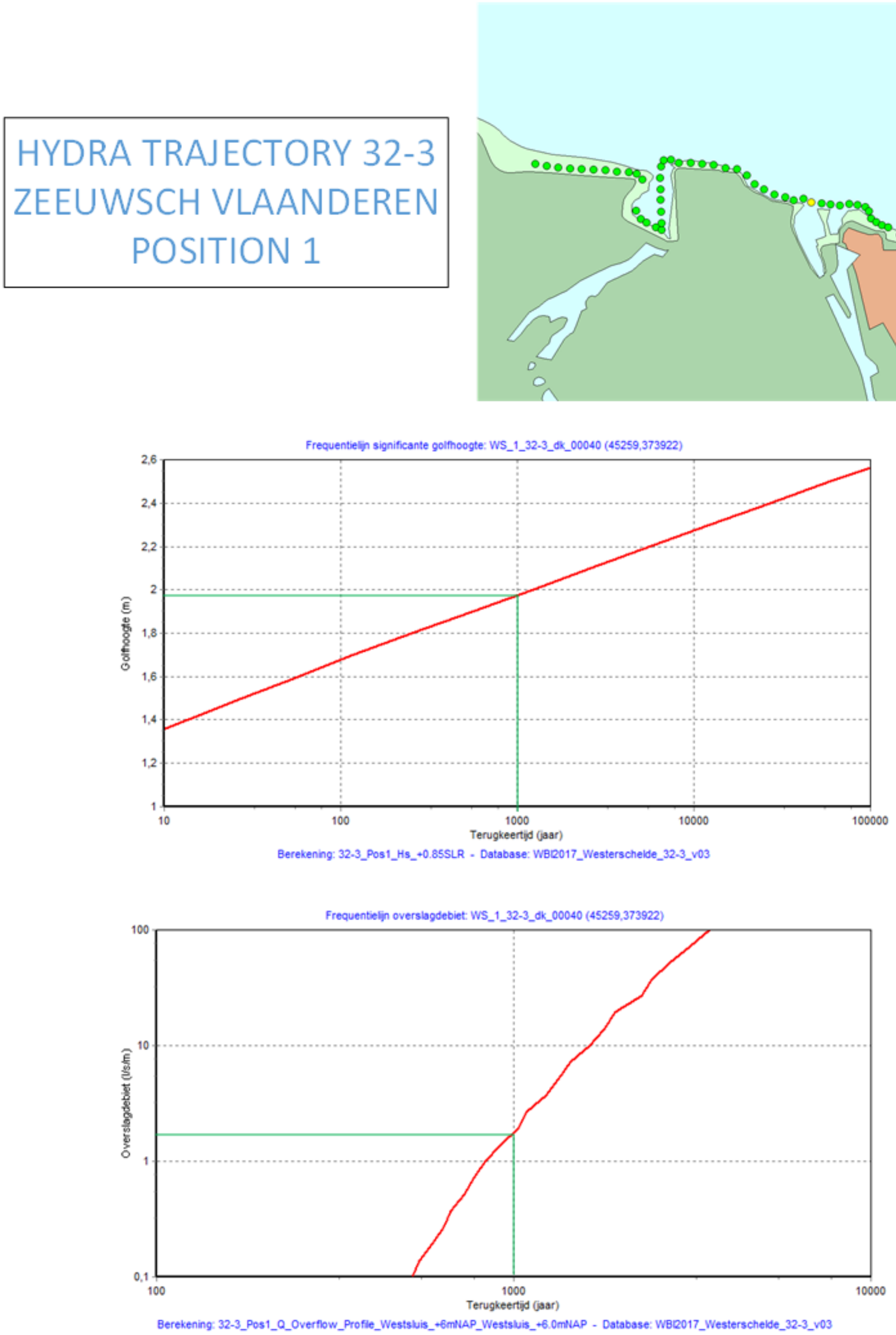


Figure 5.17: Result of Hydra-NL calculation regarding the expected wave height and overflow for a given average frequency of occurrence at the Terneuzen navigation lock complex (height complex at NAP +6.0m)

5.2.5. Overtopping resistance

The maximum acceptable overflow resistance for hydraulic structures is limited to safeguard the structural integrity (section 3.2.3). The upper limit is given in Equation 5.45:

$$Q_{max,overflow} = 1000\ [L/m/s] \tag{5.45}$$

The impact of waves and discharge variety is calculated for a 1:1,000 per year average frequency of occurrence to define the effect relative to the overflow resistance. For this calculation, Hydra-NL is used. The normative conditions are a 6-hour continuous storm event and direction of waves orthogonal to the navigation lock and the W+ climate scenario in 2100. The combination of overtopping and overflowing water is calculated to check whether the overflow resistance criterion is reached over time. The outcome of this calculation indicates much lower values than the overflow resistance value in Equation 5.45 (Figure 5.17). Therefore, the failure probability is estimated again to be equal to 1% of the norm (1E-05 per year) in 2100 (WBI,2017).

The overflow resistance criterion is not considered as an indicator for the urgency of renovation, as the expected overflow is negligible for normative conditions. The failure probability is estimated at 1% of the norm for this segment, which equals 1E-05 per year in 2100.

5.2.6. Unavailability due to high downstream water level

For the Terneuzen navigation lock complex, unavailability of the levelling function due to high downstream water levels (Westerschelde) increases in the future as a result of sea level rise. However, the unavailability is affected in two ways. At first, the increased mean sea water level results in more frequent events for which the nautical function is interrupted. On the other hand, due to the increased mean sea water level, the head difference over the lock chambers decrease, as the mean water level at KGT is at NAP +2.13m. This has a positive effect on the levelling cycle. The latter effect is explained in more detail in section 5.2.11 of this report.

The maximum water level, at which the nautical function is active, is limited to water levels at the Westerschelde of NAP +3.5m for both the Eastern and the Western lock chambers. The water level exceedance frequency for the NAP +3.5m water level is twice in a year in 2020. Each event takes 3 hours/event (Celie, 2011). This results in an unavailability of (Equation 5.46):

$$Unavailability_{HDWL,2020} = F_{occurrence} * T_{event} = 2 * 3 = 6\ hours/year \tag{5.46}$$

The expected sea level rise at Terneuzen is estimated to be equal to 0.22m, 0.58m and 0.85m for the years 2030, 2070, and 2100, respectively (Table 5.9). The so-called ”decimeringshoogte” for the Terneuzen navigation lock complex equals 0.6m, which is the absolute water level difference for a 10 times more stringent norm (Figure 5.13). The ratio of the expected sea level rise to the ”decimeringshoogte” is used as an indicator to determine the effect of sea level rise on the unavailability of the nautical function, defined as β (Helpdeskwater, 2017). This β is determined for the periods 2030, 2070, and 2100, respectively:

$$\beta_{2030} = \frac{expected\ sea\ level\ rise}{decimeringshoogte} = \frac{0.22}{0.6} = 36.7\% \tag{5.47}$$

$$\beta_{2070} = \frac{expected\ sea\ level\ rise}{decimeringshoogte} = \frac{0.58}{0.6} = 96.7\% \tag{5.48}$$

$$\beta_{2100} = \frac{expected\ sea\ level\ rise}{decimeringshoogte} = \frac{0.85}{0.6} = 141.7\% \tag{5.49}$$

Based on the values for β, the unavailability is calculated by multiplying the value β with the unavailability due to high downstream water level, in 2020:

$$Unavailability_{HDWL,2030} = \beta * Unavailability_{HDWL,2020} = 1.367 * 6 = 8.2\ hours/year \tag{5.50}$$

$$Unavailability_{HDWL,2070} = \beta * Unavailability_{HDWL,2020} = 1.967 * 6 = 11.8\ hours/year \tag{5.51}$$

$$Unavailability_{HDWL,2100} = \beta * Unavailability_{HDWL,2020} = 2.417 * 6 = 14.5\ hours/year \tag{5.52}$$

High downstream water level events, as a result of more frequent exceedance of the maximum water level for levelling vessels, result in an unavailability of the nautical function of 8.2 hours/year in 2030, and will increase up to 11.8 hours/year in 2070 and 14.5 hours/year in 2100.

5.2.7. Unavailability due to low downstream water level

The low downstream water level conditions are primarily driven by the semi-diurnal North Sea character. Furthermore, the probability that low water events are present, decreases over time as a result of sea level rise.

A similar approach is considered as in section 5.2.6. The minimum water level at which the nautical function is active is limited to water levels in the Westerschelde of NAP -3.5m for both the Eastern and the Western lock chamber. The average frequency of occurrence of water levels lower than NAP -3.5m is equal to 1:10 per year. It is assumed that this event takes 3 hours (Celie, 2011). This results in an unavailability of (Equation 5.53):

$$Unavailability_{LDWL,2020} = F_{occurrence} * T_{event} = 1:10 * 3 = 0.3\ hours/year \tag{5.53}$$

The effect of sea level rise reduces the unavailability due to low downstream water levels even further. The inverse values of β as derived in section 5.2.6 are used to determine the unavailability of the nautical function in 2030, 2070, and 2100:

$$Unavailability_{LDWL,2030} = \beta * Unavailability_{LDWL,2020} = \frac{1}{1.367} * 0.3 = 0.22\ hours/year \tag{5.54}$$

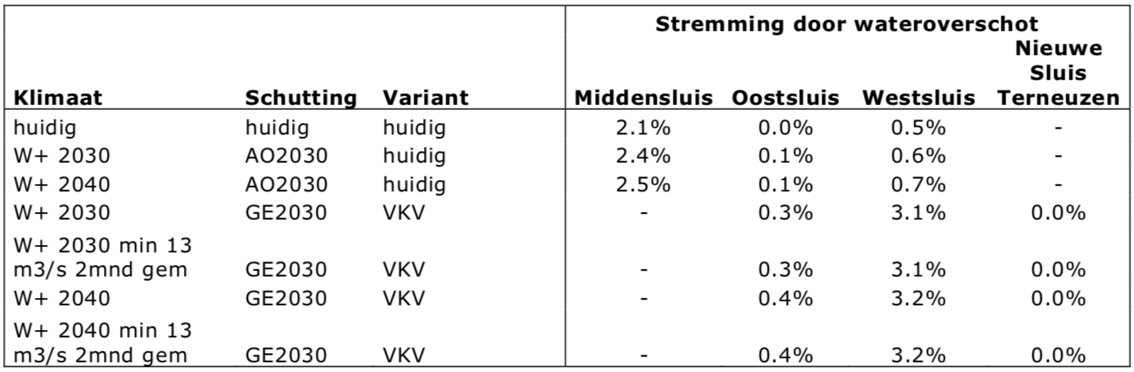
$$Unavailability_{LDWL,2070} = \beta * Unavailability_{LDWL,2020} = \frac{1}{1.967} * 0.3 = 0.15\, hours/year \tag{5.55}$$

$$Unavailability_{LDWL,2100} = \beta * Unavailability_{LDWL,2020} = \frac{1}{2.417} * 0.3 = 0.12\, hours/year \tag{5.56}$$

Low downstream water level events will occur less in the future due to sea level rise. Unavailability of the nautical function is expected to be 0.22 hours/year in 2030 and reduces further to 0.15 hours/year in 2070, and to 0.12 hours/year in 2100.

5.2.8. Unavailability due to high upstream water level

The water level in the KGT is regulated at a reference level KP that is equivalent to NAP +2.13m, due to water management regulations (section 5.2.4). Therefore, the maximum water level deviation is limited to 0.25m. The KP is preserved by discharging/pumping towards the Westerschelde tidal basin, due to flood safety reasons. During this process, the nautical function is interrupted. The sequence of lock chambers that are used for this process starts with the Western lock chamber, followed by the Eastern lock chamber, and then the new Middle lock chamber (Pfaff-Wagenaar, 2015). The procedure is that the complete capacity of the first lock chamber is reduced to zero before an additional lock chamber is interrupted. The results, as depicted in Figure 5.18, are based on the W+ climate scenario, for the existing Middle lock chamber, Eastern lock chamber, Western lock chamber, and the new Middle lock chamber, respectively.



			Stremming door wateroverschot			
Klimaat	**Schutting**	**Variant**	**Middensluis**	**Oostsluis**	**Westsluis**	**Nieuwe Sluis Terneuzen**
huidig	huidig	huidig	2.1%	0.0%	0.5%	-
W+ 2030	AO2030	huidig	2.4%	0.1%	0.6%	-
W+ 2040	AO2030	huidig	2.5%	0.1%	0.7%	-
W+ 2030	GE2030	VKV	-	0.3%	3.1%	0.0%
W+ 2030 min 13 m3/s 2mnd gem	GE2030	VKV	-	0.3%	3.1%	0.0%
W+ 2040	GE2030	VKV	-	0.4%	3.2%	0.0%
W+ 2040 min 13 m3/s 2mnd gem	GE2030	VKV	-	0.4%	3.2%	0.0%

Figure 5.18: Overview of interruption due to high discharge on the nautical function of Terneuzen navigation lock complex with the reference year 2020 (source: MER Water VNSC, 2015)

Given the data of Figure 5.18, the focus is on the Eastern and the Western lock chambers, since the existing Middle lock chamber is replaced by the new Middle lock chamber. Furthermore, new levelling regimes are implemented (GE2030) as a result of a changed distribution of vessels. The percentages are based on the operational hours (OH) of the navigation lock:

$$OH_{Eastern\, lock\, chamber} = OH_E = 8694\, hours/year \tag{5.57}$$

$$OH_{Western\, lock\, chamber} = OH_W = 8608\, hours/year \tag{5.58}$$

For the Eastern lock chamber, the unavailability due to high upstream water level conditions are calculated for 2020, 2030, and 2040, respectively:

$$Unavailability_{HUWL,E,2020} = Interruption * OH_E = 0.0\% * 8694 = 0\ hours/year \tag{5.59}$$

$$Unavailability_{HUWL,E,2030} = Interruption * OH_E = 0.3\% * 8694 = 26.1\ hours/year \tag{5.60}$$

$$Unavailability_{HUWL,E,2040} = Interruption * OH_E = 0.4\% * 8694 = 34.8\ hours/year \tag{5.61}$$

For the Western lock chamber, the unavailability due to high upstream water level conditions are calculated for 2020, 2030, and 2040, respectively:

$$Unavailability_{HUWL,W,2020} = Interruption * OH_W = 0.5\% * 8608 = 43\ hours/year \tag{5.62}$$

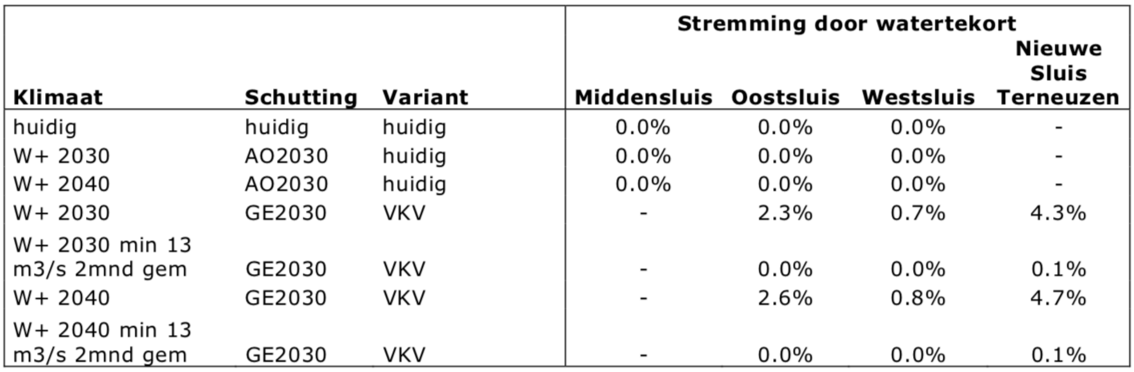
$$Unavailability_{HUWL,W,2030} = Interruption * OH_W = 3.1\% * 8608 = 267\ hours/year \tag{5.63}$$

$$Unavailability_{HUWL,W,2040} = Interruption * OH_W = 3.2\% * 8608 = 276\ hours/year \tag{5.64}$$

The policy for high water levels in KGT prescribes that the Western lock chamber is first interrupted, as it has to perform as a discharge sluice, before the Eastern lock chamber is interrupted. The unavailability of the nautical function of the Eastern lock chamber is, therefore, equal to 0, 26.1, and 34.8 hours/year in 2020, 2030, and 2040, respectively. For the Western lock chamber, this unavailability is equal to 43, 267 and 276 hours/year in 2020, 2030, and 2040, respectively.

5.2.9. Unavailability due to low upstream water level

The unavailability of the nautical function due to low upstream water conditions is the result of low discharge and runoff towards the KGT. In contrast to the high upstream water conditions, the sequence of levelling interruption starts with the existing Middle lock chamber, followed up by the Eastern lock chamber and finally the Western lock chamber. The results of the interruption, as depicted in Figure 5.19, are based on the W+ climate scenario.



			Stremming door watertekort			
Klimaat	**Schutting**	**Variant**	**Middensluis**	**Oostsluis**	**Westsluis**	**Nieuwe Sluis Terneuzen**
huidig	huidig	huidig	0.0%	0.0%	0.0%	-
W+ 2030	AO2030	huidig	0.0%	0.0%	0.0%	-
W+ 2040	AO2030	huidig	0.0%	0.0%	0.0%	-
W+ 2030	GE2030	VKV	-	2.3%	0.7%	4.3%
W+ 2030 min 13 m3/s 2mnd gem	GE2030	VKV	-	0.0%	0.0%	0.1%
W+ 2040	GE2030	VKV	-	2.6%	0.8%	4.7%
W+ 2040 min 13 m3/s 2mnd gem	GE2030	VKV	-	0.0%	0.0%	0.1%

Figure 5.19: Overview of interruption due to low discharge on the nautical function of Terneuzen navigation lock complex (source: MER Water VNSC, 2015)

Given the data of Figure 5.19, the focus is again on the Eastern and the Western lock chambers. Furthermore, the same levelling regime is considered as for the high upstream water conditions (defined as GE2030). The percentages of interruption are based on the operational hours (OH):

$$OH_{Eastern\ lock\ chamber} = OH_E = 8694\ hours/year \tag{5.65}$$

$$OH_{Western\ lock\ chamber} = OH_W = 8608\ hours/year \tag{5.66}$$

For the Eastern lock chamber, the unavailability due to low upstream water level conditions are calculated for 2020, 2030, and 2040, respectively:

$$Unavailability_{LUWL,E,2020} = Interruption * OH_E = 0.0\% * 8694 = 0\ hours/year \tag{5.67}$$

$$Unavailability_{LUWL,E,2030} = Interruption * OH_E = 2.3\% * 8694 = 200\ hours/year \tag{5.68}$$

$$Unavailability_{LUWL,E,2040} = Interruption * OH_E = 2.6\% * 8694 = 226\ hours/year \tag{5.69}$$

For the Western lock chamber, the unavailability due to low upstream water level conditions are calculated for 2020, 2030, and 2040, respectively:

$$Unavailability_{LUWL,W,2020} = Interruption * OH_W = 0.0\% * 8608 = 0\ hours/year \tag{5.70}$$

$$Unavailability_{LUWL,W,2030} = Interruption * OH_W = 0.7\% * 8608 = 60\ hours/year \tag{5.71}$$

$$Unavailability_{LUWL,W,2040} = Interruption * OH_W = 0.8\% * 8608 = 69\ hours/year \tag{5.72}$$

The policy for low water levels in KGT prescribes that the Eastern lock chamber is first interrupted, as it has to perform as a discharge sluice, before the Western lock chamber is interrupted. The unavailability of the nautical function of the Eastern lock chamber is, therefore, equal to 0, 200 and 226 hours/year in 2020, 2030 and 2040 respectively. For the Western lock chamber, the unavailability is equal to 0, 60 and 69 hours/year in 2020, 2030, and 2040, respectively.

5.2.10. Intensity/Capacity economy 2015

The combination of an old and small Middle lock chamber and a capacity shortage were the main drivers for the renovation of the Terneuzen navigation lock complex. For this complex, the software programme SIVAK is used to simulate for different scenarios the expected intensity, transit time and waiting time over a period of time up to 2040. The software considers different economic scenarios and their effect on the nautical sector. Based on the SIVAK simulation, of which more information can be found in Appendix I (Table C.1 and Figures C.1 and C.2) 16 SIVAK-simulations are conducted. Each simulation is based on a number of parameters among which the economic scenarios and varying operational conditions are the most important. Furthermore, the W+ climate scenario is used for all the scenarios.

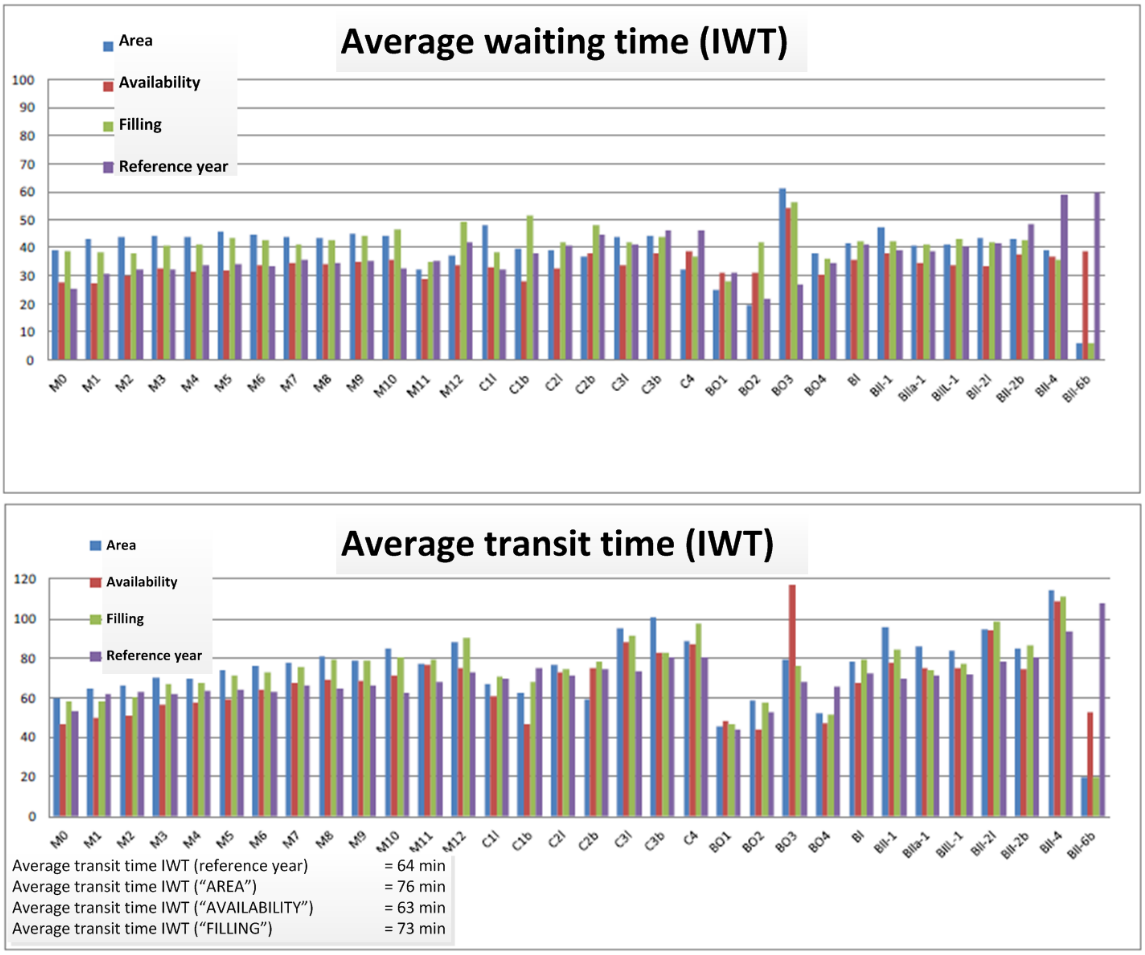
All numbers are indexed on the reference year 2012, the pre-design phase of the navigation complex expansion. Furthermore, a tidal window is not considered in the vessel arrival distribution. In a number of situations, a vessel has to wait in case the draught exceeds the shallow water level condition in front of the navigation lock.

Validation of the existing situation

Validation of the SIVAK model is executed on the basis of the reference year 2012, for which data was available at the moment of the SIVAK model set-up. For this process, three levelling regimes were used:

1. **Area**: Prefer the lock chamber with the smallest possible area
2. **Availability**: Prefer the lock chamber that is first available
3. **Filling**: Prefer the lock chamber that is heading to the vessel to maximise filling or prefer the lock chamber that has the smallest area which is heading in the opposite direction

For all the three existing lock chambers, the average waiting time and average transit time are calculated. As defined in the Mobility Act, the maximum waiting time is limited to 30 minutes. There are a number of vessel classes for which this waiting time is exceeded, which holds for the different levelling regimes (Figure 5.20). The output of the simulations regarding waiting and transit times have a high correlation with the actual measured waiting and transit times. The levelling regime ”availability” has the best fit (64 minutes for the reference year 2012 and 63 minutes for the filling regime ”availability”) and is, therefore, considered as the designated levelling regime during the SIVAK simulations.



Average transit time IWT (reference year) = 64 min
Average transit time IWT ("AREA") = 76 min
Average transit time IWT ("AVAILABILITY") = 63 min
Average transit time IWT ("FILLING") = 73 min

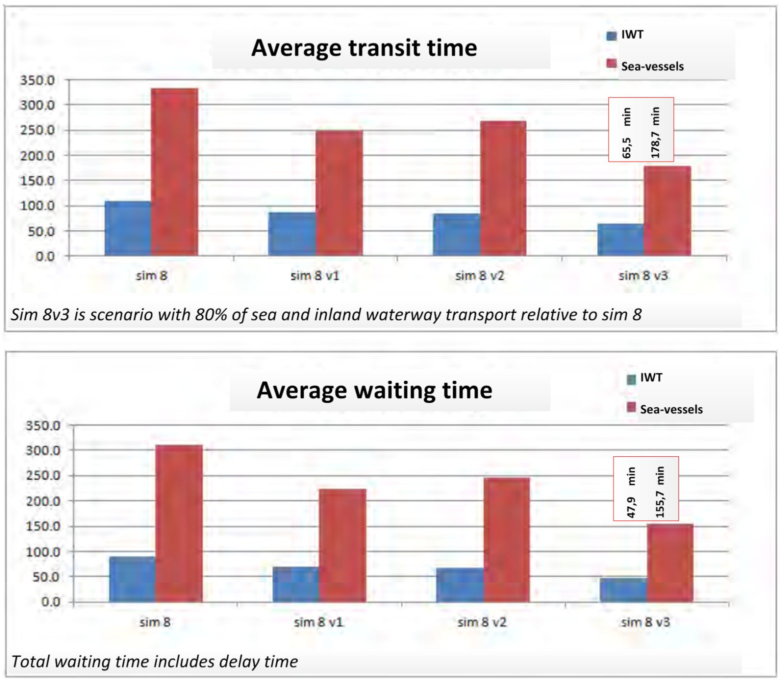
Figure 5.20: Average waiting and transit times for Inland Waterway Transport (IWT) in 2012 (source: MARIN Capaciteitsonderzoek Zeesluis Gent-Terneuzen)

Autonomous developments in the existing situation

For the analysis of the impact of autonomous developments in the nautical sector (increasing vessel dimensions and different cargo distribution, section 4.2), four simulations are developed that consider the ”availability” of the levelling regime, and that reflect on the scenarios as defined in Table C.1. These scenarios are based on the reference year 2012 and the prognosis for 2020, 2030, and 2040 without interventions of the existing navigation lock complex (defined as NULGE2020, NULGE2030, and NULGE2040). In the NULGE2020 scenario, the capacity shortage becomes apparent already, which is the motive of the actual capacity expansion. In the NULGE2040 scenario, repression was considered, which is the result of high transit times and/or other modes of transport are used. In all the three scenarios, the influence of traffic volume reduction is also considered (section 4.2). All the three simulations do consider *ceteris paribus*, which implies that waterway modifications or operational conditions are not adjusted. The output of these simulations is depicted in Figures 5.21, 5.22, and 5.23.

Based on the autonomous developments within the nautical sector, the average waiting time is for all the three simulations (NULGE2020 = 47.9 minutes, NULGE2030 = 70.3 minutes, and NULGE2040 = 127.3 minutes) exceeds the requirement as defined in the Mobility Act. Reflecting on section 4.3, this requirement equals:

$$\text{NoMo} = \text{SVIR criterion} = 30 \text{ minutes waiting time} \equiv I/C_{max} = 0.5$$

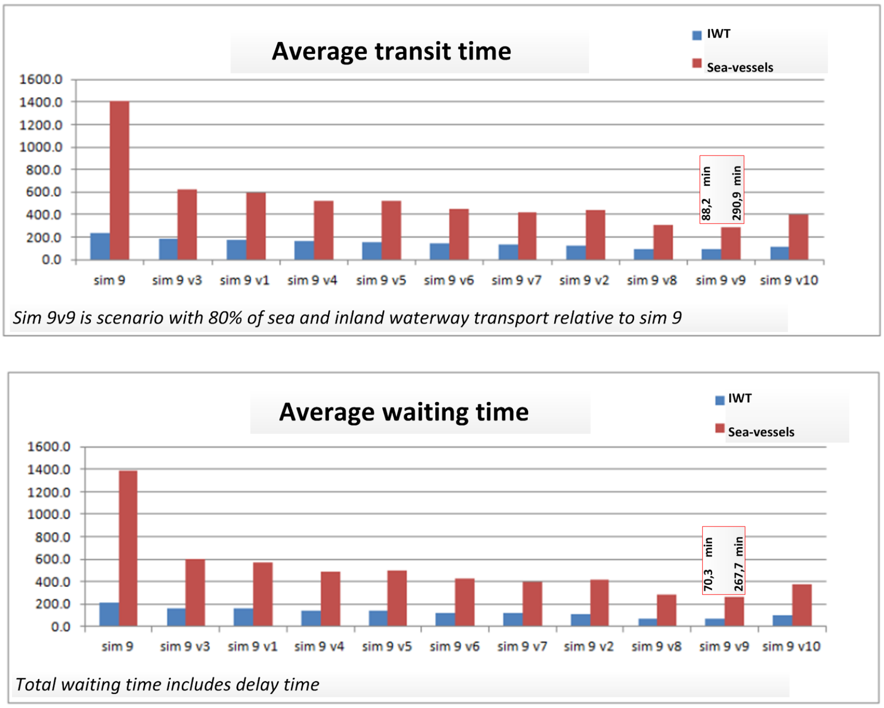


Sim 8v3 is scenario with 80% of sea and inland waterway transport relative to sim 8

Total waiting time includes delay time

Figure 5.21: SIVAK output for the scenario NULGE2020 for autonomous developments, numbers in minutes (source: MARIN Capaciteitsonderzoek Zeesluis Gent-Terneuzen)

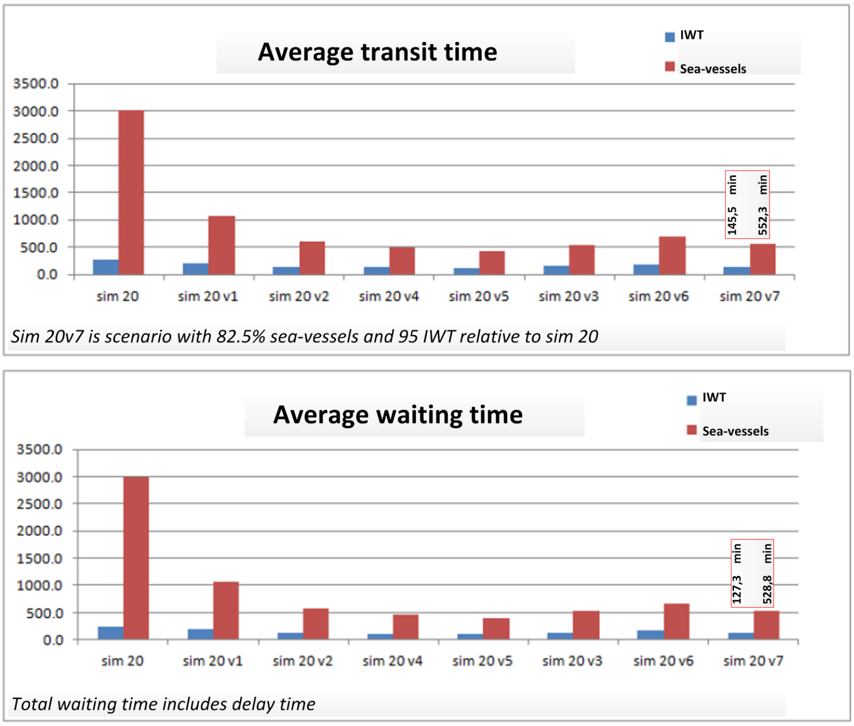
For the NULGE2020 simulation (Figure 5.21), the average waiting time is for the most optimal condition 48 minutes for Inland Waterway Transport (IWT) and 155 minutes for sea vessels. Considering the NULGE2030 simulation (Figure 5.22), the most optimal conditions already give an average waiting time of 70 minutes for IWT and 267 minutes for sea vessels. Finally, the NULGE2040 simulation (Figure 5.23) confirms once more the urgency of capacity expansion in 2015, as the most optimal condition gives an average waiting time of 127 minutes for IWT and 529 minutes for sea-vessels.



Sim 9v9 is scenario with 80% of sea and inland waterway transport relative to sim 9

Total waiting time includes delay time

Figure 5.22: SIVAK output for the scenario NULGE2030 for autonomous developments, numbers in minutes (source: MARIN Capaciteitsonderzoek Zeesluis Gent-Terneuzen)



Sim 20v7 is scenario with 82.5% sea-vessels and 95 IWT relative to sim 20

Total waiting time includes delay time

Figure 5.23: SIVAK output for the scenario NULGE2040 for autonomous developments, numbers in minutes (source: MARIN Capaciteitsonderzoek Zeesluis Gent-Terneuzen)

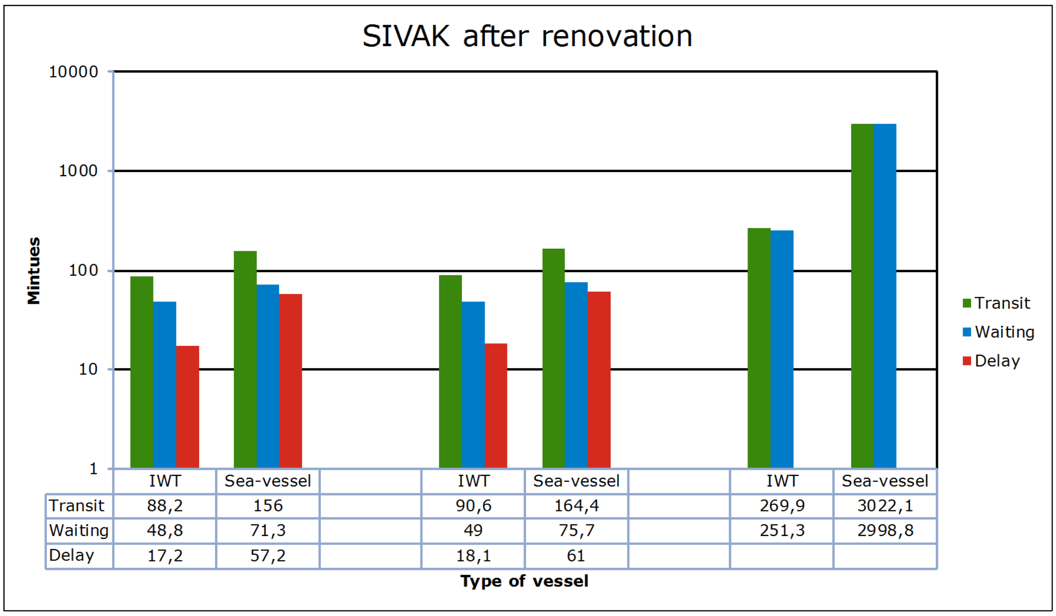
The intensity as a function of the capacity for the Terneuzen navigation lock complex exceeds the requirement. The equivalent maximum waiting time (SVIR = 30 minutes waiting time) for all types of nautical transport is exceeded in 2020, according to the NULGE2020 scenario. This waiting time increases even further over time.

5.2.11. Intensity/Capacity economy 2040

The renovation of the new Middle lock chamber at Terneuzen is in progress and is expected to be operational mid-2020. Three simulations were conducted that define the expected traffic volumes in 2040 after renovation. This implies that a larger capacity is available for the increased nautical transport sector. Furthermore, the boundary conditions are not assumed to be stationary. The three simulations for the reference year 2040 have the following characteristics:

1. **Simulation 1**: Traffic volume prognosis for 2040, renovation of the Middle lock chamber, and no adjustment regarding the existing operational conditions.
2. **Simulation 2**: Traffic volume prognosis for 2040, renovation of the Middle lock chamber, and no adjustments regarding the accessibility restrictions of waterway (width limitations).
3. **Simulation 3**: Traffic volume prognosis for 2040, no renovation of the Middle lock chamber, and no adjustments of the operational conditions.

The results of the three simulations are depicted in Figure 5.24. The focus is on the waiting time that should be limited to the SVIR requirement of 30 minutes. For simulation one, the waiting time equals 49 minutes for IWT and 71 minutes for sea vessels. In simulation 2, the waiting time equals 49 minutes for IWT and 76 minutes for sea vessels. For both simulations 1 and 2, that incorporate the optimisation of the operational conditions or waterway characteristics respectively, the expected waiting time exceeds the SVIR requirement of 30 minutes. This concludes that a capacity shortage can again be expected before 2040, after the capacity increase by means of a new Middle lock chamber.



	IWT	Sea-vessel		IWT	Sea-vessel		IWT	Sea-vessel
Transit	88,2	156		90,6	164,4		269,9	3022,1
Waiting	48,8	71,3		49	75,7		251,3	2998,8
Delay	17,2	57,2		18,1	61			

Figure 5.24: SIVAK output for the scenario NULGE2040 after renovation for traffic volumes in 2040 (left: simulation 1, middle: simulation 2, right: simulation 3)

The intensity as a function of the capacity of the Terneuzen navigation lock complex exceeds the requirement, as the SVIR waiting time criterion of 30 minutes, is exceeded for both simulations. Despite the increased capacity of the Terneuzen navigation lock complex, capacity shortage is expected again before 2040.

5.2.12. Unavailability due to scheduled maintenance

Ageing of material is the main driver for maintenance, that often results in an increase of the unavailability of the nautical function (section 2.2). In 2011, IV-Infra conducted a RAMS analysis regarding the performance of the complex in which the water retaining function and levelling function are assessed (Celie, 2011).

Scheduled maintenance is variable according to interviews with the asset manager of the Terneuzen navigation lock complex. Despite the age of both Eastern and Western lock chamber, the unavailability as a result of maintenance is small. The annual unavailability of the Eastern lock chamber is estimated at P_{unav}=0.08% OH. For the Western lock chamber, the unavailability due to scheduled maintenance is estimated at P_{unav}=0.055% OH (Celie, 2011).

$$Unavailability_{maintenance,EASTERN,2020} = P_{unav} * OH = 0.08\% * 8694h = 6.8\ hours/year \tag{5.73}$$

$$Unavailability_{maintenance,WESTERN,2020} = P_{unav} * OH = 0.055\% * 8608h = 4.8\ hours/year \tag{5.74}$$

For the period 2020-2050, the expected increase of the unavailability is estimated based on expert judgement. The result is an expected increase in the unavailability of α = 1.2 relative to the unavailability in 2020. The unavailability in this period is the product of the unavailability in 2020 times alpha. This gives the following unavailability for both the Eastern and the Western lock chamber:

$$Unavailability_{maintenance,EASTERN,2020-2050} = \alpha * 6.8 = 8.2\ hours/year \tag{5.75}$$

$$Unavailability_{maintenance,WESTERN,2020-2050} = \alpha * 4.8 = 5.8\ hours/year \tag{5.76}$$

For the period 2050-2100, the expected increase of the unavailability is estimated based on expert judgement. The result is an expected increase in the unavailability of 2α = 1.4 relative to the unavailability in 2020. The unavailability in this period is the product of the unavailability in 2020 times alpha. This gives the following unavailability for both the Eastern and the Western lock chamber:

$$Unavailability_{maintenance,EASTERN,2050-2100} = 2\alpha * 6.8 = 9.5\ hours/year \tag{5.77}$$

$$Unavailability_{maintenance,WESTERN,2050-2100} = 2\alpha * 4.8 = 6.7\ hours/year \tag{5.78}$$

The unavailability of the Eastern lock chamber, due to scheduled maintenance, equals 6.8, 8.2, and 9.5 hours/year in the periods 2020, 2020-2050, and 2050-2100 respectively. The unavailability of the Western lock chamber, due to scheduled maintenance, equals 4.8, 5.8, and 6.7 hours/year in the periods 2020, 2020-2050, and 2050-2100 respectively.

Table 5.13: Unavailability of the nautical function of the Terneuzen navigation lock complex (source: RAMS analysis, IV Infra, 2011)

	Eastern lock chamber		**Western lock chamber**	
	Annual [hours]	**Annual [%]**	**Annual [hours]**	**Annual [%]**
Operational hours (OH)	8694		8608	
Unavailability as a result of natural boundary conditions	66	0.75	152	1.7
Unavailability as a result of technical failure	239.1	2.7	117	1.3
Unavailability as a result of scheduled maintenance	6.8	0.08	4.8	0.0548
Total unavailability for nautical function	312	3.59	274	3.18

5.2.13. Unavailability due to technical failure

Technical failure can have a number of causes for the Terneuzen navigation lock complex. For the Eastern lock chamber, the unavailability as a result of technical failure equals P_{unav}=2.7% OH in 2020 (Celie, 2011). The main drivers for these technical failures are the electronic engines that actuate the hydraulic pumps and the CCTV safety system. The unavailability as a result of technical failures of the Western lock chamber equals P_{unav}=1.3% OH in 2020 (Celie, 2011). The main driver for these failures is the electronic engines. The unavailability as a result of technical failures equals:

$$Unavailability_{techfail,EASTERN,2020} = P_{unav} * OH = 2.7\% * 8694h = 239\ hours/year \tag{5.79}$$

$$Unavailability_{techfail,WESTERN,2020} = P_{unav} * OH = 1.3\% * 8608h = 117\ hours/year \tag{5.80}$$

Ageing will increase the unavailability of the levelling function. Nevertheless, experts at Rijkswaterstaat do not expect that this increase will be more than α = 1.2 relative to the unavailability in 2020. Therefore, the unavailability for the period 2020-2060 is calculated for both the Eastern and the Western lock chamber (Equations 5.81 and 5.82):

$$Unavailability_{techfail,EASTERN,2020-2060} = \alpha * 239 = 287\ hours/year \tag{5.81}$$

$$Unavailability_{techfail,WESTERN,2020-2060} = \alpha * 117 = 140\ hours/year \tag{5.82}$$

For 2020, the unavailability of the levelling function, due to technical failure, equals 239 and 117 hours/year for the Eastern and the Western lock chambers, respectively. In the period 2020-2060, the unavailability is expected to increase up to 287 and 140 hours/year for the Eastern and the Western lock chambers, respectively.

5.2.14. Overview assessment

The piping assessment for normative conditions results in a safety margin of more than 200% for both the Eastern and Western lock chamber. The contribution to the flooding probability is therefore considered as negligible, and makes this aspect not normative in the urgency of renovation up to 2100. The result of the storage capacity calculation implies the same conclusion. The basin, formed by the Kanaal Gent-Terneuzen, is for normative conditions much larger than the expected water it has to store during a storm event. The aspect overflow resistance is assessed with respect to the criteria set to the maximum overflow resistance. Based on the calculations, overflow values up to a few percent of the maximum overflow criteria can be expected. Summarised, the three aspects that are assessed for the flood safety function of a primary navigation lock, do not increase the urgency of renovation.

The unavailability as a result of high downstream water level conditions is small. The influence of sea level rise, on the frequency increase of nautical interruption, is present but has limited influence on the unavailability. The positive effect of sea level rise is that the unavailability, due to low downstream water level conditions, will decrease in the future. The contribution of this aspect to the unavailability is negligible. The high and low upstream water level conditions have much more effect on the unavailability. This is the result of the combined levelling and discharging function of the Terneuzen navigation lock complex. For high upstream water level conditions, the unavailability of primarily the Western lock chamber is significant. For low upstream water level conditions, it is vice-versa. In that case, the unavailability of the Eastern lock chamber is significant.

The intensity increase as a function of the capacity of the Terneuzen navigation lock complex was already an indicator for capacity expansion by means of replacement of the Middle lock chamber. In the simulations with the reference year 2015, the I/C ratio was exceeded by, on average, 80% relative to the requirement. For the increased capacity, due to the new Middle lock chamber, the results show capacity shortage again before 2040. For all simulations, the traffic volume prognoses as defined in section 4.2, are used. Summarised, based on the I/C requirement, capacity shortage is expected to occur before the scheduled moment of renovation according to V&R for both the Eastern and Western lock chamber.

Finally, the unavailability of the nautical function due to ageing is primarily driven by technical failures. The effect of scheduled maintenance on the availability is moderate. This is valid for the actual performance as well as for the performance over time. For technical failures, on the contrary, the unavailability in 2020 is almost equal to the total unavailability requirement according to the SLA, that is defined for primary navigation locks.

6

Implementation Results Case Studies

In this chapter, the results of both case studies are reviewed relative to the norm and requirements. The method that is proposed in Section 2.5, is once more presented in Figure 6.1. It consists of 11 aspects. In sections 5.1.14 and 5.2.14, it is concluded that the aspects related to the flood safety function (piping, storage capacity and overflow resistance), do not indicate that renovation is required, for normative conditions up to 2100.

The aspects that are related to the availability of the navigation lock (six in total), contribute to the SLA requirement for the unavailability of a primary navigation lock. Therefore, for these six aspects, their relative contribution to the SLA requirement must be calculated. This process is defined for both case studies in section 6.1 and 6.2 respectively.

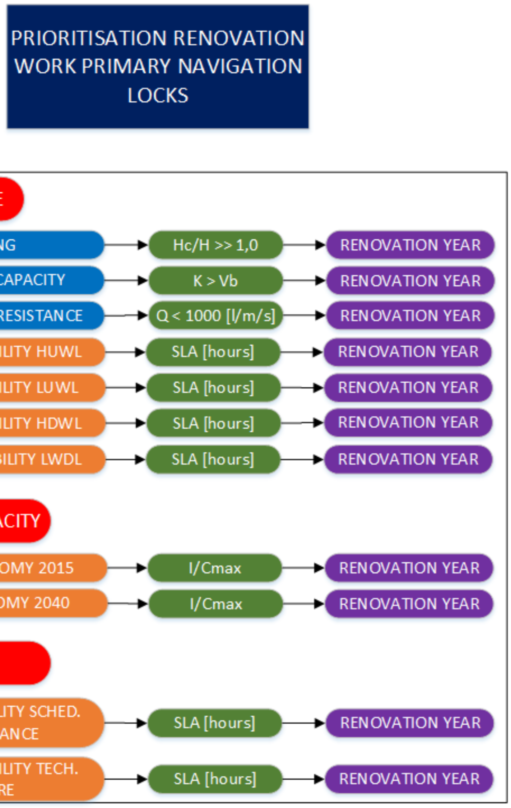


Figure 6.1: Proposed method to define urgency of renovation

6.1. Prinses Beatrix Navigation Lock Complex

The aspects IV, V, VI, VII, X, and XI contribute together to the total unavailability of the nautical function. This implies that six aspects together have to fulfil the SLA requirement. The values of the unavailability are derived from section 5.1, and summarised in Table 6.1.

> It is assumed that each aspect has a maximum acceptable contribution of 1/6th of the SLA requirement. For the Prinses Beatrix navigation lock complex, the maximum unavailability = 2% OH = 0.02 * 8736 hours/year = 175 hours/year. Therefore, the critical value is defined as (1/6 * 2% OH) = (1/6 * 175) = 29 hours/year. Furthermore, the unavailability of each aspect, as depicted in Table 6.1, is rounded to hours.

The renovation year is estimated based on the unavailability in a particular year, relative to the critical SLA value. Take for example aspect ”VII. Unavailability LDWL”. The unavailability in 2020 is equal to 26 hours/year. In 2050, this unavailability increases up to 39 hours/year, more than the critical value that is defined for the SLA = 29 hours/year. In a period of (2050-2020=) 30 years, the unavailability increases by (39-26=) 13 hours. Assuming a linear relation between unavailability and time, the expected renovation year for this aspect is equal to 5 years after 2020 = 2025. The calculated renovation year is rounded to periods of 5 years.

Table 6.1: Overview of aspects that contribute to SLA requirement

UNAVAILABILITY NAUTICAL FUNCTION	**Unavailability [hours/year]**				**Critical SLA [hours/year]**	**Renovation year**
	2020	*2050*	*2080*	*2100*		
IV. Unavailability HDWL (Lek)	0.16	0.35	0.54	0.72	29	2100+
V. Unavailability LDWL (Lek)	34	175	262	350	29	2020
VI. Unavailability HUWL (ARK)	24	26	39	n.a.	29	2060
VII. Unavailability LUWL (ARK)	26	39	52	n.a.	29	2025
X. Unavailability Scheduled Maintenance	20	22	n.a.	n.a.	29	2100+
XI. Unavailability Technical Failures	61	73	n.a.	n.a.	29	2020
TOTAL UNAVAILABILITY	165	335	n.a.	n.a.	175	

Given the data of Table 6.1, it can be concluded that the unavailability due to low upstream and downstream water level conditions, as well as unavailability due to technical failures, have a significant contribution to the unavailability requirement. These aspects are, therefore, normative for the urgency of renovation. For all remaining aspects, the expected renovation year is defined. The outcome is summarised in Table 6.2. There are a number of aspects, for which the moment of renovation is estimated to be later than 2100, indicated as ”2100+”. This implies that over the timespan up to 2100, this aspect is not normative for the urgency of renovation 6.2.

Based on data of Table 6.2 and Section 5.1, it is concluded that capacity shortage was expected back in 2015. This was the motive to expand the capacity by means of a third lock chamber. Nevertheless, the increased capacity is expected to be insufficient in 2040. From that moment, the $I/C_{max} = 0.5$ is exceeded. Summarised, five aspects indicate that the moment of renovation must be advanced. The aspects related to the flood safety function are not normative for this advancement. This conclusion follows from both the expected capacity shortage as well as the increasing unavailability of the nautical function.

Table 6.2: Overview of renovation year for the remaining aspects

Prinses Beatrix navigation lock	*Renovation year*
V&R prognosis	2055
I. Piping	2100+
II. Storage capacity	2100+
III. Overflow resistance	2100+
VIII. I/C Economy 2015	direct
IX. I/C Economy 2040	2040

6.2. Terneuzen Navigation Lock Complex

Similar to section 6.1, the aspects IV, V, VI, VII, X, and XI contribute together to the total unavailability of the nautical function. This implies that six aspects together have to fulfil the SLA requirement. The values of expected the unavailability are derived from section 5.2 and summarised in Table 6.3 for both the Eastern (E) and the Western (W) lock chambers.

> It is assumed that each aspect has a maximum acceptable contribution of 1/6th of the SLA requirement. For the Terneuzen navigation lock complex, the maximum unavailability = 2% OH. Therefore, the critical value for the Eastern lock chamber is defined as (1/6 * 2% OH) = (1/6 * 0.02 * 8694) = 29 hours/year. For the Western lock chamber, this critical value equals also (1/6 * 2% OH * 8608) = 29 hours/year. The unavailability of each aspect, as depicted in Table 6.3, is rounded to hours.

The renovation year is estimated based on the unavailability in particular year, relative to the critical SLA value. Take for example aspect ”VI. Unavailability HUWL (KGT) Eastern lock chamber”. The unavailability in 2020 is equal to 0 hours/year. In 2050, this unavailability increases up to 35 hours/year, more than the critical value that is defined for the SLA = 29 hours/year. In a period of (2050-2020=) 30 years, the unavailability increases by (35-0=) 35 hours. Assuming a linear relation between unavailability and time, the expected renovation year for this aspect is equal to 15 years after 2020 = 2035. The calculated renovation year is rounded to periods of 5 years.

Table 6.3: Overview of aspects that contribute to SLA requirement

UNAVAILABILITY NAUTICAL FUNCTION		**Unavailability [hours/year]**				**Critical SLA [hours/year]**	**Renovation year**
		2020	*2050*	*2080*	*2100*		
IV. Unavailability HDWL (Wes)	E	6	10	13	16	29	2100+
	W	6	10	13	16	29	2100+
V. Unavailability LDWL (Wes)	E	0.3	0.22	0.15	0.1	29	2100+
	W	0.3	0.22	0.15	0.1	29	2100+
VI. Unavailability HUWL (KGT)	E	0	35	n.a.	n.a.	29	2035
	W	43	276	n.a.	n.a.	29	2020
VII. Unavailability LUWL (KGT)	E	0	226	n.a.	n.a.	29	2025
	W	0	69	n.a.	n.a.	29	2030
X. Unavailability Scheduled Maintenance	E	7	8	10	n.a.	29	2100+
	W	5	6	7	n.a.	29	2100+
XI. Unavailability Technical Failures	E	239	287	n.a.	n.a.	29	2020
	W	117	140	n.a.	n.a.	29	2020
TOTAL UNAVAILABILITY	E	252	556	n.a.	n.a.	174	
	W	171	501	n.a.	n.a.	172	

Given the data of Table 6.3, it can be concluded that the unavailability due to high and low upstream water level conditions, as well as unavailability due to technical failures, have a significant contribution to the unavailability requirement. These aspects are therefore normative for the urgency of renovation. For all remaining aspects, the expected renovation year is defined (Table 6.4). There are a number of aspects, for which the moment of renovation is estimated to be later than 2100, indicated as ”2100+”. This implies that over the timespan up to 2100, this aspect is not normative for the urgency of renovation.

Based on data of Table 6.4 and section 5.2, it can be concluded that capacity shortage was expected in 2015. The new middle lock chamber will temporarily increase the capacity the coming years, however it is expected to be insufficient in 2035. From that moment, the $I/C_{max} = 0.5$ is exceeded. Summarised, five aspects indicate advancing the moment of renovation as defined in the V&R programme. The aspects related to the flood safety function are not normative for this advancement; it is the result of the expected capacity shortage and increased unavailability of the levelling function.

Table 6.4: Overview of renovation year for the remaining aspects

Terneuzen navigation lock	*Renovation year*	
	Eastern lock chamber	**Western lock chamber**
V&R prognosis	2075	2076
I. Piping	2100+	2100+
II. Storage capacity	2100+	2100+
III. Overflow resistance	2100+	2100+
IX. I/C Economy 2015	direct	direct
X. I/C Economy 2040	2035	2035

7

Criticality Assessment

The main conclusion from both case studies is that under-performance can be expected before the scheduled moment of renovation. This implies that norms are exceeded in the (near) future, resulting in nautical hindrance. Therefore, the method that is developed and used in the assessment of the case studies, gives more insight into the performance of navigation locks. The V&R prioritisation that is used for the renovation work is not sufficiently comprehensive. In the case studies, the consequences of norm exceedance are not yet evaluated. In this chapter, these consequences are investigated, and potential mitigating measures, from an economic perspective, are opted for, to acquire an insight into the criticality of renovation.

7.1. Methodologies to Determine the Performance of Assets

Asset management focuses, among other things, on the performance of assets over their lifetime. In the scope of this research, only the operational phase is considered. During the operational phase, a number of risks are present for which control measures are vital. This implies that knowledge about the effects of certain risks must be known. A risk register is ”a risk management tool, that acts as a repository for all risks identified and includes additional information about each risk, e.g. nature of the risk, reference and owner, and mitigation measures” (Cora Systems, 2019). The application of a risk register for navigation locks helps the asset manager to define the right mitigating measures, focusing on the nautical and flood safety function. In this section, a number of methodologies are reviewed to determine the assets’ performance.

7.1.1. Reliability Centred Maintenance

Reliability Centred Maintenance (RCM) is ”a concept of maintenance planning, to ensure that systems continue to do what their user requires in their present operating context” (Hastings, 2014). RCM incorporates the following criteria: reliability, availability, cost, maintainability, safety, health and the environment. A navigation lock can be seen as a system, consisting of components that have to perform a certain function. Components can fail their function which may result in a system failure. RCM starts with an inspection of components in a system to check for interaction with other components. After inspection and identification, risk acceptance levels are defined, often the result of norms or regulations. For navigation locks, these risk acceptance levels are based on the legislation of either the Water Act or Mobility Act. Given the risk acceptation level, the failure modes and effects are defined, often by conducting an FMECA (Failure Mode Effect & Criticality Analysis). The output of the FMECA is used to develop maintenance strategies and measures, after which the implementation phase starts. Furthermore, it helps to prioritise the risk mitigation measures. During the operational phase of the assets, continuous monitoring of both the performance and risks is required. The last step of the RCM process is reviewing and adjusting the assets’ performance after which the RCM process starts over (Figure 7.1).

The nautical and the flood safety functions are the two main functions distinguished in this research. Based on a number of aspects that affect either one or both of these functions, the proposed method is applied for the assessment of the case studies. It is defined in chapters two, three and four, that a number of drivers increase the probability of occurrence of events that affect the structural integrity, capacity, and availability of primary navigation locks. Therefore, the RCM concept, that is adopted in this research, is slightly modified. All risks are expressed as risk mitigation costs, which makes risks measurable and allows for comparison. As costs are quantifiable and transparent, it is considered in the application of step 3 of the RCM cycle: the FMECA analysis (Figure 7.1).

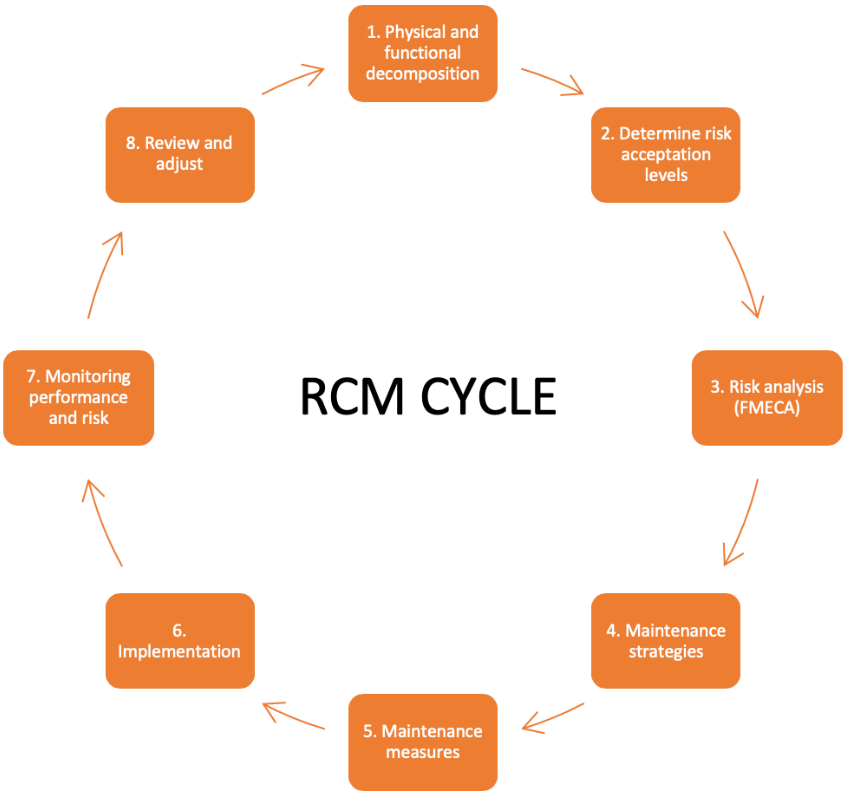


Figure 7.1: The eight steps that together form the sequential RCM process (source: Hastings, 2014)

7.1.2. FMECA assessment tool

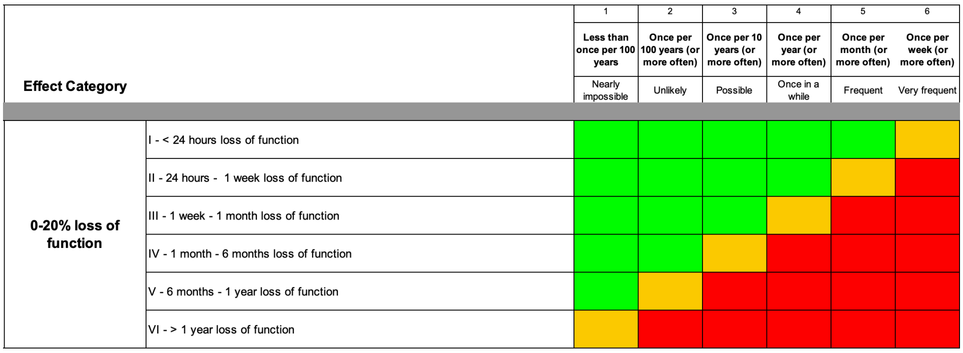
To obtain an insight into the possible effects of the asset's (sub)system failure, the FMECA method can be used. The outcome of an FMECA gives an overview of the risks that can be expected and identifies what effect the failures can have. In literature, the FMECA is defined as:

> A procedure used in assessing all the potential ways in which a product may fail, assessing the causes and effects of failure, and carrying out a numerical risk ranking (Hastings, 2014)

The step-by-step procedure of conducting an FMECA starts with organising the aspects. For each aspect, the function is defined that it has to perform. Possible failure modes are linked to the aspects; sometimes one failure mode but it might be multiple. All the aspects are given a classification. For example, the failure mode "piping" at a navigation lock is classified as evident. Action is required to prevent structural failure of the complex, resulting in flooding. For each aspect, the Mean Time Between Failure (MTBF) is defined. This is the average time of a subsystem in which it is operational before failure occurs. Sometimes, the Mean Time To Failure (MTTF) is used rather than the MTBF. The failure rate can be calculated as the inverse of either MTBF or MTTF. The next step in an FMECA analysis is to address the effects of a particular failure. These effects are linked to the main function of the (sub)system. For each effect, the probability of failure (the result of legislation for navigation locks) is identified that is multiplied with the value that is given to the effect. The outcome of this calculation indicates the risk. As the risk acceptance levels are known beforehand, the outcome of the FMECA analysis can be reviewed. If the risk acceptance levels are higher than the risk of the aspects, no action is required.

7.1.3. RCM and FMECA within Rijkswaterstaat

Most of the large Dutch hydraulic assets, like navigation locks, are managed by Rijkswaterstaat. They prefer a uniform/standardised risk approach in the viewpoint of efficiency for the organisation. In the risk matrices for hydraulic structures, subcategories are defined to indicate different levels of functional loss. For this functional loss, binned periods are defined, to distinguish when the function loss occurs (in a certain time interval) (section 7.2). Based on the function loss, the probabilities of occurrence are defined. In some cases, these probabilities are framed as a global indicator (e.g. likely, possible, impossible). Based on the probabilities of occurrence and the period over which the (undesired) event takes, the risk acceptance level is identified. In this RWS risk matrix, the green areas are classified as acceptable, the yellow areas are the limit state, and the red areas are considered as not acceptable.



Effect Category		1	2	3	4	5	6
		Less than once per 100 years	**Once per 100 years (or more often)**	**Once per 10 years (or more often)**	**Once per year (or more often)**	**Once per month (or more often)**	**Once per week (or more often)**
		Nearly impossible	Unlikely	Possible	Once in a while	Frequent	Very frequent
0-20% loss of function	I - < 24 hours loss of function	🟩	🟩	🟩	🟩	🟩	🟨
	II - 24 hours - 1 week loss of function	🟩	🟩	🟩	🟩	🟨	🟥
	III - 1 week - 1 month loss of function	🟩	🟩	🟩	🟨	🟥	🟥
	IV - 1 month - 6 months loss of function	🟩	🟩	🟨	🟥	🟥	🟥
	V - 6 months - 1 year loss of function	🟩	🟨	🟥	🟥	🟥	🟥
	VI - > 1 year loss of function	🟨	🟥	🟥	🟥	🟥	🟥

Figure 7.2: Part of an RWS risk matrix to identify the risk acceptance level for an event of function loss for a particular probability of occurrence

7.2. Modified FMECA for Case Studies

In Chapter 6 of this research, the results of the case studies are presented. Furthermore, the relative contribution of aspects, that influence the unavailability, is defined. From that point, these aspects are given a renovation year for which they do not meet the requirement. It is clarified that the existing approach, prioritising the urgency of renovation work based on the design lifetime of a navigation lock, is not optimal. There are a number of aspects that indicate advancement of the moment of renovation. The effect of norm exceedance, as well as possible mitigating measures, is not considered. Therefore, a modified FMECA assessment tool is developed, to identify the criticality of the particular aspect. Based on a possible mitigation measure, quantitative advice can be given whether the countermeasure should be adopted. Summarised, the goal of this modified FMECA assessment tool is to check the sensitivity of the results that follow from the applied method.

The following assumptions are used to develop the modified FMECA:

- The total damage that is defined for aspects I, II, and III is derived from the information as presented in ”Factsheets Normering Primaire Waterkeringen”
- The costs that are the result of the downtime of the levelling function, are based on expert judgement (Van den Brink, 2019)
- The unit costs for the possible countermeasures, as well as the residual costs as result of the detour of vessels, are based on expert judgement (Van den Brink, 2019)
- For the calculation of the Equivalent Annual Cost (EAC), a discount rate of 5% is assumed and a lifetime of 100 years
- Applying one of the mitigating measures reduces the capacity loss to zero

For each aspect, the likelihood of the event is defined that can take place in a particular ”binned” time interval (2020, 2040, 2060, 2080, 2100). The likelihood defines the probability of occurrence of the aspects I-III. These values are derived from the results of chapter 5. The effective capacity is based on the operational hours (OH), as a function of the annual hours. The criticality without a mitigating measure is based on the likelihood (aspect I-III) or downtime (aspect IV-XI), multiplied by the effective capacity, and the total damage (aspect I-III) or downtime costs (aspect IV-VI). Each aspect is given a possible mitigating measure, after which the costs of the mitigating measures are defined. The total costs are the result of the unit costs and residual costs. The residual costs are the result of the detour of vessels which is equivalent to a fixed fee per hour multiplied with the Mean Time To Construct (MTTC) of the mitigating measure. The criticality of the mitigating measure is calculated given the total costs, a discount rate, and a design lifetime. This method implies a cyclic renovation of the asset, rather than assuming the mitigating measure over an infinite period of time. Therefore, the principle of equivalent annual cost is applied rather than calculating the present value of the mitigating measure. In case that the criticality $_{\text{mit. measure}}$ < criticality$_{\text{no mit. measure}}$, it is advised to apply the mitigating measure.

EXAMPLE

To clarify the application of the modified FMECA assessment, an example is provided. In this example, the period that the navigation lock is not available for the nautical function (downtime), due to low downstream water level conditions, is considered as:

$$Downtime_{LDWL} = 60\ [hours/year] \tag{7.1}$$

The annual operational hours of the navigation lock chamber are equal to:

$$OH = 8650\ [hours/year] \tag{7.2}$$

The effective capacity, as result of the OH is equal to:

$$Effective\ capacity = \frac{8650}{8760} * 100\% = 98.75\% \tag{7.3}$$

The unit costs of downtime are, based on expert judgement, estimated at:

$$Cost_{downtime} = 45,000\ [€/hour] \tag{7.4}$$

The criticality of the aspect, without a mitigating measure, is, therefore, the product of the effective capacity, the downtime and the cost of the downtime:

$$Criticality_{no\ mit.\,measure} = 60 * 0.9875 * 45,000 = 2,666,095\ [euro/year] \tag{7.5}$$

Assume that the costs of a mitigating measure (construction of water retention basin to level fluctuations in water height) require an investment of:

$$Costs_{mit.\,measure} = 15,000,000\ [euro] \tag{7.6}$$

As for the Mean Time To Construct (MTTC), the mitigating measure, is based on expert judgement and estimated at:

$$MTTC = 12,000\ [hours] \tag{7.7}$$

The residual costs, as a result of the detours of vessels, is based on the costs of the detour of vessels (250 euro/hour) multiplied with the MTTC:

$$Cost_{res} = Cost_{detour} * MTTC = 250 * 12,000 = 3,000,000\ [euro] \tag{7.8}$$

The total costs of the risk mitigation ($\mathrm{Cost}_{\mathrm{Trmm}}$) are therefore:

$$Cost_{Trm} = Cost_{mit.\,measure} + Cost_{res} = 15,000,000 + 3,000,000 = 18,000,000\ [euro] \tag{7.9}$$

The criticality of the mitigating measure can be calculated, using the principle of equivalent annual costs of the risk mitigation ($\mathrm{EAC}_{\mathrm{rm}}$). The discount ratio is equal to r=5% and a lifetime of n=100 years is assumed:

$$Criticality_{mit.\,measure} = EAC_{rm} = \frac{r * Cost_{Trm}}{1-(1+r)^{-n}} = \frac{0.05 * 18,000,000}{1-(1.05)^{-100})} = 906,896[euro/year] \tag{7.10}$$

Based on the results of Equation 7.5 and 7.10, it is advised to apply this mitigating measure as the criticality of the mitigating measure is smaller than the criticality of no mitigating measure:

$$Criticality_{mit.\,measure} < Criticality_{no\ mit.\,measure} \tag{7.11}$$

7.2.1. FMECA Prinses Beatrix navigation lock complex

The result of the modified FMECA assessment for the Prinses Beatrix navigation lock is depicted in Figure 7.3. According to the V&R prognosis, the scheduled moment of renovation is 2055 for both the lock chambers. For the application of the proposed mitigating measure, the construction of a water retention basin is advised due to the large expected unavailability as a result of high and low upstream water level conditions in the near future. Next to the unavailability, the intensity increase is also an indicator to apply the mitigating measure, ”increase the capacity of the navigation lock”, as the costs of no mitigating measure are much higher than the expected costs of the mitigating measure.

The results of the modified FMECA assessment indicate that mitigating measures are advised. The unavailability due to fluctuating upstream water level conditions, as well as the expected capacity shortage, shows that the criticality of the mitigating measure is much lower than the criticality for no mitigating measure. This conclusion is in line with the outcome of case study Prinses Beatrix navigation lock.

7.2.2. FMECA Terneuzen navigation lock complex

The results of the modified FMECA assessment for the Eastern and the Western lock chambers of the Terneuzen complex, are depicted in Figure 7.4 and Figure 7.5. According to the V&R prognosis, the scheduled moment of renovation of the Eastern and Western lock chambers are 2075 and 2076, respectively.

Eastern lock chamber

For the Eastern lock chamber, mitigating measures are advised regarding the expected capacity shortage in the near future. The criticality of the mitigating measure ”increase navigation lock capacity” shows much lower costs relative to the criticality of no mitigating measures. This starts already in 2040, which is 35 years prior to the moment of renovation according to V&R. Also, the expected unavailability due to ageing, shows that mitigating measures are advised, as the costs of no mitigating measures are much higher relative to the expected costs in the case that nothing is done.

Western lock chamber

For the Western lock chamber, mitigating measures are advised regarding the expected unavailability due to fluctuating upstream water level conditions. The criticality of the mitigating measure ”constructing a water-retention basin” shows much lower costs relative to the costs if no mitigating measures are considered. The same conclusion holds for the expected unavailability due to ageing. For the two aspects maintenance and technical failure, that are driven by ageing, mitigating measures are advised, as the costs of no mitigating measures are much higher relative to the expected costs in the case of no mitigating measures.

The results of the modified FMECA assessments of both the Eastern and the Western lock chambers, indicate that mitigating measures are advised. The expected capacity shortage, fluctuating upstream water level conditions, and more frequent maintenance and technical failures in the near future show that the criticality of the proposed mitigating measures is much lower than the criticality of no mitigating measures. These conclusions are in line with the outcome of the Terneuzen navigation lock complex case study.

MODIFIED FMECA

Object: *Prinses Beatrix navigation lock*

ID	Driver	Aspect	Impact	Consequence	Occurence [year]	Likelihood [-/year]	Downtime [hours/year]	Operational Hours (OH) [hours/year]	Effective capacity	Total damage if aspect result to flooding [€]	Cost downtime (€/hour)	Criticality without mitigating measure [€/year]	Possible mitigating measure	Unit Cost	Type	Quantity	Cost mitigating measure	MTTC [h]	Residual cost due to detour vessels	Total cost	Criticality mitigating measure based on EAC [€/year]	Advice mitigating measure
I	CLIMATE CHANGE	Piping	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	*2020*	*1,00E-10*		8736	99,73%	€ 22.000.000.000,00		€ 2,19	Apply larger seepage screens	€ 200,00	per m2	1,20E+03	€ 240.000,00	8600	€ 2.150.000,00	€ 2.390.000,00	€ 120.415,70	No
					2040	1,00E-09						€ 21,94										No
					2060	1,00E-08						€ 219,40										No
					2080	1,00E-07						€ 2.193,97										No
					2100	1,00E-06						€ 21.939,73										No
II		Storage capacity	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	*2020*	*1,00E-08*				€ 22.000.000.000,00		€ 219,40	Increase height adjacent levees	€ 60,00	m3/m	1,16E+05	€ 6.960.000,00	10440	€ 2.610.000,00	€ 9.570.000,00	€ 482.166,63	No
					2040	1,00E-07						€ 2.193,97										No
					2060	1,00E-06						€ 21.939,73										No
					2080	n.a.																No
					2100	n.a.																No
III		Overflow resistance	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	*2020*	*1,00E-08*				€ 22.000.000.000,00		€ 219,40	Increase height navigation lock	€ 10.000.000,00	complex	1,00E+00	€ 10.000.000,00	12528	€ 3.132.000,00	€13.132.000,00	€ 661.631,37	No
					2040	1,00E-07						€ 2.193,97										No
					2060	1,00E-06						€ 21.939,73										No
					2080	n.a.																No
					2100	n.a.																No
IV		Unavailability HDWL (LEK)	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		0,16		99,73%		€ 45.000,00	€ 7.180,27	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	No
					2040		0,3					€ 13.463,01										No
					2060		0,44					€ 19.745,75										No
					2080		0,58					€ 26.028,49										No
					2100		0,72					€ 32.311,23										No
V		Unavailability LDWL (LEK)	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		33,6					€ 1.507.857,53	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	Yes
					2040		104					€ 4.667.178,08										Yes
					2060		175					€ 7.853.424,66										Yes
					2080		262					€ 11.757.698,63										Yes
					2100		350					€ 15.706.849,32										Yes
VI		Unavailability HUWL (ARK)	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		24					€ 1.077.041,10	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	Yes
					2040		28					€ 1.256.547,95										Yes
					2060		32					€ 1.436.054,79										Yes
					2080		36					€ 1.615.561,64										Yes
					2100		40					€ 1.795.068,49										Yes
VII		Unavailability LUWL (ARK)	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		26					€ 1.166.794,52	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	Yes
					2040		33					€ 1.480.931,51										Yes
					2060		39					€ 1.750.191,78										Yes
					2080		51					€ 2.288.712,33										Yes
					2100		62					€ 2.782.356,16										Yes
VIII	INTENSITY & CAPACITY	I/C 2015	Capacity of navigation lock	Reduction availability of nautical function	*2020*		*88*	8736	99,73%		€ 45.000,00	€ 3.931.200,00	Increase navigation lock capacity	€ 60.000.000,00	per lock chamber	1,00E+00	€ 60.000.000,00	18792	€ 4.698.000,00	€64.698.000,00	€ 3.259.688,27	Yes
					2040		*175*					€ 7.862.400,00										Yes
					2060		*n.a.*															No
					2080		*n.a.*															No
					2100		*n.a.*															No
IX		I/C 2040	Capacity of navigation lock	Reduction availability of nautical function	2020		n.a.						Increase navigation lock capacity	€ 60.000.000,00	per lock chamber	1,00E+00	€ 60.000.000,00	18792	€ 4.698.000,00	€64.698.000,00	€ 3.259.688,27	No
					2040		175					€ 7.862.400,00										Yes
					2060		*438*					€ 19.656.000,00										Yes
					2080		*701*					€ 31.449.600,00										Yes
					2100		*964*					€ 43.243.200,00										Yes
X	AGEING	Unavailability due to scheduled maintenance	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		20	8736	99,7%		€ 45.000,00	€ 897.534,25	Increase interval for inspection during non-operational hours	€ 500.000,00	per lock chamber	1,00E+00	€ 500.000,00	2088	€ 5.000.000,00	€ 5.500.000,00	€ 277.107,26	Yes
					2040		22					€ 987.287,67										Yes
					2060		24					€ 1.077.041,10										Yes
					2080		n.a.															No
					2100		n.a.															No
XI		Unavailability due to technical failure	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		61					€ 2.737.479,45	Increase redundancy by layered system configuration	€ 3.500.000,00	per lock chamber	1,00E+00	€ 3.500.000,00	2088	€ 5.000.000,00	€ 8.500.000,00	€ 428.256,67	Yes
					2040		67					€ 3.006.739,73										Yes
					2060		73					€ 3.276.000,00										Yes
					2080		n.a.															No
					2100		n.a.															No

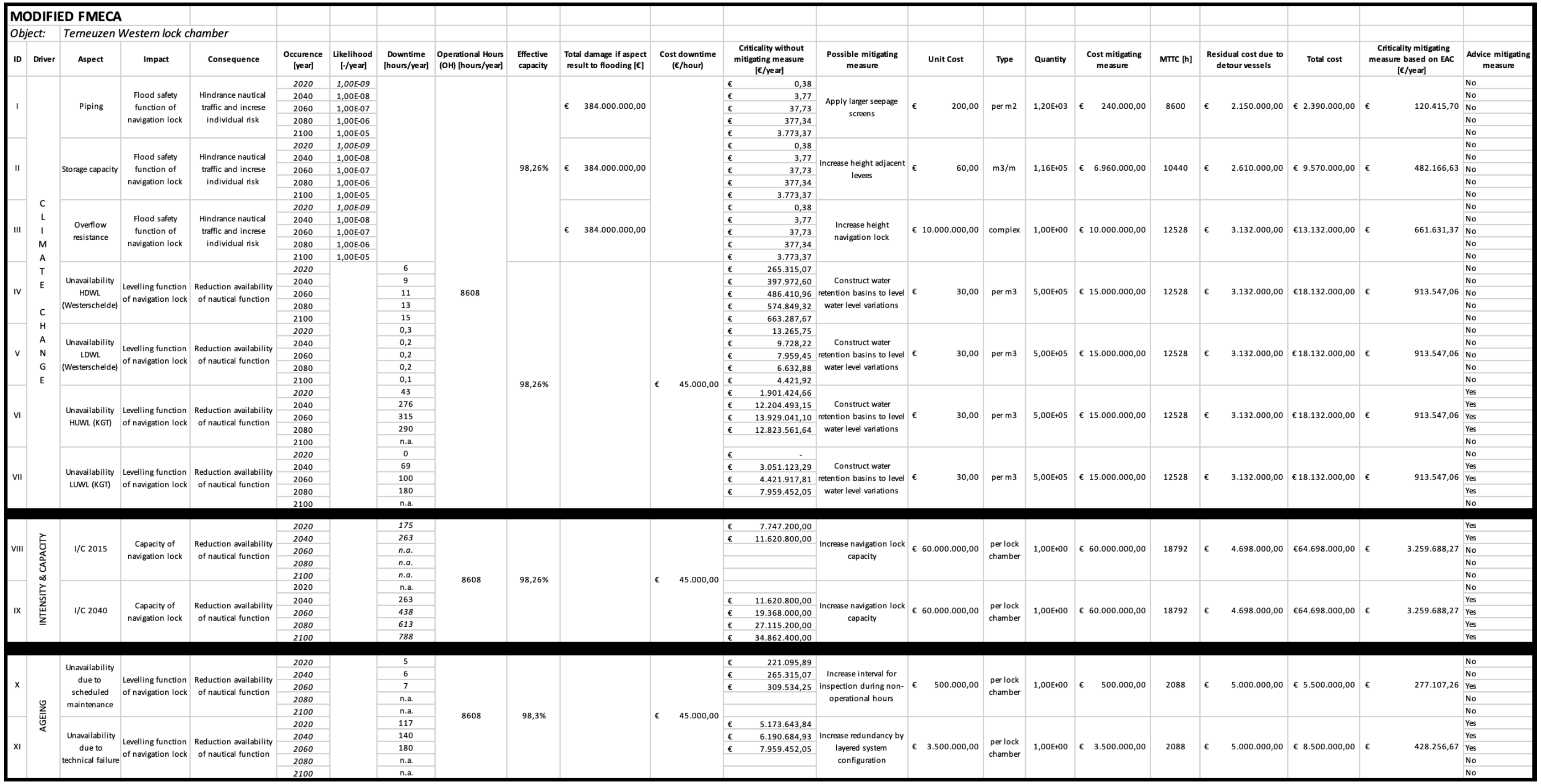
Figure 7.3: Prinses Beatrix navigation lock - modified FMECA

MODIFIED FMECA

Object: *Terneuzen Eastern lock chamber*

ID	Driver	Aspect	Impact	Consequence	Occurence [year]	Likelihood [-/year]	Downtime [hours/year]	Operational Hours (OH) [hours/year]	Effective capacity	Total damage if aspect result to flooding [€]	Cost downtime (€/hour)	Criticality without mitigating measure [€/year]	Possible mitigating measure	Unit Cost	Type	Quantity	Cost mitigating measure	MTTC [h]	Residual cost due to detour vessels	Total cost	Criticality mitigating measure based on EAC [€/year]	Advice mitigating measure
I	CLIMATE CHANGE	Piping	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	*2020*	*1,00E-09*		8694	99,25%	€ 384.000.000,00		€ 0,38	Apply larger seepage screens	€ 200,00	per m2	1,20E+03	€ 240.000,00	8600	€ 2.150.000,00	€ 2.390.000,00	€ 120.415,70	No
					2040	1,00E-08						€ 3,81										No
					2060	1,00E-07						€ 38,11										No
					2080	1,00E-06						€ 381,11										No
					2100	1,00E-05						€ 3.811,07										No
II		Storage capacity	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	*2020*	*1,00E-09*				€ 384.000.000,00		€ 0,38	Increase height adjacent levees	€ 60,00	m3/m	1,16E+05	€ 6.960.000,00	10440	€ 2.610.000,00	€ 9.570.000,00	€ 482.166,63	No
					2040	1,00E-08						€ 3,81										No
					2060	1,00E-07						€ 38,11										No
					2080	1,00E-06						€ 381,11										No
					2100	1,00E-05						€ 3.811,07										No
III		Overflow resistance	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	*2020*	*1,00E-09*				€ 384.000.000,00		€ 0,38	Increase height navigation lock	€ 10.000.000,00	complex	1,00E+00	€ 10.000.000,00	12528	€ 3.132.000,00	€13.132.000,00	€ 661.631,37	No
					2040	1,00E-08						€ 3,81										No
					2060	1,00E-07						€ 38,11										No
					2080	1,00E-06						€ 381,11										No
					2100	1,00E-05						€ 3.811,07										No
IV		Unavailability HDWL (Westerschelde)	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		6		99,25%		€ 45.000,00	€ 267.965,75	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	No
					2040		9					€ 401.948,63										No
					2060		11					€ 491.270,55										No
					2080		13					€ 580.592,47										No
					2100		15					€ 669.914,38										No
V		Unavailability LDWL (Westerschelde)	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		0,3					€ 13.398,29	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	No
					2040		0,2					€ 9.825,41										No
					2060		0,2					€ 8.038,97										No
					2080		0,2					€ 6.699,14										No
					2100		0,1					€ 4.466,10										No
VI		Unavailability HUWL (KGT)	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		0					€ -	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	No
					2040		35					€ 1.563.133,56										Yes
					2060		60					€ 2.679.657,53										Yes
					2080		80					€ 3.572.876,71										Yes
					2100		n.a.															No
VII		Unavailability LUWL (KGT)	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		0					€ -	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	No
					2040		226					€ 10.093.376,71										Yes
					2060		300					€ 13.398.287,67										Yes
					2080		440					€ 19.650.821,92										Yes
					2100		n.a.															No
VIII	INTENSITY & CAPACITY	I/C 2015	Capacity of navigation lock	Reduction availability of nautical function	*2020*		*175*	8684	99,13%		€ 45.000,00	€ 7.815.600,00	Increase navigation lock capacity	€ 60.000.000,00	per lock chamber	1,00E+00	€ 60.000.000,00	18792	€ 4.698.000,00	€64.698.000,00	€ 3.259.688,27	Yes
					2040		*263*					€ 11.723.400,00										Yes
					2060		*n.a.*															No
					2080		*n.a.*															No
					2100		*n.a.*															No
IX		I/C 2040	Capacity of navigation lock	Reduction availability of nautical function	2020		n.a.						Increase navigation lock capacity	€ 60.000.000,00	per lock chamber	1,00E+00	€ 60.000.000,00	18792	€ 4.698.000,00	€64.698.000,00	€ 3.259.688,27	No
					2040		263					€ 11.723.400,00										Yes
					2060		*438*					€ 19.539.000,00										Yes
					2080		*613*					€ 27.354.600,00										Yes
					2100		*788*					€ 35.170.200,00										Yes
X	AGEING	Unavailability due to scheduled maintenance	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		7	8694	99,2%		€ 45.000,00	€ 312.626,71	Increase interval for inspection during non-operational hours	€ 500.000,00	per lock chamber	1,00E+00	€ 500.000,00	2088	€ 5.000.000,00	€ 5.500.000,00	€ 277.107,26	Yes
					2040		8					€ 357.287,67										Yes
					2060		10					€ 446.609,59										Yes
					2080		n.a.															No
					2100		n.a.															No
XI		Unavailability due to technical failure	Levelling function of navigation lock	Reduction availability of nautical function	*2020*		239					€ 10.673.969,18	Increase redundancy by layered system configuration	€ 3.500.000,00	per lock chamber	1,00E+00	€ 3.500.000,00	2088	€ 5.000.000,00	€ 8.500.000,00	€ 428.256,67	Yes
					2040		255					€ 11.388.544,52										Yes
					2060		287					€ 12.817.695,21										Yes
					2080		n.a.															No
					2100		n.a.															No

Figure 7.4: Terneuzen Eastern lock chamber - modified FMECA



MODIFIED FMECA

Object: *Terneuzen Western lock chamber*

ID	Driver	Aspect	Impact	Consequence	Occurence [year]	Likelihood [-/year]	Downtime [hours/year]	Operational Hours (OH) [hours/year]	Effective capacity	Total damage if aspect result to flooding [€]	Cost downtime (€/hour)	Criticality without mitigating measure [€/year]	Possible mitigating measure	Unit Cost	Type	Quantity	Cost mitigating measure	MTTC [h]	Residual cost due to detour vessels	Total cost	Criticality mitigating measure based on EAC [€/year]	Advice mitigating measure
I	CLIMATE CHANGE	Piping	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	2020	1,00E-09		8608	98,26%	€ 384.000.000,00		€ 0,38	Apply larger seepage screens	€ 200,00	per m2	1,20E+03	€ 240.000,00	8600	€ 2.150.000,00	€ 2.390.000,00	€ 120.415,70	No
					2040	1,00E-08						€ 3,77										No
					2060	1,00E-07						€ 37,73										No
					2080	1,00E-06						€ 377,34										No
					2100	1,00E-05						€ 3.773,37										No
II		Storage capacity	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	2020	1,00E-09				€ 384.000.000,00		€ 0,38	Increase height adjacent levees	€ 60,00	m3/m	1,16E+05	€ 6.960.000,00	10440	€ 2.610.000,00	€ 9.570.000,00	€ 482.166,63	No
					2040	1,00E-08						€ 3,77										No
					2060	1,00E-07						€ 37,73										No
					2080	1,00E-06						€ 377,34										No
					2100	1,00E-05						€ 3.773,37										No
III		Overflow resistance	Flood safety function of navigation lock	Hindrance nautical traffic and increse individual risk	2020	1,00E-09				€ 384.000.000,00		€ 0,38	Increase height navigation lock	€ 10.000.000,00	complex	1,00E+00	€ 10.000.000,00	12528	€ 3.132.000,00	€13.132.000,00	€ 661.631,37	No
					2040	1,00E-08						€ 3,77										No
					2060	1,00E-07						€ 37,73										No
					2080	1,00E-06						€ 377,34										No
					2100	1,00E-05						€ 3.773,37										No
IV		Unavailability HDWL (Westerschelde)	Levelling function of navigation lock	Reduction availability of nautical function	2020		6		98,26%		€ 45.000,00	€ 265.315,07	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€18.132.000,00	€ 913.547,06	No
					2040		9					€ 397.972,60										No
					2060		11					€ 486.410,96										No
					2080		13					€ 574.849,32										No
					2100		15					€ 663.287,67										No
V		Unavailability LDWL (Westerschelde)	Levelling function of navigation lock	Reduction availability of nautical function	2020		0,3					€ 13.265,75	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€ 18.132.000,00	€ 913.547,06	No
					2040		0,2					€ 9.728,22										No
					2060		0,2					€ 7.959,45										No
					2080		0,2					€ 6.632,88										No
					2100		0,1					€ 4.421,92										No
VI		Unavailability HUWL (KGT)	Levelling function of navigation lock	Reduction availability of nautical function	2020		43					€ 1.901.424,66	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€ 18.132.000,00	€ 913.547,06	Yes
					2040		276					€ 12.204.493,15										Yes
					2060		315					€ 13.929.041,10										Yes
					2080		290					€ 12.823.561,64										Yes
					2100		n.a.															No
VII		Unavailability LUWL (KGT)	Levelling function of navigation lock	Reduction availability of nautical function	2020		0					€ -	Construct water retention basins to level water level variations	€ 30,00	per m3	5,00E+05	€ 15.000.000,00	12528	€ 3.132.000,00	€ 18.132.000,00	€ 913.547,06	No
					2040		69					€ 3.051.123,29										Yes
					2060		100					€ 4.421.917,81										Yes
					2080		180					€ 7.959.452,05										Yes
					2100		n.a.															No
VIII	INTENSITY & CAPACITY	I/C 2015	Capacity of navigation lock	Reduction availability of nautical function	2020		175	8608	98,26%		€ 45.000,00	€ 7.747.200,00	Increase navigation lock capacity	€ 60.000.000,00	per lock chamber	1,00E+00	€ 60.000.000,00	18792	€ 4.698.000,00	€64.698.000,00	€ 3.259.688,27	Yes
					2040		263					€ 11.620.800,00										Yes
					2060		n.a.															No
					2080		n.a.															No
					2100		n.a.															No
IX		I/C 2040	Capacity of navigation lock	Reduction availability of nautical function	2020		n.a.						Increase navigation lock capacity	€ 60.000.000,00	per lock chamber	1,00E+00	€ 60.000.000,00	18792	€ 4.698.000,00	€64.698.000,00	€ 3.259.688,27	No
					2040		263					€ 11.620.800,00										Yes
					2060		438					€ 19.368.000,00										Yes
					2080		613					€ 27.115.200,00										Yes
					2100		788					€ 34.862.400,00										Yes
X	AGEING	Unavailability due to scheduled maintenance	Levelling function of navigation lock	Reduction availability of nautical function	2020		5	8608	98,3%		€ 45.000,00	€ 221.095,89	Increase interval for inspection during non-operational hours	€ 500.000,00	per lock chamber	1,00E+00	€ 500.000,00	2088	€ 5.000.000,00	€ 5.500.000,00	€ 277.107,26	No
					2040		6					€ 265.315,07										No
					2060		7					€ 309.534,25										Yes
					2080		n.a.															No
					2100		n.a.															No
XI		Unavailability due to technical failure	Levelling function of navigation lock	Reduction availability of nautical function	2020		117					€ 5.173.643,84	Increase redundancy by layered system configuration	€ 3.500.000,00	per lock chamber	1,00E+00	€ 3.500.000,00	2088	€ 5.000.000,00	€ 8.500.000,00	€ 428.256,67	Yes
					2040		140					€ 6.190.684,93										Yes
					2060		180					€ 7.959.452,05										Yes
					2080		n.a.															No
					2100		n.a.															No

Figure 7.5: Terneuzen Western lock chamber - modified FMECA

8

Conclusions and Recommendations

The main conclusion of this research is that the existing method used to schedule and prioritise the renovation work is not optimal, as it only considers the need for renovation on a general design lifetime minus the operational time. It generalises the performance of a navigation lock that consists of multiple components that contribute together to the adequate performance of the main functions. The result is that the predefined norms or requirements are exceeded before the scheduled moment of renovation, affecting the flood safety and/or leading to hindrance in the HVWN for the nautical sector.

8.1. Conclusions

For clarification, the research objective of this report is defined in section 1.4.2, and is presented once more:

"Determine relevant aspects that are an indicator of the urgency of renovation, in order to get an insight into the nautical and flood safety performance of navigation locks over time. The relevant aspects are combined in a method that enables the asset manager to conduct a risk-based and comprehensive prioritisation of renovation work."

The research questions that were formulated were subsequently:

1. What types of risk exist for navigation locks and how are these linked to legislation regarding the flood safety and nautical function of the objects?
2. Is it possible to combine legislation and requirements of primary navigation locks with risk drivers that change in the future, and can these be framed in a method to identify the urgency of a renovation?
3. What are the requirements for the flood safety function of a navigation lock, how are they affected by the boundary conditions, and how can they be assessed?
4. What are the requirements for the nautical function of a navigation lock, how are they affected by the boundary conditions, and how can they be assessed?
5. Do the case studies, that are combined with a criticality assessment, prove that a risk-based prioritisation is preferred over the actual V&R prioritisation?

The conclusions are given per research question, as well as on an overall level.

1. Risk and legislation
There are a number of risk drivers that will change in the future. In this research, climate change, economic growth, and ageing of material are distinguished. Based on these drivers, a number of aspects are defined that are influenced by these drivers. The aspects contribute together to the performance of either nautical function or the flood safety function. All aspects are linked to the Dutch legislation. For the flood safety function, norms are derived based on the Dutch Water Act. The assessment of navigation locks is executed according to the predefined method as defined in the WBI2017. For the nautical function, the Dutch Mobility Act prescribes requirements that reflect on the availability and capacity of navigation locks.

2. Requirements and prioritisation method
In this research, three risk drivers are defined: climate change, economic growth, and ageing of material. Based on these three drivers, a set of aspects are defined. From flood safety viewpoint, three mechanisms are reviewed: piping, storage capacity, and overflow resistance. From the nautical point of view, the unavailability of navigation locks is used as an indicator, as a result of both climate change and ageing of material. Furthermore, the influence of economic growth is translated, assuming an indicator for the intensity as a function of the capacity. 11 aspects are considered, that form the basis of the prioritisation method. Given the requirement or norm the aspect has to fulfil, a renovation year can be estimated. Compared to the existing method that is based on the design lifetime of a navigation lock, the proposed method considers many parameters that result in a more comprehensive prioritisation.

3. Flood safety function
Sea level rise and discharge variety, that are the result of climate change, are considered as aspects that affect the flood safety function of a navigation lock. One of the effects of climate change is the more frequent high loading condition. Piping can become relevant if higher loading conditions result in pressures that induce the flow of water under the structure, which affects the structural integrity and therefore the risk of structural failure. A similar line of reasoning is applicable for the storage capacity. More frequent extreme discharge variety result, during high discharge, in an increase of the water level and therefore more frequent overtopping and overflow events. As long as the maximum storage capacity, or the maximum overflow resistance threshold, is not exceeded, the impact on the flood safety function can be considered as negligible. Nevertheless, the flood safety function of a primary navigation lock prevails over the nautical function.

4. Nautical function
Discharge level alterations directly affect the nautical function of a navigation lock. High discharge levels limit the vessels' air draught at bridges. Low discharge values limit the draught of larger vessels sailing in the main waterway network. Therefore, a number of situations have to be investigated whether these impact the levelling function at both sides of the lock complex. Next to the effects of discharge fluctuations, the network development in the HVWN results in an increase in the intensity. CPB and PBL conducted research on how this will develop in the coming decades. Different scenarios are considered as well as the impact of the energy transition. However, the latter fact is prone to public debate. Due to ageing material, it is expected that the unavailability of the nautical function increases as a result of more scheduled maintenance and increase of probability of occurrence regarding technical failure. If the annual unavailability of the navigation lock increases, the capacity of the complex decreases and therefore the I/C_{max} will be reached earlier. This additionally, gives rise to advancing the urgency for renovation.

5. Case studies and criticality assessment

For the Prinses Beatrix navigation lock complex, there are three aspects that deviate significantly from the V&R prognoses. According to the prognoses, the renovation of both lock chambers is scheduled for 2055. However, the method that is used in this research indicates that the capacity in 2040 is already insufficient. Furthermore, the low water level conditions as a result of drought, which have a large effect on the unavailability of the navigation lock, do also indicate the urgency of renovation. Both the aspects negatively impact the levelling function of the lock complex. This demonstrates that the V&R prognosis is, on the basis of these aspects, not accurate for indicating the correct moment of renovation.

For the Terneuzen navigation lock complex, four aspects indicate that renovation is needed at an ealier moment of time. V&R estimates the renovation of the Eastern lock chamber and Western lock chamber in 2075 and 2076, respectively. However, the contribution to the SLA for unavailability due to the low upstream water level conditions, indicates advancing the moment of renovation to the next decade already. Furthermore, the technical failure events indicate direct renovation, as these have a significant contribution to the total unavailability requirement. Finally, capacity shortage can be expected in 2035 again, which is only a decade after the capacity expansion by the new Middle lock chamber. This is almost 40 years prior to the expected renovation according to V&R. This case study demonstrates that the V&R prognosis is, on the basis of these aspects, not accurate for indicating the correct moment of renovation. Neglecting these effects hampers the overall performance of the navigation lock complex.

Criticality assessment

The modified FMECA assessment is used to define the criticality in case that no mitigating measures are considered, relative to the criticality of mitigating measures. The result of this assessment provides quantitative insight into the performance of a navigation lock. The consequences of norm exceedance can be financially assessed, and mitigating measures can be considered to reduce the impact on the flood safety or nautical function of a primary navigation lock.

For the case study Prinses Beatrix navigation lock, it is analysed whether the application of retention basins is advisable, to level the discharge variety at the upstream side of the complex. The equivalent annual costs of this mitigating measure show a lower criticality relative to the option ”no mitigating measure”. The latter implies a higher unavailability of the levelling function and detour of vessels, as waiting times increase significantly. The same conclusion holds for the expected capacity shortage in the near future. The costs that result from unavailability show a much higher criticality relative to the equivalent annual costs of constructing a new lock chamber (Table 8.1). The modified FMECA assessment, that is conducted for the Terneuzen navigation lock complex, indicates that the criticality of the expected costs as a result of insufficient capacity relative to the intensity growth, are much higher than the criticality of capacity expansion by constructing an additional lock chamber. The mitigating measures opted for ageing, that result in an expected increase of the unavailability due to more maintenance and more technical failures, also indicate the cost-effectiveness of the measures. The costs related to the increased unavailability of the levelling functions are expected to be much higher than the equivalent annual costs of the mitigating measures (Table 8.1) (e.g. more scheduled maintenance during non-operational hours).

Table 8.1: Overview of target years and costs with and without mitigating measures for the two most critical aspects

	Pr. Beatrix	Terneuzen East	Terneuzen West
Renovation V&R	2055	2075	2076
Intensity/Capacity	**2040**	**2035**	**2035**
Criticalilty (excl. mit. measure)	**€7,862,400**	**€11,723,400**	**€11,620,800**
Criticalilty (incl. mit. measure)	**€6,519,350**	**€3,259,688**	**€3,259,688**
Technical failures	**2020**	**2020**	**2020**
Criticalilty (excl. mit. measure)	**€2,737,479**	**€10,673,969**	**€5,173,643**
Criticalilty (incl. mit. measure)	**€856,512**	**€428,256**	**€428,256**

Conclusion
The method that is developed in this research, and validated with the case studies, show that the existing method can be improved by adopting a risk-based approach. Considering multiple aspects, on which the urgency of renovation is based, gives the asset manager much more information on the actual performance of navigation locks. From this perspective, the extensive renovation programme, that costs a lot of money and man-hours, can be further optimised. The execution of the method is more time consuming relative to the existing method. On the contrary, the gained insight into the actual navigation lock performance might be much more valuable.

8.2. Recommendations

This research is based on information derived from a number of technical reports and contains information taken from interviews and peer reviews. Nevertheless, for a number of missing links, assumptions had to be made that are primarily based on expert opinions. As this research is an ongoing process and is founded on aspects for which certain parts have high uncertainties over longer periods of time (e.g. intensity growth), the following recommendations are proposed to further improve the validity and usage of the risk-based performance approach:

1. The unavailability of the navigation lock is often the bottleneck in the performance according to the norms of the nautical function. For the two case studies, it has been observed that the operational hours are not equal to the total annual hours. Rijkswaterstaat should consider whether the availability of lock complexes can be increased by considering a ”24/7 operational” regime to increase the capacity.

2. The boundary conditions for particular aspects are highly uncertain when considered over a longer period of time. In principle, navigation locks have a long functional lifetime. This gives difficulties when assessing the long performance lifetime with, for example, economic prosperity. It is advised to apply the method every six or twelve years, in analogy with the WBI procedures.

3. To improve the comprehensiveness of a risk-based prioritisation method, the environmental impact might be considered as well. The actual focus is on the performance of the two main functions: the flood safety function and the nautical function. It should be investigated whether the extension of the method is preferred in the viewpoint of the time-effectiveness that this method already has, relative to the existing method.

4. Based on the two case studies, the aspects that are assessed regarding the flood safety function are never an indicator for advancing the moment of renovation. It should be analysed whether the Water Act is not already conservative enough, in order to neglect these aspects in the proposed method of this research, in favour of the effectiveness.

5. The modified FMECA that is used to define the impact and the criticality of the aspects, is based on expert judgement regarding the costs of a proposed mitigating measure. It might be that other mitigating measures are more cost-effective, resulting in weighing

variations, which makes other aspects more important. Research has to be done to find out whether this is the case, and how different mitigating measures might deviate from the results of the risk-based performance approach.

6. The workload that is the result of the prioritisation of renovation work, in an economic point of view, might not be optimal. The availability of resources and the application of standardised components are parameters that influence the financial performance. More research is required regarding the implication of the MWW programme in the V&R programme of Rijkswaterstaat.
7. The I/C ratio, that follows from the NoMo report, is in this research used as an indicator to determine the urgency of renovation. The relation between the I/C relative to the unavailability of the navigation lock is not yet clear. More research should be done to determine the correlation between the I/C and unavailability, expressed in the SLA requirement, which might simplifyy the method even further.
8. Rijkswaterstaat should consider an information management system for information on its assets. Nowadays, due to the size of the organisation, information is often available, but it is hard to find where it is located and how accurate they are. In this research, accurate information regarding the nautical performance was not available and was sometimes inconsistent.

A

Technical Characteristics of Dutch Primary Navigation Locks

The following abbreviations are used in the tables A.1 to A.4:

- **Region**: Location of the navigation lock in one of the areas defined by RWS areas
- **Corridor**: The waterway the navigation lock is located, as defined in Figure 1.1
- **Fe**: Exceedance frequency of flood defence the navigation lock is part of
- **MWH**: Mean high water level relative to the NAP of the outer head or inner head of the navigation lock
- **MLW**: Mean low water level relative to the NAP of the outer or inner head of the navigation lock
- **YoC**: The year of construction of the navigation lock
- **EoL**: Expected year of renovation on the basis of (extended) design lifetime
- **Vessel class**: Normative size of a vessel that can access the navigation lock
- **LC**: Number of annual levelling cycles
- **OH**: Operational Hours
- **Icomm**: Annual intensity of commercial traffic
- **Irecr**: Annual intensity of recreational traffic
- **Tlevel**: Time needed to level a vessel in one direction
- **AoL**: Availability of the levelling function as a percentage of the OH
- **Activity**: The capacity level of the navigation lock that is in use (source: Anton Huurman, RWS)

Table A.1: Characteristics of navigation locks (ID, name, region, corridor and exceedance frequency) (source: Sluizenboekje 2017)

Object Code	Name	Region	Corridor	F_e
07F-002-01	Zeesluizen Farmsum kamer 1	NN	5	1/10,000
07F-002-02	Zeesluizen Farmsum kamer 2	NN	5	1/10,000
10B-001-05	Lorentzsluizen kamer 1	MN	5	1/10,000
14E-001-01	Stevinsluizen	MN	5	1/10,000
15F-001-01	Prinses Margrietsluis	NN	5	1/100
20A-001-01	Krabbersgatsluis	MN	5	1/10,000
20A-100-02	Naviduct krabbersgat	MN	5	1/10,000
20D-001-01	Houtribsluizen	MN	5	1/10,000
20D-001-02	Houtribsluizen	MN	5	1/10,000
21C-001-01	Roggebotsluis	MN	5	
21G-350-01	Spooldersluis	ON	6	
25A-001-01	Noordersluis	WNN	8	1/10,000
25A-001-02	Middensluis	WNN	8	1/10,000
25A-001-03	Zuidersluis	WNN	8	1/10,000
25A-001-04	Kleine Sluis	WNN	8	1/10,000
25E-001-01	Noordersluis	WNN	2	1/1,250
25E-001-02	Middensluis	WNN	2	1/1,250
25E-001-03	Zuidersluis	WNN	2	1/1,250
25E-001-07	Prins Willem Alexander sluis	WNN	2	1/1,250
31H-006-01	Zuidersluis	MN	2	
32E-001-01	Nijkerkersluis	MN	5	
37C-001-01	Goereese sluis	WNZ	8	
37H-001-02	Algerasluis	WNZ	1	1/10,000
38F-006-01	Koninginnensluis	MN	2	
38F-352-01	Prinses Beatrixsluis oostelijke sluis	MN	2	1/1,250
38F-352-02	Prinses Beatrixsluis westelijke sluis	MN	2	1/1,250
39B-001-01	Prinses Marijkesluis westelijke sluis	MN	2	1/1,250
39B-001-02	Prinses Marijkesluis oostelijke sluis	MN	2	1/1,250
39B-002-01	Prinses Irenesluis Duwvaartsluis (sluis 2)	MN	2	1/1,250
39B-002-02	Prinses Irenesluis Oude sluis (sluis 1)	MN	2	1/1,250
39D-001-01	Prins Bernhardsluis Oude sluis (west)	MN	2	1/1,250
39D-001-02	Prins Bernhardsluis Duwvaartsluis (oost)	MN	2	1/1,250
40C-004-01	Sluis Weurt west	ZN	7	1/1,250
40C-004-02	Sluis Weurt oost	ZN	7	1/1,250
42D-001-05	Roompotsluis	ZD	3	
43C-001-01	Grevelingensluis	ZD	3	
43C-002-01	Krammersluizencomplex 2e Jachtensluis (Noord)	ZD	3	
43C-002-02	Krammersluizencomplex 2e Duwvaartsluis (Noord)	ZD	3	
43C-002-03	Krammersluizencomplex 1e duwvaartsluis (Zuid)	ZD	3	
43C-002-04	Krammersluizencomplex 1e Jachtensluis (Zuid)	ZD	3	
43G-001-01	Sluis 1	WNZ	3	
43G-001-02	Sluis 2	WNZ	3	
43G-001-03	Sluis 3	WNZ	3	
43G-001-05	Jachtensluis sluizencomplex Volkerak	WNZ	3	
44B-001-01	Biesboschsluis	WNZ	3	
44D-002-01	Sluis I	ZN	7	
45B-001-01	Sluis St. Andries	ZN	7	1/1,250
45B-352-01	Sluis Empel	ZN	7	1/1,250
46A-001-01	Sluis Heumen	ZN	7	1/1,250
48E-001-01	Zandkreeksluis	ZD	3	
48H-353-01	Hansweert Oostelijke sluis	ZD	3	
48H-353-02	Hansweert Westelijke sluis	ZD	3	
49B-001-01	Bergsediepsluis	ZD	3	
54E-001-01	Oostsluis, Terneuzen	ZD	4	
54E-001-04	Middensluis, Terneuzen	ZD	4	
54E-001-07	Westsluis, Terneuzen	ZD	4	
61F-002-01	Sluis Bosscherveld	ZN	7	1/250

Table A.2: Characteristics of navigation locks (Length, width, MHW, and MLW, relative to NAP) (source: Sluizenboekje 2017)

Object Code	Length [m]	Width [m]	MHW_out [m]	MLW_out [m]	MHW_in [m]	MLW_in [m]
07F-002-01	174	16	5.95	-1.8	1.3	0.33
07F-002-02	123	16	5.95	-1.8	1.3	0.33
10B-001-05	137.8	14	4.75		1.2	-1.13
14E-001-01	138.75	14	4.5		1.2	-1.13
15F-001-01	260	16	2.3	-0.5		
20A-001-01	115	11.8	1.2	-1.13	1.5	-1.16
20A-100-02	125	12.3	1.2	-1.13	1.5	-1.16
20D-001-01	196	18	1.2	-1.13	1.5	-1.16
20D-001-02	196	18	1.2	-1.13	1.5	-1.16
21C-001-01	90	9.5				
21G-350-01	142	14	5.5		5.5	
25A-001-01	400	47.3	5.15	-3	-0.3	-0.5
25A-001-02	200	25	5.15	-3	-0.3	-0.5
25A-001-03	104	18	5.15	-3	-0.3	-0.5
25A-001-04	111	11	5.15	-3	-0.3	-0.5
25E-001-01	72	14	0.7	-3.17	0.89	-0.71
25E-001-02	95	18	0.7	-3.17	0.89	-0.71
25E-001-03	72	14	0.7	-3.17	0.89	-0.71
25E-001-07	204	24	0.7	-3.17	0.89	-0.71
31H-006-01	120	12	0.8	0	-0.2	-0.5
32E-001-01	90	9.5	2	-1.38	0.9	-0.6
37C-001-01	144.5	16.38	5.15	-2.05	2.6	0
37H-001-02	135	23.9	2.6		2.6	
38F-006-01	220	22	6.5	-1.15	0.8	0.3
38F-352-01	225	18	6.4	-1.15	-0.2	-0.5
38F-352-02	225	18	6.4	-1.15	-0.2	-0.5
39B-001-01	260	18	8.15	1.2	5.55	
39B-001-02	260	18	8.15	1.2	5.55	
39B-002-01	260	24	8.4	1.2	-0.2	-0.5
39B-002-02	350	18	8.4	1.2	-0.2	-0.5
39D-001-01	350	18	11.5		5.55	
39D-001-02	260	24	11.5		5.55	
40C-004-01	263	16	14.66	4.22	8.6	7.6
40C-004-02	266	16	14.66	4.22	8.6	7.6
42D-001-05	95	16	1.54	-1.34	1.31	-1.2
43C-001-01	125	16	-0.1	-0.3	1.63	-1.39
43C-002-01	75	9	4.65	-3.3	0.75	-1.25
43C-002-02	280	24.1	4.65	-3.3	0.75	-1.25
43C-002-03	280	24.1	4.65	-3.3	0.75	-1.25
43C-002-04	75	9	4.65	-3.3	0.75	-1.25
43G-001-01	331	24.1	0.9	-0.75	2.8	-1
43G-001-02	331	24.1	0.9	-0.75	2.8	-1
43G-001-03	331	24.1	0.9	-0.75	2.8	-1
43G-001-05	128	16.2	0.9	-0.75	2.8	-1
44B-001-01	55	7	4.5	0.3	3.3	-0.62
44D-002-01	120	14	0.65	0.3		
45B-001-01	110	14	10.05	4.86	6.96	4.2
45B-352-01	105	12.6	6.83	-0.9	2.1	
46A-001-01	250	16	12.46	7.4	8.3	7.6
48E-001-01	123	20	5		1.2	-1
48H-353-01	280	24	6.1			
48H-353-02	280	24	6.1			
49B-001-01	34	6.55	1.81	-1.56	0.15	-0.1
54E-001-01	258	24	5.8	-3.5	2.38	1.88
54E-001-04	140	24	5.8			
54E-001-07	245	38	5.8			
61F-002-01	132	16	44.2	43.9	40.48	40.3

Table A.3: Characteristics of navigation locks (Construction year, expected year of renovation, vessel class, levelling cycles, operation hours and intensity) (source: Sluizenboekje 2017)

Object Code	YoC	EoL	Vessel class	LC	OH	I_comm	I_recr
07F-002-01	1958	2067	CEMT V	15,045	8736	449	5330
07F-002-02	1958	2067	CEMT V	3168	8736	10,449	795
10B-001-05	1931	2051	CEMT Va	10,689	8616	3327	28,181
14E-001-01	1930	2051	CEMT Va	7583	8616	1946	18,064
15F-001-01	1950	2059	CEMT IV	16,065	7540	16,961	18,482
20A-001-01	1969	2069	CEMT Va	3008	8616	1828	125
20A-100-02	2000	2109	CEMT Vb	11,243	8616	2462	29,457
20D-001-01	1972	2072	CEMT Vb	18,133	8616	16,195	8606
20D-001-02	1972	2072	CEMT Vb	17,077	8616	15,541	8338
21C-001-01	1955	2064	CEMT II	8715	3742	1100	18,658
21G-350-01	1961	2070	CEMT Va	10,032	4511	4643	8191
25A-001-01	1923	2051	CEMT VIa		8736		
25A-001-02	1891	2047	CEMT VIa		8736		
25A-001-03	1876	2051	CEMT Va		8736		
25A-001-04	1876	2051	CEMT IV		8736		
25E-001-01	1870	2059	CEMT III	14,773	8736	3763	45,454
25E-001-02	1870	2059	CEMT IV	15,187	8736	12,239	13,973
25E-001-03	1870	2059	CEMT III	2030	8736	1070	3845
25E-001-07	1991	2100	CEMT VIa en VIb	19,353	8736	25,992	655
31H-006-01	1937	2046	CEMT Va	7174	4130	1538	9394
32E-001-01	1962	2071	CEMT II	8938	4125	2480	19,313
37C-001-01	1960	2069	CEMT Va	6703	6240	660	4478
37H-001-02	1958	2067	CEMT V	15	3159	11	3
38F-006-01	1885		CEMT Va	3897	4130	399	10,038
38F-352-01	1938	2055	CEMT Vb en VIa	20,210	8736	24,633	2179
38F-352-02	1933	2055	CEMT Vb en VIa	19,824	8736	24,410	2193
39B-001-01	1937	2046	CEMT Vb				
39B-001-02	1937	2046	CEMT VIb				
39B-002-01	1974	2083	CEMT VIa	12,703	8736	18,435	1087
39B-002-02	1937	2046	CEMT Vb	13,094	8736	18,034	1111
39D-001-01	1952	2061	CEMT Vb	8974	8736	10,909	603
39D-001-02	1973	2082	CEMT VIb	9424	8736	12,061	632
40C-004-01	1977	2086	CEMT Vb	14,227	8760	15,151	1614
40C-004-02	1927	2050	CEMT Vb	11,873	8760	11,548	3391
42D-001-05	1982	2091	CEMT Va	10,129	8760	3350	9571
43C-001-01	1960	2069	CEMT Va	7546	8760	1015	36,005
43C-002-01	1995	2096	CEMT III	5833	2737	845	16,109
43C-002-02	1987	2096	CEMT VIb	10,542	8760	19,204	1877
43C-002-03	1987	2096	CEMT VIb	10,582	8760	19,474	151
43C-002-04	1987	2096	CEMT III	6057	2737	1251	15,465
43G-001-01	1967	2073	CEMT VIb	14,012	6240	32,838	1090
43G-001-02	1967	2073	CEMT VIb	14,082	6240	34,387	7
43G-001-03	1977	2084	CEMT VIb	14,261	6240	34,561	14
43G-001-05	1977	2083	CEMT Va	13,036	6240	5156	31,117
44B-001-01	1952	2062	CEMT II	8078	2882	346	13299
44D-002-01	1968	2077	CEMT IV	6916	8760	4658	1847
45B-001-01	1934	2043	CEMT Va	14,050	8760	11257	4020
45B-352-01	2012	2121	CEMT IV	12,115	8760	9248	1928
46A-001-01	1927	2036	CEMT Vb		8760		
48E-001-01	1958	2067	CEMT Va	7445	8760	1945	28,243
48H-353-01	1988	2097	CEMT VIb	14,935	8760	21,676	3154
48H-353-02	1988	2097	CEMT VIb	13,041	8760	192,61	3068
49B-001-01	1984	2093	CEMT 0	5629	8760	280	7699
54E-001-01	1966	2075	CEMT VIb	12,961	8760	29,532	1787
54E-001-04	1910	2034	CEMT VIb	7538	8760	9644	425
54E-001-07	1967	2076	CEMT VIb	9262	8760	19702	5
61F-002-01	1930	2039	CEMT Va	4900	8760	2786	1589

Table A.4: Characteristics of navigation locks (Levelling time, availability, activity, gate height and monumental status) (source: Sluizenboekje 2017)

Object Code	T_level	AoL	Activity	H_doors [m]	Monument
07F-002-01		99.93%		11.68	No
07F-002-02		99.93%		12.82	No
10B-001-05		99.73%	Normal	5.13	No
14E-001-01		99.90%	Normal	4.88	No
15F-001-01		100.00%	High	5.77	No
20A-001-01		99.89%		2.85	No
20A-100-02				2.15	No
20D-001-01		100%		1.9	No
20D-001-02		100%		1.9	No
21C-001-01		99.90%	Normal	2.65	No
21G-350-01	15 min	99.90%		5.5	No
25A-001-01			Normal	5.85	No
25A-001-02	<12 min		Normal	5.85	No
25A-001-03			Less	4.85	No
25A-001-04			Normal	4.85	No
25E-001-01	<7,5 min	96.00%	High	1.85	No
25E-001-02	<7,5 min	96.00%	High	1.85	No
25E-001-03	<7,5 min	96.00%	High	1.85	No
25E-001-07			High	2.85	No
31H-006-01		99.96%	Less		No
32E-001-01		100.00%		1.65	No
37C-001-01		99.75%		5	No
37H-001-02		100.00%		6	Yes
38F-006-01		100.00%		7.12	Yes
38F-352-01	<7 min	100.00%	High		Yes
38F-352-02	<7 min	100.00%	High		Yes
39B-001-01			High	9	No
39B-001-02			High	9	No
39B-002-01		99.95%		9.1	No
39B-002-02		99.95%	Normal	9.1	No
39D-001-01		99.51%	Normal	12	No
39D-001-02		99.51%		11.5	No
40C-004-01	<7 min	100.00%		15.13	No
40C-004-02		100.00%	Normal	13	No
42D-001-05		99.67%		5.8	No
43C-001-01		99.72%		4	No
43C-002-01		100%			No
43C-002-02	<24 min	100%			No
43C-002-03	<24 min	100%			No
43C-002-04		100%			No
43G-001-01	<6 min			5	No
43G-001-02	<6 min			5	No
43G-001-03	<6 min			5	No
43G-001-05	<5 min	100.00%		5	No
44B-001-01			Normal	5.05	No
44D-002-01		100.00%			No
45B-001-01	<8 min	99.64%	High	10.5	No
45B-352-01	<10 min	99.97%		8.18	No
46A-001-01	<21 min		Less	13.4	No
48E-001-01	<10 min	99.33%			No
48H-353-01	<10 min	99.94%		7	No
48H-353-02	<10 min	99.94%		7	No
49B-001-01	<3 min	99.31%		5	No
54E-001-01	<12 min	100%			No
54E-001-04		100%	High		No
54E-001-07		100%			No
61F-002-01		99.91%	Normal	47.3	Yes

B

Navigation Lock Requirements

Dimensioning of navigation locks is dependent on the type of vessels that are expected. This should be minimised with respect to the construction costs and the volume of water that has to be discharged during the levelling process. The depth of the navigation lock is related to the trim of the vessel. The ratio of the wet cross-sectional area in the lock to the cross-sectional area of the vessel is used to guarantee safe operations, in a formula:

$$A_S/A_c <= 0.75 \tag{B.1}$$

- A_S = cross-sectional area of the vessel
- A_c = wet cross-sectional area inside the lock chamber

Classification of inland vessels in Europe is based on morphological characteristics of the waterway. The CEMT-classification (Conférence Européenne des Ministres des Transports) was initiated in 1954 as an international system of classifying waterways in favour of the nautical transport throughout Europe. By doing so, vessels were constructed in a way that they can be used on particularly aimed trenches, reducing the total transport costs (as transhipment was less needed). The CEMT-classification is modified a few times over the past decades and Rijkswaterstaat initiated their own system in 2010; the RWS 2010-classification. An overview of the relation between CEMT, RWS2010, and dimensioning is illustrated in the Tables B.1, B.2, and B.3 for motor vessels, barges and convoys, respectively.

In the planning phase of navigation locks, the design is adapted on the type of vessels that will transit at certain navigation locks in the HVWN. In the previous sections, intensity growth is expected for multiple types of vessels. Renovation on the basis of these growth prognoses is expected, in order to meet the NoMo-criterion and facilitate the nautical sector in minimising travel times. On the basis of the characteristics of motor vessels, barges, and convoys, the dimensions as depicted in Table B.4 are needed for the navigation lock chambers.

Table B.1: Classification of inland transport: motor vessels

MOTORVESSELS						
CEMT	***RWS2010***	***Name***	***Length (m)***	***Width (m)***	***Draught(m)***	***Load cap. (ton)***
I	M1	Spits	38.5	5.05	2.5	251-400
II	M2	Kempenaar	50-55	6.6	2.6	401-650
III	M3	Hagenaar	55-70	7.2	2.6	651-800
	M4	Dortmund	67-73	8.2	2.7	801-1050
	M5	Verl. Dortmund	80-85	8.2	2.7	1051-1250
IVa	M6	Rijn-Herne	80-85	9.5	2.9	1251-1750
	M7	Verl. Rijn-Herne	105	9.5	3.0	1751-2050
IVb	-	-	-	-	-	-
Va	M8	Groot Rijnschip	110	11.4	3.5	2051-3300
	M9	Verl. Groot Rijnschip	135	11.4	3.5	3301-4000
Vb	-	-	-	-	-	-
VIa	M10	-	110	13.5	4	4001-4300
	M11	-	135	14.2	4	4301-5600
	M12	Rijnmax schip	135	17	4	>5601

Table B.2: Classification of inland transport: barges

BARGES					
CEMT	***RWS2010***	***Length (m)***	***Width (m)***	***Draught(m)***	***Load cap. (ton)***
I	B01	55	5.2	1.9	0-400
II	B02	60-70	6.6	2.6	401-600
III	B03	80	7.5	2.6	601-800
	B04	85	8.2	2.7	801-1250
IVa	BI	85-105	9.5	3.0	1251-1800
IVb	-	-	-	-	-
Va	BII-1	95-110	11.4	3.5	1801-2450
	BIIa-1	92-110	11.4	4.0	2451-3200
	BIIL-1	125-135	11.4	4.0	3201-3950
Vb	BII-2l	170-190	11.4	3.5-4.0	3951-7050
VIa	BII-2b	95-145	22.8	3.5-4.0	3951-7050
VIb	BII-4	185-195	22.8	3.5-4.0	7051-12,000
VIc	BII-6l	270	22.8	3.5-4.0	12,001-18,000
VIIa	BII-6b	195	34.2	3.5-4.0	12,001-18,000

Table B.3: Classification of inland transport: convoys

CONVOYS					
CEMT	***RWS2010***	***Length (m)***	***Width (m)***	***Draught(m)***	***Load cap. (ton)***
I	C1l	77-80	5.05	2.5	<=900
	C1b	38.5	10.1	2.5	<=900
II	-	-	-	-	-
III	-	-	-	-	-
IVa	-	-	-	-	-
IVb	C2l	170-185	9.5	3.0	901-3350
Va	-		-	-	-
Vb	C3l	170-190	11.4	3.5-4.0	3351-7250
VIa	C2b	85-105	19.0	3.0	901-3350
	C3b	95-110	22.8	3.5-4.0	3351-7250
VIb	C4	185	22.8	3.5-4.0	>=7251

Table B.4: Dimensions of minimum navigation lock chamber for different CEMT-classifications

CEMT	Length lock chamber (m)	Width lock chamber (m)	Level sill (m)
I	43	6.0	2.8-3.1
II	60	7.5	3.1-3.2
III	80-95	9.0	3.1-3.3
IV	95-115	10.5	3.5-3.7
Va	125-150	12.5	4.2
Vb	210	12.5	4.7
VIa	160	23.8	5.0
VIb	215	23.8	5.0

C

SIVAK Simulation Process

Nautical studies are conducted for the Terneuzen navigation lock to get an overview of future nautical traffic conditions and factors that can influence it. The SIVAK-model is a software tool that gives the user insight into nautical traffic control, on the basis of real-time simulations. With the input of this model, the following insights can be gained:

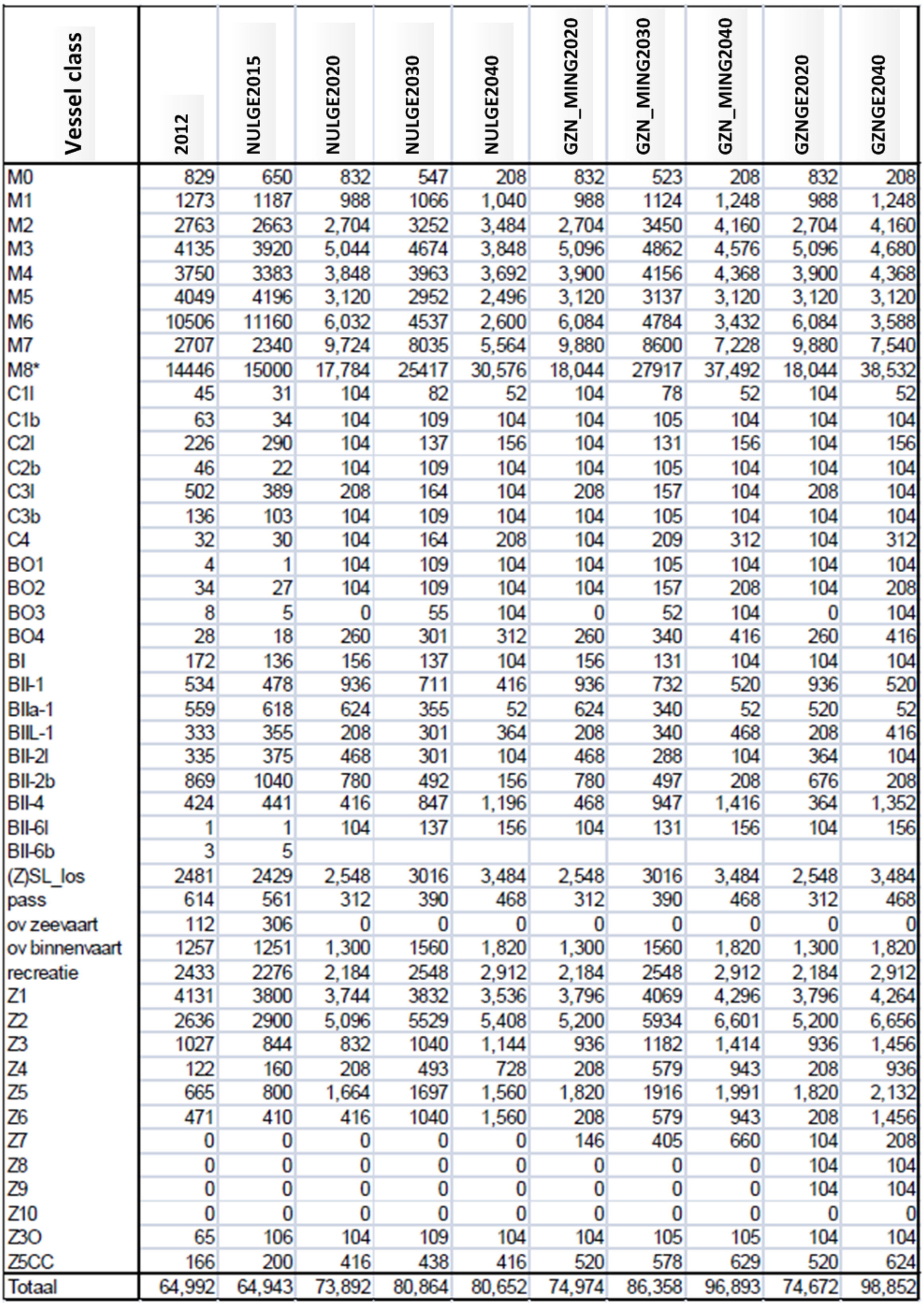
- The effects of design criteria regarding navigation lock capacity
- Validation of design conditions regarding maximum acceptable transit time
- Determine the effect of construction works on the capacity and transit time

For the Terneuzen navigation lock expansion, a capacity analysis is conducted in 2015 (MARIN Consulting, 2015). In this analysis, the total nautical traffic is categorised in fleets. These fleets are a combination of characteristics, based on the number of vessels and the arrival distribution. The applied distribution is based on the type of usage: sea-classified vessels, inland vessels and recreational vessels. A number of traffic volume prognoses are considered, which are related to whether or not a new navigation lock is implemented for different target years. An overview of these prognoses is presented in Table C.1

Table C.1: Definition of traffic volumes for different scenarios (source: MARIN Capaciteitsonderzoek Zeesluis Gent-Terneuzen

Scenarios	**Description**
2012	Traffic volume for 2012
NULGE2015	Traffic volume 2015 including autonomous developments (excl. new navigation lock)
NULGE2020	Traffic volume 2020 including autonomous developments (excl. new navigation lock)
NULGE2030	Traffic volume 2030 including autonomous developments (excl. new navigation lock)
NULGE2040	Traffic volume 2040 including autonomous developments (excl. new navigation lock)
GZN_MINGE2020	Traffic volume 2020 including new navigation lock (excl. waterway modifications)
GZN_MINGE2030	Traffic volume 2030 including new navigation lock (excl. waterway modifications)
GZN_MINGE2040	Traffic volume 2040 including new navigation lock (excl. waterway modifications)
GZN_GE2020	Traffic volume 2020 including new navigation lock (incl. waterway modifications)
GZN_GE2040	Traffic volume 2040 including new navigation lock (incl. waterway modifications)

With the input of the scenarios as defined in Table C.1, the traffic volume estimations are done, itemised per type of vessel class. In this, the M-category is motor class, the C-category is convoy, the B-category is convoy, and the Z-category is sea vessel. This overview can be found in Figure C.1.



Vessel class	2012	NULGE2015	NULGE2020	NULGE2030	NULGE2040	GZN_MING2020	GZN_MING2030	GZN_MING2040	GZNGE2020	GZNGE2040
M0	829	650	832	547	208	832	523	208	832	208
M1	1273	1187	988	1066	1,040	988	1124	1,248	988	1,248
M2	2763	2663	2,704	3252	3,484	2,704	3450	4,160	2,704	4,160
M3	4135	3920	5,044	4674	3,848	5,096	4862	4,576	5,096	4,680
M4	3750	3383	3,848	3963	3,692	3,900	4156	4,368	3,900	4,368
M5	4049	4196	3,120	2952	2,496	3,120	3137	3,120	3,120	3,120
M6	10506	11160	6,032	4537	2,600	6,084	4784	3,432	6,084	3,588
M7	2707	2340	9,724	8035	5,564	9,880	8600	7,228	9,880	7,540
M8*	14446	15000	17,784	25417	30,576	18,044	27917	37,492	18,044	38,532
C1l	45	31	104	82	52	104	78	52	104	52
C1b	63	34	104	109	104	104	105	104	104	104
C2l	226	290	104	137	156	104	131	156	104	156
C2b	46	22	104	109	104	104	105	104	104	104
C3l	502	389	208	164	104	208	157	104	208	104
C3b	136	103	104	109	104	104	105	104	104	104
C4	32	30	104	164	208	104	209	312	104	312
BO1	4	1	104	109	104	104	105	104	104	104
BO2	34	27	104	109	104	104	157	208	104	208
BO3	8	5	0	55	104	0	52	104	0	104
BO4	28	18	260	301	312	260	340	416	260	416
BI	172	136	156	137	104	156	131	104	104	104
BII-1	534	478	936	711	416	936	732	520	936	520
BIIa-1	559	618	624	355	52	624	340	52	520	52
BIIL-1	333	355	208	301	364	208	340	468	208	416
BII-2l	335	375	468	301	104	468	288	104	364	104
BII-2b	869	1040	780	492	156	780	497	208	676	208
BII-4	424	441	416	847	1,196	468	947	1,416	364	1,352
BII-6l	1	1	104	137	156	104	131	156	104	156
BII-6b	3	5								
(Z)SL_los	2481	2429	2,548	3016	3,484	2,548	3016	3,484	2,548	3,484
pass	614	561	312	390	468	312	390	468	312	468
ov zeevaart	112	306	0	0	0	0	0	0	0	0
ov binnenvaart	1257	1251	1,300	1560	1,820	1,300	1560	1,820	1,300	1,820
recreatie	2433	2276	2,184	2548	2,912	2,184	2548	2,912	2,184	2,912
Z1	4131	3800	3,744	3832	3,536	3,796	4069	4,296	3,796	4,264
Z2	2636	2900	5,096	5529	5,408	5,200	5934	6,601	5,200	6,656
Z3	1027	844	832	1040	1,144	936	1182	1,414	936	1,456
Z4	122	160	208	493	728	208	579	943	208	936
Z5	665	800	1,664	1697	1,560	1,820	1916	1,991	1,820	2,132
Z6	471	410	416	1040	1,560	208	579	943	208	1,456
Z7	0	0	0	0	0	146	405	660	104	208
Z8	0	0	0	0	0	0	0	0	104	104
Z9	0	0	0	0	0	0	0	0	104	104
Z10	0	0	0	0	0	0	0	0	0	0
Z3O	65	106	104	109	104	104	105	105	104	104
Z5CC	166	200	416	438	416	520	578	629	520	624
Totaal	64,992	64,943	73,892	80,864	80,652	74,974	86,358	96,893	74,672	98,852

Figure C.1: Traffic volume estimations, itemized per type of vessel at Terneuzen (source: MARIN Capaciteitsonderzoek Zeesluis Gent-Terneuzen)

The distribution pattern is of importance as the total traffic volume is not equally distributed over the availability of the navigation lock. For the year 2012, the distribution over the week for the three vessel categories is analysed (Figure C.2). The inland waterway transport is dominant in the total number of navigation lock transits, peaking on Wednesday and Thursday. For the recreational vessels, the opposite pattern can be observed. Besides the day-to-day distribution, the spread over 24 hours is of importance for the navigation lock transit times (Figure C.2). From this data, a pattern for the inland waterway transport can be seen for inbound-headed vessels in the afternoon/evening and outbound-headed vessels in the morning. The arrival pattern of sea vessels is more equally distributed over the day. In the scope of this report, it is assumed that these distributions will not change for the future scenarios.

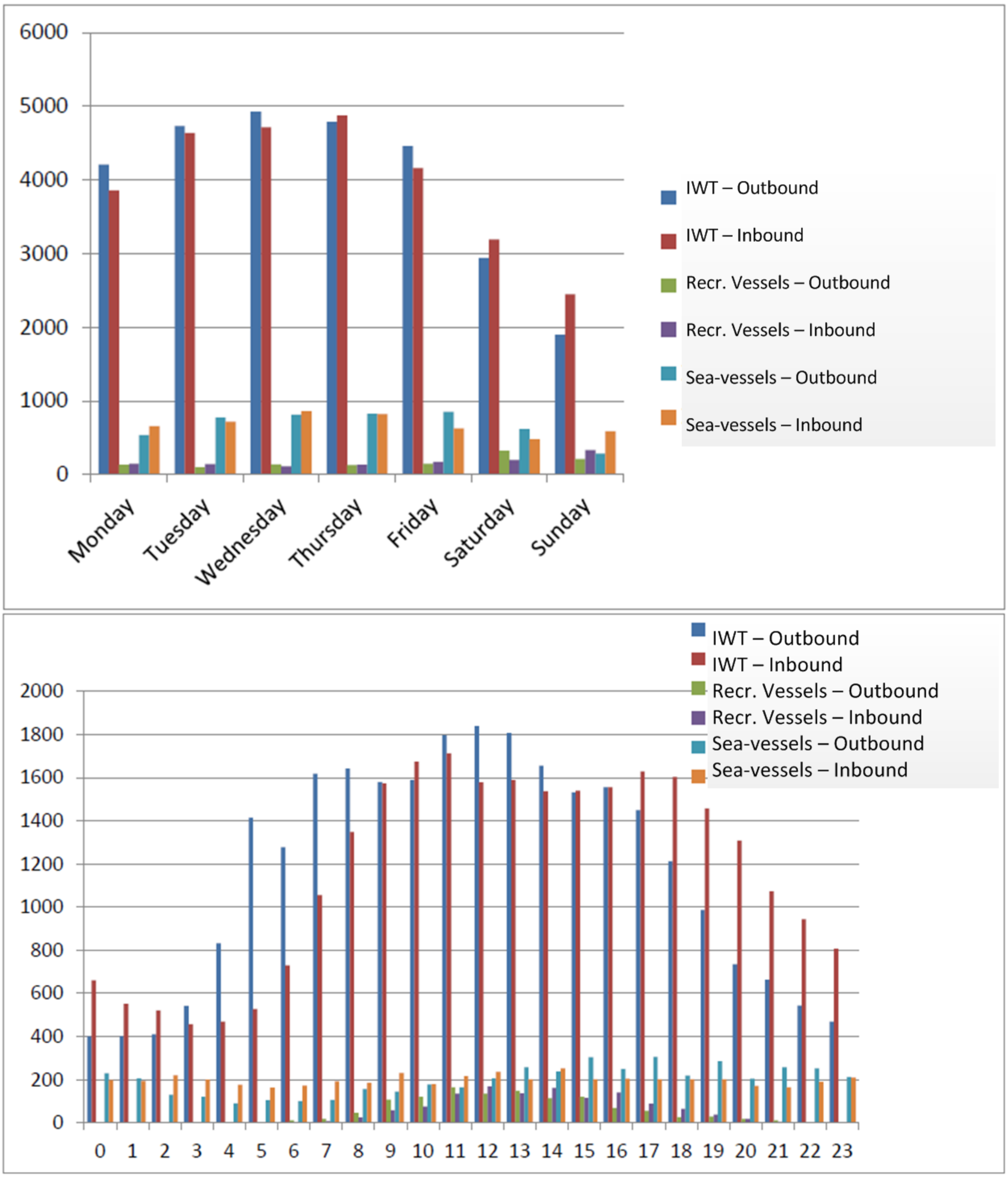
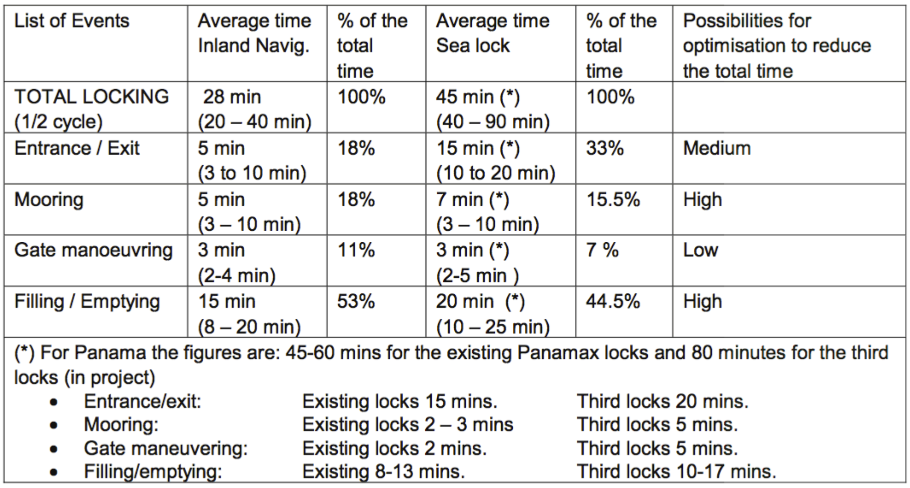


Figure C.2: Traffic volume distribution over the week (top) and over the day (bottom) for the year 2012 (source: MARIN Capaciteitsonderzoek Zeesluis Gent-Terneuzen)

D

Levelling Process

The lock cycle process is one of the criteria that is of importance for the efficiency level of the navigation complex. Therefore, it should be considered in the prioritisation as a criterion as it impacts the Life Cycle Cost Analysis (LCCA) that forms part of the research. The levelling process is considered from entering the lock chamber towards sailing out (which is half the lock cycle). From the perspective of autonomous developments regarding the climate, higher discharges and, therefore, increasing water levels will be the consequence. The result of these changing boundary conditions has an impact on the filling and emptying of the lock chambers (Molenaar, 2011). It can be seen in Figure D.1 that the time needed for filling and emptying takes 50% of the total levelling process (averaging the inland and sea lock navigation). The consequence is that for increasing lift heights, this part of the process will become even larger.



List of Events	Average time Inland Navig.	% of the total time	Average time Sea lock	% of the total time	Possibilities for optimisation to reduce the total time
TOTAL LOCKING (1/2 cycle)	28 min (20 – 40 min)	100%	45 min (*) (40 – 90 min)	100%	
Entrance / Exit	5 min (3 to 10 min)	18%	15 min (*) (10 to 20 min)	33%	Medium
Mooring	5 min (3 – 10 min)	18%	7 min (*) (3 – 10 min)	15.5%	High
Gate manoeuvring	3 min (2-4 min)	11%	3 min (*) (2-5 min)	7 %	Low
Filling / Emptying	15 min (8 – 20 min)	53%	20 min (*) (10 – 25 min)	44.5%	High

(*) For Panama the figures are: 45-60 mins for the existing Panamax locks and 80 minutes for the third locks (in project)

- Entrance/exit: Existing locks 15 mins. Third locks 20 mins.
- Mooring: Existing locks 2 – 3 mins Third locks 5 mins.
- Gate maneuvering: Existing locks 2 mins. Third locks 5 mins.
- Filling/emptying: Existing 8-13 mins. Third locks 10-17 mins.

Figure D.1: Duration of navigation through a lock (source: Manual Hydraulic Structures)

From a financial point of view, increasing lock cycle times will result in higher costs for the users, which hampers the efficiency of the navigation lock. The cost increase rate mainly depends on the water table differences. It should be assessed whether, and, if so, to what extent this is the case. By means of the enumerated equations (Molenaar, 2011), a rough cost calculation can be done:

$$t = t_q * t_s \tag{D.1}$$

$$t_s = \alpha + \beta * \sqrt{H} \tag{D.2}$$

$$t = t_w + n * t_s = t_w + n * \alpha + \beta * \sqrt{n * H_{tot}} \tag{D.3}$$

$$C = P * N * t \tag{D.4}$$

- t = delay time [s]
- t_w = queue time [s]
- t_s = lock cycle time [s]
- α = time for opening and closing of the lock gates including entering and leaving [s]
- β = coefficient dependent on dimensions and capacity pump system [-]
- n = number of locks [-]
- H = average water head [m]
- P = cost of delay [euro/hour]
- C = cost per year [euro/year]

E

Navigation lock transit process

The Kooman method, developed by engineer C. Kooman of Rijkswaterstaat, has been used as a method of determining the lock capacity and traffic resistance of navigation locks before the existing modelling programmes like SIVAK and Lockfill came into picture. The transit time of a vessel is equal to the total extra time required by a lockage, compared to an imaginary situation in which there was no lock and the vessel could proceed at its cruising speed.

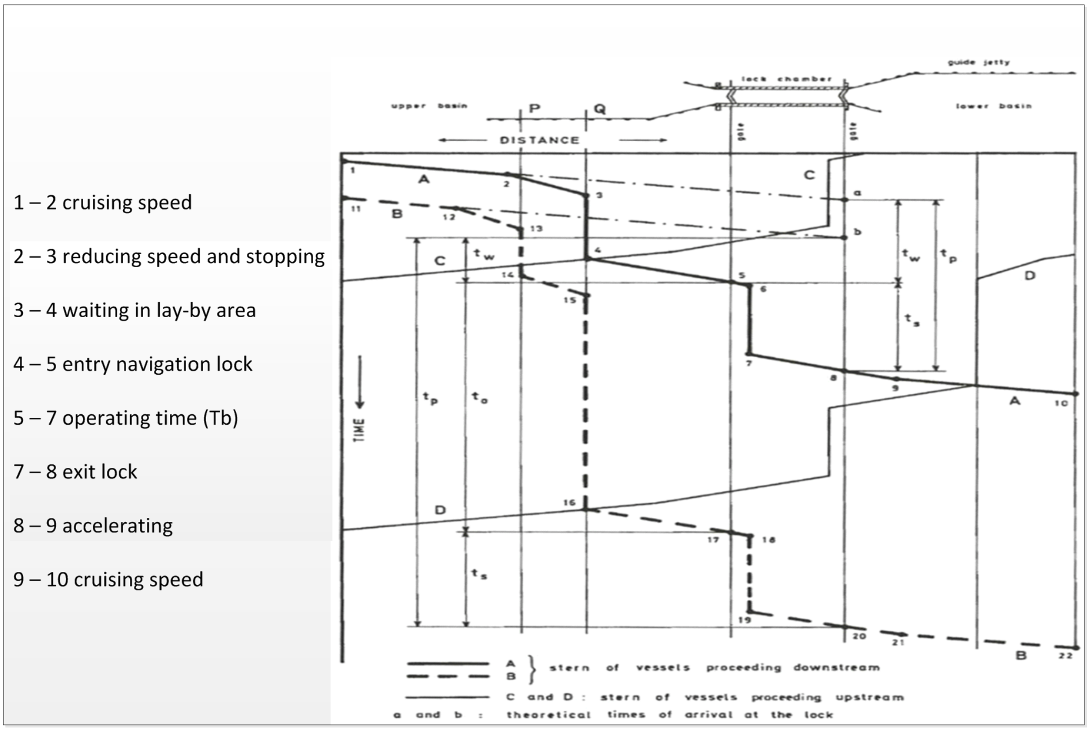


Figure E.1: Vessel transit process of navigation lock

The delay time is dependent on the traffic volume, the arrival pattern of vessels, and the lock capacity.

- $t_p = t_w + t_s + t_o$
- t_p = transit time, t_w = waiting time, t_s = locking time, t_o = delay time

In the evaluation of the navigation lock transit for different scenarios, the transit time, the waiting time, and the delay time as assessment criteria are defined as follows:

- **Waiting time** starts at the moment of arrival of the vessel at the navigation lock and ends at the moment that locking time or delay time begins.
- **Locking time** starts when all vessels are inside the lock chamber and the gates at entry side start to close, until the moment that the vessels sail out and cross the line parallel to the exit gates with the stern of the last vessel.
- **Delay time** starts for the waiting vessel from the closure of the entry gates and ends when the waiting vessel can enter the next levelling cycle.
- **Transit time** is the summation of waiting time, locking time, and delay time.

F

Navigation Lock Complex Schematisation

Most of the primary navigation locks are part of a lock complex, consisting of multiple lock chambers. Hydraulic boundary conditions can, therefore, be simplified by assuming that they are of equal magnitude and direction. In this research, this analogy is considered which implies that approach channels for the navigation lock complexes are assumed to be similar, and water tables on the same side of the lock chambers are at an equal level. This is clarified in Figure F.1 in which for lock chamber 1 and 2, the same hydraulic boundary conditions hold for either the sea side or the waterway side. The system aspects (e.g dimensions or mechanical objects) are not similar as these are dependent on the configuration of the aimed navigation lock chamber.

Figure F.1: Hydraulic boundary condition simplification for multiple navigation lock chambers in a complex (source: Beeldbank RWS, edited)

G

Interview with Giel Klanker

1. **Wat is exact uw functie en hoe houdt dit verband met de renovatie opgave?**

   Binnen RWS ben ik op de afdeling Instandhouding en Constructief Onderhoud bezig met een 2-jarigse prognose voor het komende decennium. Hierbinnen houd ik mij bezig met de natte kunstwerken welke vervangen dienen te worden Waarvan ik een kostenoverzicht op stel. Qua aanpak hanteren wij hiervoor de volgende methode:
   ISSUES -> SLUISCOMPLEX -> WERKHYPOTHESE -> VERVANGEN OF RENOVEREN

2. **Worden er break-even analyses gemaakt en indien zo hoe gebeurt dat precies?**

   Qua kosten worden er twee aanpakken gehanteerd. Het kunstwerk kan 1-op-1 vervangen worden waarbij vanaf scratch begonnen wordt. De andere mogelijkheid is om specifieke onderdelen te vervangen waarbij de elementen individueel geraamd worden en daarvan de vervangingswaarde opgesteld.

3. **Is iedere sluis apart geraamd of worden er clusteringen toegepast?**

   Het areaal wordt verdeeld in groepen met gelijksoortige natte kunstwerken. Deze clustering kan toegepast worden op zowel locatie alsmede functie van het object. Uiteindelijk wordt er een kostenplaatje gemaakt wat uitgedrukt wordt in €/m^3 *kolkinhoud. Hierbij moet opgemerkt worden dat de geraamde kosten gemiddeld genomen een bandbreedte hebben van 50%.*

4. **Hoe zit het qua rapportage richting ministerie en daaruitvolgende beslissingen?**

   Er worden verschillende varianten opgesteld welke verschillen in aanpak alsmede het prijskaartje. In deze rapportages die richting het ministerie gaan is aan RWS de taak om de voorstellen te doen. Hierna is het de verantwoordelijkheid van de minister om een van de mogelijke varianten te selecteren, in hoeverre dit binnen de visie en Rijksbegroting past.

5. **Hoe is de afweging tussen renovatie of vervanging?**

   Er wordt onderscheid gemaakt tussen de levensduur van bestaande sluizen welke gerenoveerd worden (80 jaar) en voor nieuwe sluizen (100 jaar). In de beslissing of er voor renovatie of vervanging wordt gekozen is de levensduur leidend. Verder speelt mee in hoeverre de verwachtingen anders kunnen zijn ten gevolge van externe factoren (klimaat en economie) wat vervolgens meegenomen wordt in verschillende alternatieven richting ministerie. In beperkte zin spelen de SLA's hier ook nog in mee welke verkend dienen te worden in de afweging van renovatie/vervanging.

6. **Wat is de toepasbaarheid van LCCA binnen schutsluizen?**

   Voor elk alternatief dat opgesteld wordt, is de LCC-analyse onderdeel. Hierbij wordt rekening gehouden met de verschillende functionaliteiten van het complex. Verder speelt de NCMA-rapportage een rol welke de lange termijn beschrijft ten aanzien van markt en capaciteitsontwikkelingen in Nederland, gerelateerd aan wegen, vaarwegen en spoorwegen.

7. **In hoeverre wordt er circulair en/of adaptief geraamd en welke afwegingen spelen hier een rol in?**

   In de praktijk wordt adaptief ontwerpen nog niet heel veel toegepast. Er wordt wel gekeken naar hoe investeringen gecombineerd kunnen worden om tot een zo laag mogelijke overall kosten niveau te komen, echter worden potentiele wijzigen in de toekomst nog te weinig meegenomen. Er is wel een trend om dit verder te gaan ontwikkelen waarbij dit in de prognoses verwerkt zal worden. Duurzaamheid speelt wel een steeds grotere rol in het geheel waarbinnen een circulaire economie, energiebesparing en gebiedsontwikkeling de voornaamste aandrijvers zijn. Binnen VNR lopen er een aantal pilots waarin duurzaamheid het centrale thema is ten aanzien van de renovatie exercitie.

8. **Hoe worden beschikbaarheid en economische schade die hier gevolg aan zijn verdisconteert?**

   Dit komt voornamelijk naar voren in de NCMA-rapportages die worden opgesteld. Elk nat kunstwerk moet minimaal zijn huidige functionaliteitsniveau behouden na renovatie of vervanging van het object. Binnen de economische afweging wordt, zover mijn kennis reikt, geen prioritering toegepast als zijnde welk object logischerwijs als eerst aangepakt zou moeten worden. Contactpersoon voor meer informatie omtrent de NMCA en achtergrond hiervan is Michel Steijn (WVL).

H

Interview with Ruben Jongejan

1. **Wat is precies uw achtergrond en huidige werkzaamheden?**

   Ik ben afgestudeerd in civiele techniek aan de TU Delft alsmede politieke wetenschappen aan de Universiteit Leiden. In het huidige werkzame leven ben ik zelfstandig adviseur en verbonden aan de TU Delft, vakgroep Waterbouwkunde.

2. **Hoe worden risico's exact aanvaardbaar geacht in de huidige tijd?**

   In feite worden de te gelden normeringen door de minister beslist welke in de rapportage van het Delta Programma opgenomen worden alsmede uitgebreid beschreven staan in de Waterwet. Het Deltaprogramma schrijft het beleid voor waarin de kans dat een overstroming optreedt en vermenigvuldigd wordt met het gevolg van betreffende overstroming. Het is aan de minister in hoeverre de risico's als aanvaardbaar worden gesteld.

3. **Hoe zit het onderscheid tussen VNK2 en WTI exact?**

   Het VNK2, dat de opvolger is van het niet-succesvolle VNK, beschrijft de kansen en gevolgen van het falen van een dijktraject (daar waar er voorheen dijkringen in zijn geheel getoetst werden) en is zodoende meer onderzoeksgericht. Het WTI is de formele beschrijving van het VNK2 waarbinnen het WBI het instrument is om onderzoeksgerichte VNK2 te toetsen. Uiteindelijk wordt het geheel gevat in het Deltaprogramma dat het beleid voorschrijft ten aanzien van onder meer waterveiligheid.

4. **Op welke wijze wordt het ALARA principe toegepast (As Low As Reasonably Achievable) binnen de risico reductie strategie?**

   Het ALARA-principe wordt vaak geïnterpreteerd als een continue inspanning om risico's te reduceren, echter wordt het niet toegepast in Nederland daar waar alles door de norm omvat wordt welke leidend is. Deze normen, die in de Waterwet beschreven staan, geven indirect opdracht aan de beheerder om te zorgen dat zijn assets voldoen aan de gestelde eisen en beschrijft hiermee een bepaald doel. Aan de hand van de normen wordt de toewijzing van budgetten gekoppeld.

5. **Op welke wijze wordt economische groei meegenomen in het prioriteringsvraagstuk?**

   In principe wordt dit ondergebracht in een geïndexeerde norm welke een zichtjaar hebben voor het jaartal 2050. Hierna wordt gekeken in hoeverre een project een bepaalde afstand heeft van de norm waarbij gerekend wordt met een middenkans. Deze middenkans heeft een bepaalde bandbreedte waarbij een max- en ondergrens vooraf wordt vastgesteld. Op *deze wijze kan gevolgschade ten gevolge van bijvoorbeeld groei (neem de stad Almere) meegenomen worden in de indexatie. Dit leidt uiteindelijk tot het programmeren van de natte kunstwerken waarna het aan de politiek is om een definitief besluit te nemen.*

6. **Hoe wordt in het ontwerpproces de norm gehanteerd in combinatie met de ROK en daaruit voortvloeiende Eurocode?**

   Voor het ontwerp moet naast de norm vanuit de Waterwet ook het bouwbesluit voldaan worden. Daar waar de waterwet de faalkansprestatie definieert, schrijft het bouwbesluit voorschriften voor die Europees geldig zijn (de Eurocode). Tezamen met de nationale bijlage, schrijven deze beide voorschriften voor waar civiele kunstwerken zoals sluizen aan moeten voldoen. In principe zijn deze eisen strikter dan de Waterwet normen waardoor de Eurocode leidend zijn in het ontwerpproces.

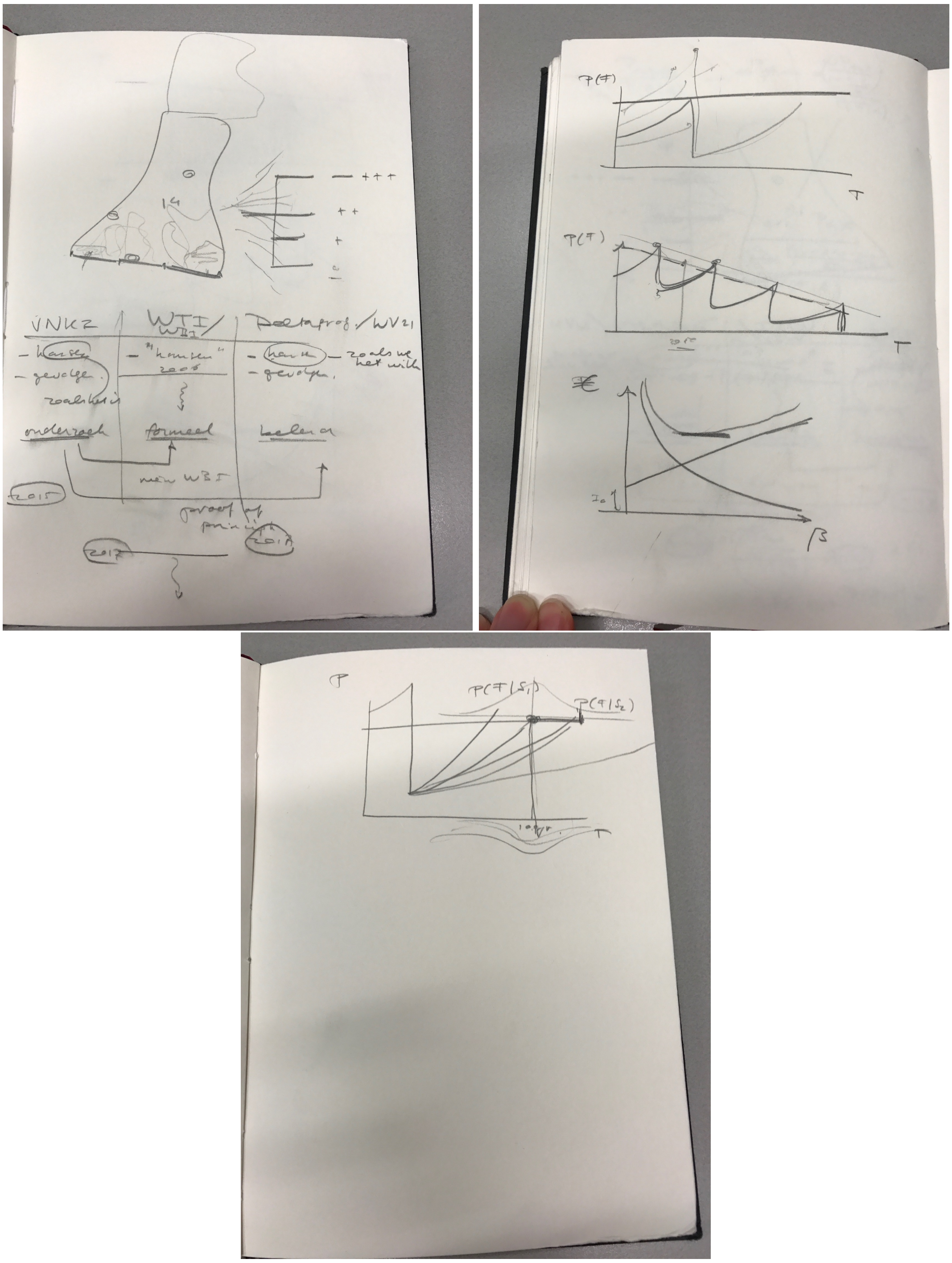


Figure H.1: Notes by Ruben Jongejan

I

Rijkswaterstaat

Rijkswaterstaat is responsible for ”the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands. This includes the motorways, the main waterway network and the water systems” (Rijkswaterstaat, 2017).

Motorways
The Dutch mobility policy serves 2 goals: reliable journey times and better accessibility. ”By the year 2020, motorists travelling in rush hour must be able to arrive punctually 95% of the time, despite increased mobility and unexpected congestion” (Rijkswaterstaat, 2017). The Dutch economy relies heavily on transport and logistics, the main economic centres must remain accessible over time.

Waterways
Reliable and useful information, together with dry feet and sufficient clean water, are the topics of concern for Rijkswaterstaat. These principles are part of the integrated water management within Rijkswaterstaat. Smooth and safe transport by water is another way of using water. The Dutch waterway network is the densest in Europe. ”About 6000 kilometres of rivers and canals, many of the latter serving as drainage as well as navigation, form a complex system serving all parts of the country” (Rijkswaterstaat, 2017).

”The main commercial waterways (Class IV and higher), with a total length of 2200 kilometres, account for about 40% of the international freight movements in the Netherlands and 20% of the domestic freight” (Rijkswaterstaat, 2017). The main network, with more than 120 locks, is state-owned and operated by Rijkswaterstaat. Smaller waterways are managed by many different provincial authorities or water boards.

Systems
The goal of the integrated water management is ”to achieve the most efficient and flexible construction, management and maintenance of the main water systems in the Netherlands: the major rivers, the coast, the Wadden Sea, the Southwest Delta, the IJsselmeer region, and the North Sea” (Rijkswaterstaat, 2017).

- *Dry feet*
  The Dutch coast protects the Netherlands from the influence of the North Sea. Rijkswaterstaat, as execution agency, is responsible the flood safety of the country. ”By means of beach nourishment, we replenish the sand along the entire coastline, both on the beaches and underwater. On average, we add 12 million m^3 of sand every year” (Rijkswaterstaat, 2017). The Dutch rivers and canals are bounded by over 20000km of dikes; without these dikes, more than 26% of the Netherlands may flood during extreme

events.

- *Sufficiently clean water*
  Clean and healthy water is a matter of life and death for people, animals and nature. Rijkswaterstaat is taking 3 types of measure to improve water quality:
  1. Create space for and ensure the manoeuvrability of water-life
  2. Provide clear and clean water for drinking and recreational purposes
  3. Habitat recovery

Figure I.1: Headquarters of Rijkswaterstaat, Utrecht, the Netherlands

J

Glossary

Asset manager
A person that, in a systematic way, controls activities for an organisation with a goal to optimise the trade-off between performance, risks, costs, and lifetime of an asset

Availability of levelling function
The number of hours that the nautical function is operational

Calamity
An event causing great and often sudden damage or distress

Drainage sluice
Hydraulic structure that can be used to drain water from inside of a protected area and at the same time retains outer water

Economic loss
Losses directly or indirectly caused by the disruption of economic processes

Exceedance frequency
The average number of times that a certain value is reached or exceeded in a certain period

Engineering structure
Man-made civil structure as part of infrastructure. Most hydraulic structures are engineering structures. Exceptions are dunes and dikes, that are also denominated as hydraulic structures

ENW, Expertise Netwerk Waterveiligheid
Expertise Network Flood Risk (ENW), a network of specialists on flood risk. ENW advises governmental institutions on current issues and innovations

Expected probability
The probability that the maximum permissible level will be reached or exceeded

Expected value
The probability-weighted sum of all possible outcomes

Failure
Instability of a structure or a structural component to fulfil the specified functional requirements

Failure mechanism
A particular manner in which a flood defence may fail their flood safety function

Flood
The temporary covering of land by water

Flood protection standard
Requirement that a primary flood defence should meet, expressed as the average annual probability that the highest water level that the primary flood defences intended to directly retain outer waters must be able to withstand will be exceeded, considering the water-retention capacity (Rijkswaterstaat WVL, 2017)

Flood risk
Combination of the probability and consequences of flooding

Flood scenario
A combination of failing flood protection system that results in flooding in all or part of the hinterland

Freeboard
Retaining height needed to compensate for wave overtopping, local wave set-up, shower gusts and seiches

HVWN, Hoofdvaarwegennet
Main waterway network in the Netherlands

Human error
A departure from acceptable or desired practice on part of an individual that can result in unacceptable or undesired results

Hydraulic structure
An arrangement and organisation of interrelated elements in a material object or system, which is used to divert, restrict, stop or otherwise manage the natural flow of water, or to facilitate sailing or mooring of vessels

Individual risk
The probability that a person who is present at a certain spot will die as a result of flooding

Loss-of-life risk
The risk of being killed at a certain place as a result of flooding

NAP
Vertical datum in use in the Netherlands and large parts of Western Europe

National Market and Capacity Analysis (NMCA)
The National Market and Capacity Analysis presents long term potential accessibility issues in the Netherlands

Navigation lock delay time
The period of time needed for the lockage, other than levelling and waiting, which is dependent on the traffic volume, arrival pattern, and locking capacity

Navigation lock levelling time
The period of time needed for the levelling process

Navigation lock transit time

The total period of time needed for the lockage of a vessel

Navigation lock waiting time
The period of time, starting at the moment of arrival at a navigation lock until the moment that the levelling time starts

Navigation lock travel time reliability
The reliability of 90% of all vessels passing the navigation lock on time

Operational hours navigation lock
The number of hours a navigation lock is available for the nautical function

Overflow
The phenomenon whereby water flows over the flood defence as the water level is higher than the design height of the structure

Overtopping discharge
The average quantity of water passing over a flood defence structure due to wave action per unit of length and time

Polder
Low lying area, often below sea level, protected against floods by a surrounding embankment or hydraulic structure in combination with drainage for rainfall and upcoming groundwater

Primary flood defence
Flood defence (levee, dune, hydraulic structure) along the sea coast, a major river or lake that provides protection against major flooding

Regional flood defence
Flood defence which is built behind a primary flood defence to protect the hinterland in the event of breaching of the primary flood defence

RWS, Rijkswaterstaat
Government agency as part of the Ministry of Infrastructure and Water Management, responsible for the practical execution of the public works and water management

Probability of flooding
The probability that an area will flood because the water defences around it fail in one or more sports

Storm surge
High water with an average exceedance frequency of once per two years. This high water is usually caused by a storm, coinciding with astronomic high (spring) tides and an hour-averaged wind velocity > 15 m/s

ViN / Vaarwegkenmerken in Nederland / Fairway Information Services
A database consisting of information on the availability of the waterway

VNK, Veiligheid Nederland in Kaart
Project 'Flood Risk in the Netherlands', initiated by Rijkswaterstaat and executed between 2001 and 2014 to analyse the flood risks in the Netherlands

Water board
Regional authority that is administratively responsible for the quantitative and qualitative water management in an area

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