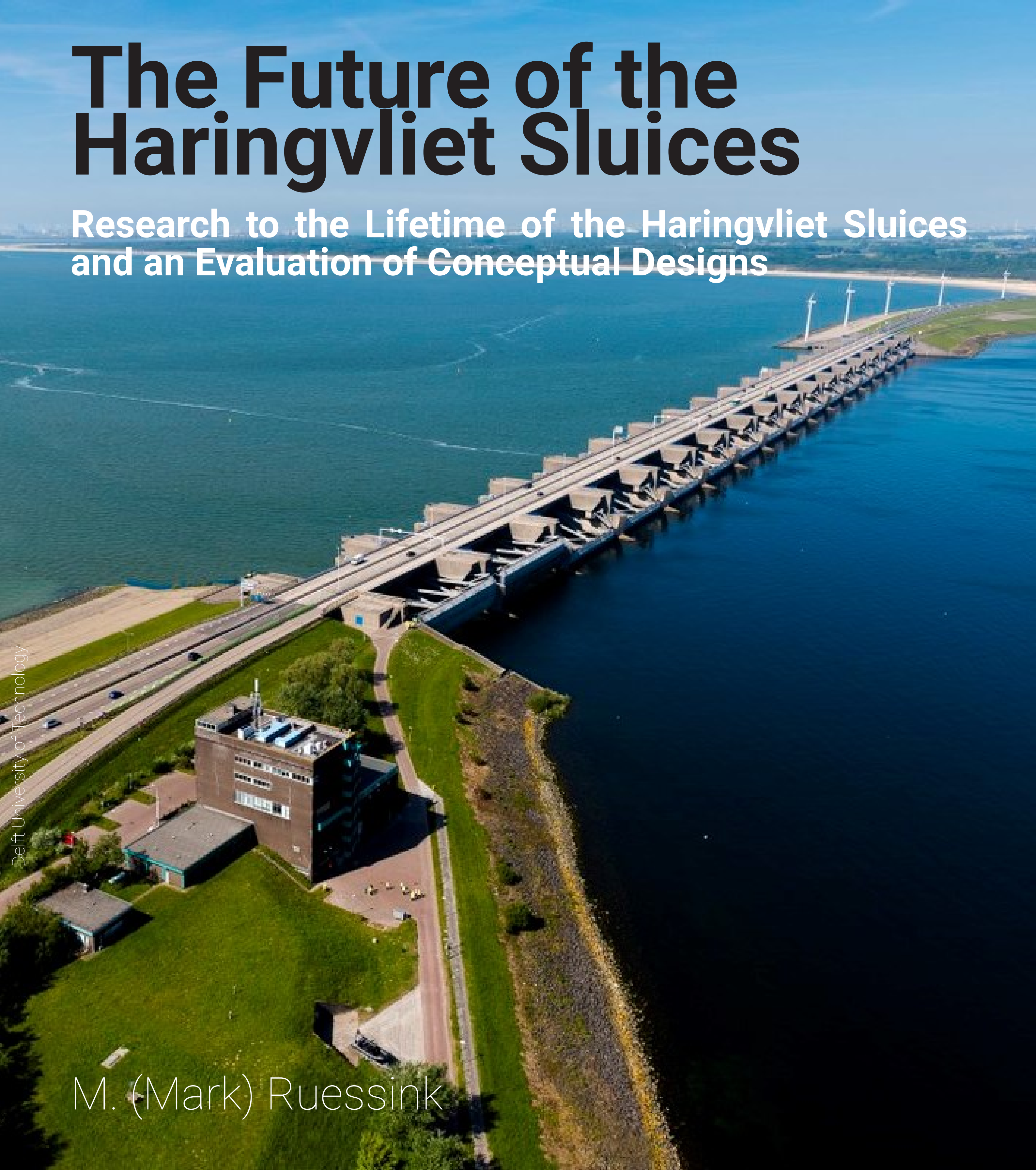
The Future of the Haringvliet Sluices

Research to the Lifetime of the Haringvliet Sluices and an Evaluation of Conceptual Designs



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HKV LIJN IN WATER

The Future of the Haringvliet Sluices

Research to the Lifetime of the Haringvliet Sluices and an Evaluation of Conceptual Designs

by

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to obtain the degree of Master of Science,
at the Delft University of Technology,
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Preface

This graduation project was carried out as conclusion of the Master of Science Civil Engineering at the faculty of Civil Engineering and Geosciences at the Delft University of Technology. This thesis has been conducted at HKV - lijn in water.

In this thesis, the aim was to conclude on the lifetime of the Haringvliet sluices. The lifetime is mainly dependent on climate change concerning the effects of sea level rise and change of the river discharge distribution. This research and the concluded lifetime can be used as directive for Rijkswaterstaat, the owner of the sluices. After concluding on the lifetime strategies are developed and analysed.
Due to the multidisciplinarity of this thesis, many people from different disciplines have contributed to this thesis, which is seen as very valuable.

I therefore would like to express my gratitude towards my graduation committee. The conversations and meetings during this master thesis have been very valuable to me. This master thesis would not have been possible without the input and guidance of Ton Botterhuis at HKV lijn in water and Matthijs Kok, Mark Voorendt and Hessel Winsemius of the Delft University of Technology. The meetings at HKV and the periodic meetings with the committee lead to new valuable insights and knowledge which have been of great value for this thesis.

I also would like to thank all the other contributors from HKV lijn in water for their interest and valuable input during this research. In addition, I would like to thank Bas Roels (WNF), Frank Spaargaren (retired, e.g. Rijkswaterstaat), Sacha de Goederen and Robert Slomp (Rijkswaterstaat) and Leo van Gelder (Waterschap Hollandse Delta) for the interviews from which I gathered new insights and information for all different disciplines.

I would also like to thank my fellow students, who became friends, from both the Delft University of Technology and HKV lijn in water. Thanks for the great time, support, advices or help in any other way during my studies and this thesis.

And last but not least, I would like to thank my family and girlfriend for always supporting me. Without your support and help in any possible way, I would never have come to where I am now.

M. (Mark) Ruessink
Kudelstaart, September 2019

Abstract

The Haringvliet sluices is one of the Delta Works. The sluices were finished in 1970 and are thus 50 years old. This research is initiated because the expected lifetime of hydraulic structures is thought to decrease significantly due to climate change. This study aims to provide insight in the functions the Haringvliet sluices fulfill and to what extent climate change influences the functioning of the Haringvliet sluices. If the lifetime of the current structure is reached multiple other strategies are suggested.

The lifetime of the sluices is determined, based on the effect of climate change on the functions the sluices fulfils. The climate scenarios used for the assessment of the sluices are the KNMI'14 climate scenarios (G_l and W_h). These are the most mild and most extreme scenarios. The amount of sea level rise and the change in annual river discharge distribution of these scenarios are used for the assessment of the sluices.

For the assessment of the Haringvliet sluices, multiple tools are used. Calculations are made with the programs SOBEK and Hydra-BS, available literature is used, information received from interviews with experts and hand calculations have been used as tools to assess the Haringvliet sluices.

Flood protection, fresh water availability and ecology are the functions for which the sluices have been assessed. Navigation/ accessibility and recreation are thought to be of less importance and are not in the scope of this thesis. Another failure mechanism for which the sluices have been assessed is structural failure. The lifetime for which the sluices fail constructively are conducted by a semi-structured interview. Not opening, not closing, overtopping and overflow are the failure mechanisms included in the assessment for flood protection. The effect of the failure mechanisms in combination with climate change may not lead to hydraulic loads which exceed the retaining height with 0.2 meter of at least two dike sections at the hinterland. With the Kierbesluit, the Haringvliet sluices are opened during high-tide. The requirement concerning fresh water availability is that the chloride concentration at Middelharnis-Spui may not exceed 300 mg/litre. The requirement for ecology is based on fish migration in combination with the Kierbesluit. Multiple fish species must be able to migrate from the North-Sea to the Haringvliet for at least 50% of the time as indicated for each specie in the migration calender. The sluices may also not be closed for 50 consecutive days. This reduces migration via the Haringvliet.

The lifetime for which the function of flood protection is reached, is based on literature, spreadsheet calculations and the use of the models SOBEK-RE and Hydra-BS. With SOBEK-RE water level calculations are carried out in which the failure mechanisms of not opening and not closing are added. The results have been stored in a database which is used as input for Hydra-BS. Hydra-BS probabilistically calculates water levels through the south western delta. The effect of the failure mechanism of overtopping is calculated by calculating overtopping volumes with formulas found in prior research (Van der Meer, 2008). The overtopping volumes can be significant but due to the large storage area at the Haringvliet, the effect is relatively small. Also, the coincidence between a storm at the North Sea and large discharges at the Rhine is relatively low.

The assessments of the functions fresh water availability and fish migration are based on the aggregation of multiple researches in combination with the effect of a changing climate, for which the KNMI'14 climate scenarios are used. Concluded is that the function for fish migration cannot be fulfilled in the most extreme scenario around 2050. First strategy proposed to extend the lifetime is to change the Kierbesluit. Sluices may be opened by lower discharges during high tide. However, this decreases the lifetime for fresh water availability. The lifetime with another Kierbesluit can be enlarged by circa 30 years. With this measure the functions of fresh water availability and fish migration still reach the lifetime first around the year 2080. Life time extending measures can be thought of and can be of both economic and social points of view. Closing the sluices more frequently (social point) reduces the fish migration. Relocating the fresh water intake locations more upstream or by building a fish passage from the North-Sea to the Haringvliet is a measure which is coming from an economical viewing point.

When taking into account the extending measure concerning ecology, the lifetime of the sluices become as follows. In case of an extreme scenario the functional lifetime can be met until at least 2050 and the structural lifetime is reached around 2100. In case of an average climate scenario, all the functions fail in a relatively short time span of 20 years, around the year 2130. With the G_l climate scenario used in this thesis the sluices fail first structurally, which is around the year 2170.

In case of an average or mild climate scenario, the sluices need to be removed or covered because they fail structurally. To replace or cover the current Haringvliet sluices when the lifetime is reached, multiple functional strategies have been developed.

For the development of the new functional strategies it is assumed that the requirements do not change compared to the current requirements. The functional strategies are based on three possible designs for the Haringvliet: a permanent closure of the Haringvliet in which pumps are installed, a similar sluice complex or creating an open estuary again. These three strategies are used in combination with other structures. Eventually two verified designs are evaluated. It turned out that closing of the Haringvliet can fulfil all the requirements. A larger sluice complex including a fish passage turned out to be the best functional design. With the rough assumptions used in the evaluation, the variant in which larger sluices combined with a fish passage is suggested comes out as the best strategy. Other strategies could turn out to be more suitable for the requirements, criteria and boundary conditions valid at that moment. Therefore adaptive coastal and river management is recommended.

What must be noted is that backward salt intrusion, intrusion via the Nieuwe Waterweg and Spui to the Haringvliet can cause problems concerning the quality (salt concentration) of drinking water. Closing the Nieuwe Waterweg is a solution concerning the requirements composed for the Haringvliet. However, the effect on the Port of Rotterdam and the costs involved for this closure are not estimated and are therefore not included in the functional designs.

In this thesis multiple methods are used to calculate the effect of a failure mechanism of the Haringvliet sluices on the hydraulic loads at the hinterland. Suggested is to come up with a model in which the failure mechanisms not opening, not closing and overtopping of the sluices are included. Further, with the data from Rijkswaterstaat of the chloride concentrations in the Haringvliet, a salt intrusion model can be made to improve the Kierbesluit.

Contents

1

Introduction

In this thesis the functioning of the Haringvliet Delta Work is studied. The delta work consists of dikes, a lock and a sluice complex. The main focus in this thesis will be on the sluice complex. In this chapter a brief introduction of the Haringvliet Delta Work history and location are given. This is followed by an exploration of the system, problem analysis and motivation of this study. This chapter ends with a method and structure description.

1.1. Introduction and Location of the Haringvliet Delta Work

The Haringvliet dam and sluices have been built as a part of the Delta Programme. The Delta Programme arose after the floods in the South-West of the Netherlands in 1953. The programme was started to ensure safety against flooding from the North Sea. The Delta Commission, the composers of the Delta Programme, consisted of 12 civil engineers, one economist and an agricultural engineer. Since the establishment of the Delta Programme 13 Delta works have been built in the South-Western delta.

Figure 1.1: Location of the Haringvliet (Google Earth, 2018) and an overview picture of the Haringvliet sluice complex (Interprojectmanagement, 2015).

The Haringvliet is located between the islands of Goeree-Overflakkee (North) and Voorne-Putten (South), see Figure 1.1. Before the closure, the Haringvliet was an estuary in the province of South-Holland. At the

Haringvliet the North-Sea and water originating from the rivers Rhine and Meuse interacted without the interference of a structure. Since 1970 the Haringvliet is closed of from the North Sea by 17 discharging sluice segments and two sea dikes, Figure 1.1.

The closure of the Haringvliet led to a more controlled water level at the Haringvliet. During storms at sea the sluices at the Haringvliet and the Maeslantkering at the Nieuwe Waterweg needs to be closed. During large river discharges, the sluices must be opened to discharge the water to the North Sea. With low river discharges, the sluices need to be closed to avoid salt intrusion in both the Haringvliet and Nieuwe Waterweg. Because of the closure and the incoming fresh water from the rivers Rhine and Meuse, the Haringvliet turned from brackish to fresh.

In the delta several fresh water intake locations are present which are used for agricultural and drink water purposes, see Figure 1.2. With the sluices, the salt intrusion lengths are regulated.

After the construction of the sluices the ecology in and around the Haringvliet changed. The influence of the hard sluice border, the water turning fresh and the large decrease of the tidal effects are the main reasons. Brackish fish and plant species disappeared, fish were unable to migrate upstream and multiple bird species disappeared due to the fact that tidal flats disappeared (Reeze et al., 2018). To stimulate the fish migration at the Haringvliet again, the western part of the Haringvliet is allowed to become brackish again (since November 2018). This is achieved by opening some doors during high tide. Salt and fresh water mix at the western part of the Haringvliet, which is a condition needed for migratory fish to migrate, see Figure 1.2.

Figure 1.2: The incoming river flows from both the Rhine and Meuse. The exchange of fresh and sea water at the Nieuwe Waterweg and Haringvliet. The discharge distribution between the Haringvliet and Nieuwe Waterweg is regulated with multiple structures upstream and by the Haringvliet Sluices. The salt and fresh water mix at the mouth of the Nieuwe Waterweg. The location of mixture is expected to be dependent on the Rhine discharge, wind velocity and direction, water level at sea and the flow area at the Haringvliet sluices.

This delta and the Haringvliet has a large societal and economical value. Multiple cities, the harbour of Rotterdam, chemical industries, agricultural industries and drinking water companies are located in the south western delta. Also recreation and tourism are of importance. The Haringvliet and the Haringvliet sluices are of great importance for both the economical and societal value of the delta. The complexity and the value of the south western delta, and especially the Haringvliet, make it an interesting area.

1.2. Motivation of the Study

Climate change and the corresponding rise of the sea level are becoming more important for a low lying country as the Netherlands. Multiple studies on climate change show that sea levels are expected to rise faster than previously thought (IPCC, 2014a; le Bars et al., 2017). In the design of the Haringvliet Delta Work, 0.20 meter sea level rise per century was taken into account (Ferguson, 1971). Since the construction of the Haringvliet multiple researches show scenarios in which the global sea level rise in 2100 is in the order of meters.

During a conversation with Sacha de Goederen from Rijkswaterstaat, which maintain the Haringvliet Delta Work, it became clear that not much is known about the expected technical and functional lifetime of the sluices. Therefore, research to the lifetime of the sluices and what to do when the lifetime is reached is chosen as topic. Haasnoot et al. (2018), which is part of the Deltaprogramme 2019 (Deltadienst, 2018), showed that with sea level rise the water levels for which the Haringvliet sluices are designed will be reached more frequently.

Another topic which gets lots of attention nowadays is the effect of structures on the environment. The Haringvliet sluices and dams created a hard border between the North-Sea and Haringvliet. Therefore, the function of fish migrating and propagating upstream on the rivers has vanished. The hard border created a fresh basin which caused that animals and plants that thrive best at brackish or salt waters, disappeared from the Haringvliet. To increase the ecological activity (fish migration) the doors of the Haringvliet sluices will be kept open during high-tide. The implementation of this so called 'Kierbesluit' caused water intake points to be replaced. Since November 2018 a 'Kier' (small opening) of the sluices will allow fish to migrate from the North-Sea to the Haringvliet and further upstream again.

The Haringvliet is an area in which multiple disciplines come together: flood protection, fresh water availability and ecology. The lifetime of the sluices, the effect of climate change on the lifetime and which lifetime extending measures can be taken in the future, are all unknown.

1.3. Problem Analysis

The Haringvliet sluices are not yet assessed with the statutory assessment tool of 2017 (Dutch = Wettelijk Beoordelings Instrumentarium 2017, or short WBI-2017). The effect of the failure mechanisms not opening, not closing and overtopping of the sluices were not included in the previous assessments, because the effect on the hydraulic loads is assumed to be negligible.

The interest of stakeholders caring about ecology increases. The effect of structures on the ecology need to be taken into account during the design phase. During the design of the Haringvliet sluices only fish passages were included. Research from Kemper (1997) shows that these fish passages do not function under all conditions. To stimulate fish migration the sluices can be opened during high tide. When the discharge of the river Rhine is large enough, the sluices are (partially) opened to stimulate the fish migration. This discharge regime is called the Kierbesluit. The conditions which are beneficial for fish migration are contradictory compared to those of flood protection and fresh water availability. Also, the effect of climate change on the functions of fresh water availability and flood protection are negative. With an increasing sea level and more extreme river discharges, the hydraulic loads increase. Due to a larger sea level and more extreme river discharges (lower discharges in the summer) it is thought that salt water is able to intrude further inland. Structurally the Haringvliet sluices are designed for a sea level rise of 20 centimetre per century. Therefore, in case of the more extreme sea level scenarios, the strength and stability of the structure could not be sufficient.

The influence of climate change on hydraulic structures can lead to problems in the future. The different stakes and interests at the Haringvliet can conflict with each other. Expected is that fresh water availability and ecological improvements will conflict due to opposite solutions.

Climate change and especially sea level rise could cause structural failure. Due to sea level rise the static and wave forces could become significantly larger if the sea level increases, Figure 1.3.

The uncertainty of climate change on the functions of the sluices can become a problem. A sea level rise of 2 meter in 2100 can become reality (Haasnoot et al., 2018). Therefore, an adaptive strategy for the Haringvliet is

Figure 1.3: Highwater at the Haringvliet Sluice complex (December 8th, 2017), from Rijkswaterstaat (2017b).

needed. If a large rise of the sea level occurs in a relatively short period of time, it could become problematic for multiple functions the sluices fulfil.In the worst case scenario, the sluices fail structurally and collapse. With adaptive delta management decisions can be made on the future of the Haringvliet sluices based on the acceleration of sea level rise and river discharge distributions over the year. Monitoring of the actual sea level rise and discharge distribution are important to come to a well substantiated decision. Therefore, multiple strategies need to be ready in case of fast changing conditions.

1.4. Objectives

In this section the research and design objectives are described. Aim of the research is to determine the lifetime of the sluices for multiple climate scenarios. When the lifetime of the sluices is reached for a certain climate scenario functional strategies/designs must be thought of. These functional strategies proposed must fulfil certain requirements. Objective for the functional designs is to come up with a functional strategy fulfilling all requirements and criteria.

1.4.1. Research Objectives

Research questions are proposed for the assessment of the current structure. The main objective is:

- **Can the Haringvliet sluices fulfil the functions as it currently does till it reaches the design lifetime?**

The lifetime of the sluices is reached if the sluices can not fulfil the functional or structural requirements or when it reaches the design lifetime. For the functional lifetime of the Haringvliet sluices, multiple functions are interpreted. For the structural lifetime the structural requirements need to be fulfilled. The design lifetime is the time for which the structure is designed. For the Haringvliet sluices the design lifetime is 250 years. In this thesis the focus is on the functional lifetime of the sluices. The research questions that are answered throughout this thesis are:

- Which functions are influenced by the Haringvliet sluices?
- Which failure mechanisms must be taken into account for the assessment of the Haringvliet Sluices?
- Which indicators show that the requirements are not fulfilled any more?
- Which requirements must be met?
- What methods are used to, quantitatively and qualitatively, assess these indicators?

- Which (failure) mechanisms or requirements from the stakeholders is firstly not met?
- When will the Haringvliet sluices be at the end of its lifetime depending on the climate scenarios?
- Which measures can be implemented to extend the lifetime of the sluices?
- Which (failure) mechanisms or requirements from the stakeholders are not met after applying lifetime extending measures?

This research aims to give insight in the remaining lifetime of the Haringvliet sluices. This is investigated by considering each stakeholder and their requirement(s) separately. For all requirements the lifetime is estimated. As a result, a time line as shown in Figure 1.4, gives insight in to when the lifetime is reached per function/requirement.

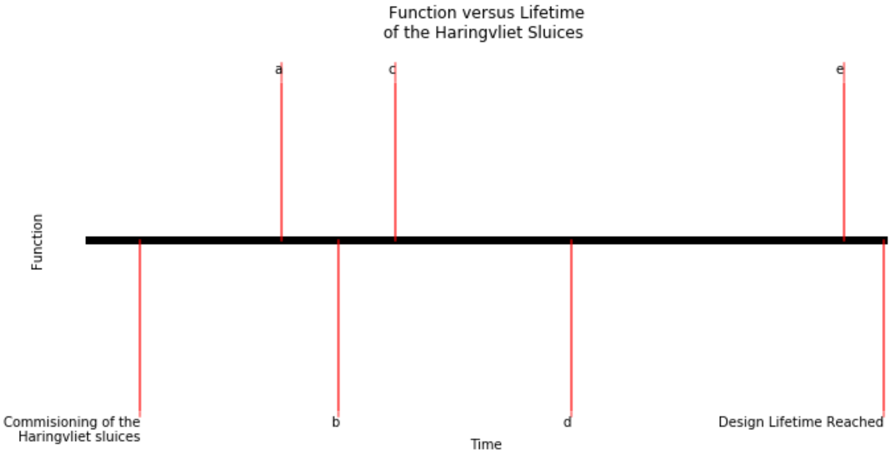


Figure 1.4: Time line indicating when the requirement of a stakeholder will not be met any more.

The influence and importance of the function and stakeholders involved needs to be taken into account when looking at the functional lifetime. Function *a* in Figure 1.4 reaches its lifetime first. Questioned is whether function/requirement *'a'* is important enough to conclude on the lifetime of the sluices. The importance of function *'a'* depends on the stakeholders. If stakeholders find function *'a'* a important, investigated is if there are any lifetime enlarging measures possible. Otherwise, the lifetime is reached for function *'b'*, and so on.

1.4.2. Design Objectives

After the lifetime of the Haringvliet sluices is determined the aim is to come up with multiple conceptual strategies. These design objective is described as follows:

- Which conceptual strategy option or options can lead to a fulfilment of the requirements?
- To what degree does each conceptual strategy fulfil the criteria coming from the stakeholders?

The conceptual strategies must fulfil the requirements described in the program of requirements for the conceptual strategies. These requirements follow from the design objectives which are stated in a program of requirements. These requirements could be structural or functional. Current thesis focussed on the functional requirements.

1.5. Design Method

This chapter explains the method which is followed during this report. The method is based on the description in Hertogh et al. (2017). The method is schematized as shown in Figure 1.5 and is slightly adjusted compared to the structure in Hertogh et al. (2017). A research is executed and this is added as an extra step compared to the traditional design method. In this research step the current Haringvliet Sluices are assessed. The outcome of the assessment is used as basis of the synthesis and boundary conditions of a new functional strategy.

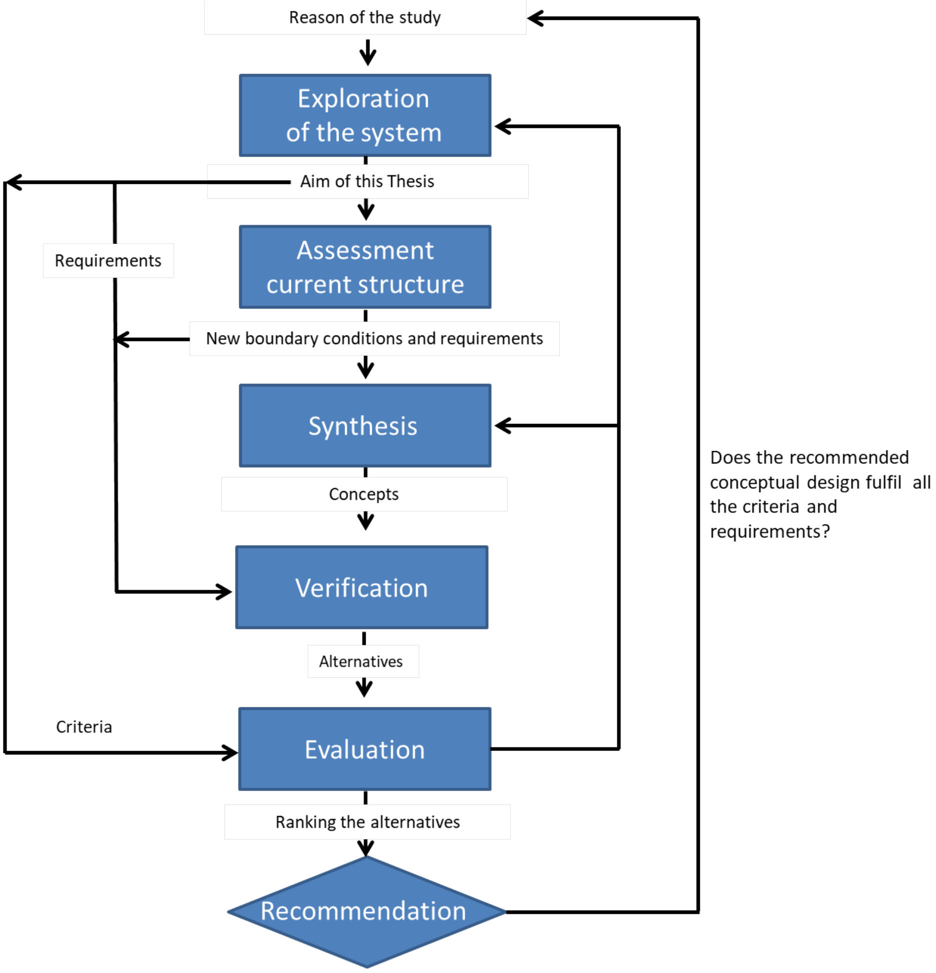


Figure 1.5: The basic design cycle used as basis for this thesis. Figure based on (Hertogh et al., 2017).

Started is with an analysis of the Haringvliet. In the analysis the functions the Haringvliet area fulfils, which stakeholders are involved, which requirements they strive for and what the current design of the Haringvliet sluices looks like, are described. This is used as starting point for a research to the lifetime of the current Haringvliet sluices.

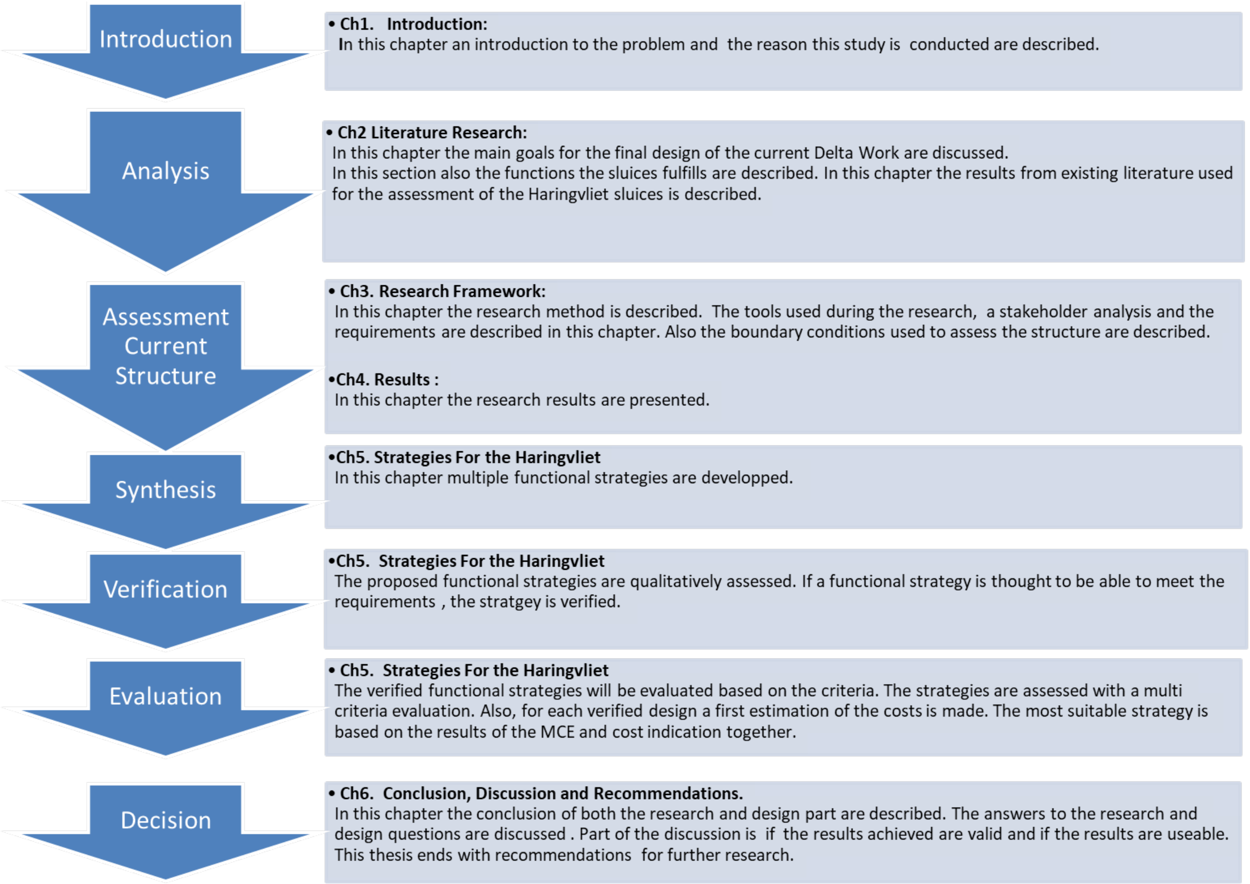
The functional requirements are multi-disciplinary, meaning that not only technical and hydraulic requirements needs to be met, also ecological, economical and other requirements coming from stakeholders must be met. These requirements could differ from the requirements of which the current Delta Work is designed. The method used for the assessment of the sluices is described in Section 3.

Multiple functional design alternatives are proposed in the synthesis. The verification of the functional design alternatives is based on the program of requirements, which needs to be fulfilled. The verified alternatives are evaluated with a multi criteria evaluation. For this multi criteria evaluation, multiple criteria derived from interests of stakeholders are assessed.

After this multi criteria evaluation and a cost evaluation a recommendation for a strategy is given. If no recommendations are given, the exploration and synthesis steps could be done again.

1.6. Structure of the Report

This thesis can roughly be divided into three parts. The first part consists of a description of the history and design conditions. The second part focusses on the functional and structural assessment of the sluices. This part concludes on the governing lifetime of the structure. In the third part new functional designs are evaluated with a Multi Criteria Evaluation (MCE) to see which strategy is most favourable. The structure of the report is shown in Figure 1.6. All steps in Figure 1.5 are incorporated in the structure, as can be seen in Figure 1.6. From Figure 1.6, the arrows Introduction and Analysis together, can be seen as Exploration of the System from Figure 1.5.



- **Ch1. Introduction:**
  In this chapter an introduction to the problem and the reason this study is conducted are described.

- **Ch2 Literature Research:**
  In this chapter the main goals for the final design of the current Delta Work are discussed.
  In this section also the functions the sluices fulfills are described. In this chapter the results from existing literature used for the assessment of the Haringvliet sluices is described.

- **Ch3. Research Framework:**
  In this chapter the research method is described. The tools used during the research, a stakeholder analysis and the requirements are described in this chapter. Also the boundary conditions used to assess the structure are described.

- **Ch4. Results :**
  In this chapter the research results are presented.

- **Ch5. Strategies For the Haringvliet**
  In this chapter multiple functional strategies are developped.

- **Ch5. Strategies For the Haringvliet**
  The proposed functional strategies are qualitatively assessed. If a functional strategy is thought to be able to meet the requirements , the stratgey is verified.

- **Ch5. Strategies For the Haringvliet**
  The verified functional strategies will be evaluated based on the criteria. The strategies are assessed with a multi criteria evaluation. Also, for each verified design a first estimation of the costs is made. The most suitable strategy is based on the results of the MCE and cost indication together.

- **Ch6. Conclusion, Discussion and Recommendations.**
  In this chapter the conclusion of both the research and design part are described. The answers to the research and design questions are discussed . Part of the discussion is if the results achieved are valid and if the results are useable. This thesis ends with recommendations for further research.

Figure 1.6: The structure of this report.

2

Literature Research

Designing and building the Haringvliet sluices was one of the toughest challenges for the Delta Commission. The dimensions and interests at stake made it difficult to design and construct. In this chapter some technical aspects of the design of the Haringvliet sluices are presented, followed by the functions the Haringvliet fulfils. The effect climate change has on these functions is described in subsection 2.3, in which the climate change scenarios used in this thesis are presented. In the subsections following the threshold levels for the indicators used in the program of requirements become clear. The requirements are based on the three main functions and the stakeholder analysis (Section 2.4). Literature and results from multiple studies used in this thesis are described in this section. The requirements following from this literature study and stakeholder analysis are summarized in Section 3.6.3.

2.1. Haringvliet Sluices Design

In this section the Haringvliet Sluice design and the functions thought of during this design process are explained.

2.1.1. Functions Considered During Design

Before the dike breaches in 1953, a construction of sluices in the Haringvliet mouth was already conceived (Ferguson and Wolff, 1983). Therefore, the construction of the sluices started relatively fast after the Delta Commission arose (Ferguson and Wolff, 1983). During the design of the Haringvliet sluices almost all functions as stated in Section 2.2 were considered. However, safety and fresh water aspects were considered most important. Two subjects were not taken into account at that time, which were creating new land and the environmental impact. The environmental effects due to the Haringvliet sluices are now visible and measurable in the Haringvliet area (Ferguson and Wolff, 1983). Examples are the decrease of the fish migration and of the diversity of plants around the water line.

The Haringvliet sluices' main functions are to keep the hinterland safe from floods and to guarantee the availability of fresh water. This fresh water is used to make drinking water or it is used for agricultural and industrial purposes. Other important aspects of the design were the location, the costs and constructional feasibility. These aspects and the functions determined the final design of the Haringvliet sluices. In Appendix A, the requirements set and the choices made during the design are described more elaborately.

2.1.2. The Bed Protection

The construction of the Haringvliet sluices started with building a bed protection of concrete and rubble filter layers. The bed protection is designed for discharging water from the Haringvliet to the sea. To avoid damage to the bed protection due to large flow velocities, a plunge pool (Dutch = 'woelbak') is included in the design. The plunge pool causes a more gradual outflow which ensures that the forces on the bottom protection decrease.

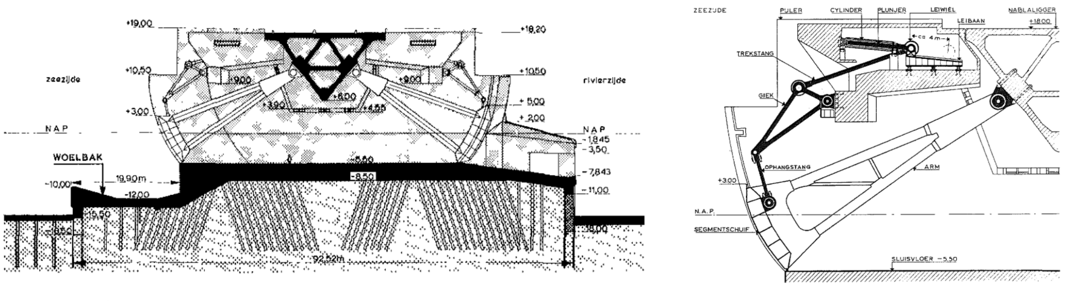
The bed protection at the seaside consists of a 64.0 m length reinforced concrete slab which is 0.5 m thick. This slab is attached to piles to avoid buoyancy. More seawards, the bottom protection consists of 125.5

m rubble (Ferguson, 1971). Model tests showed that a horizontal bed protection with at the end a transitional slope of 1:2, causes the least dangerous scour holes at the end of the bed protection (Waterloopkundig Laboratorium, 1968). Another measure to decrease the scour holes at the end of the bed protection is the construction of three rows of concrete tetrahedrons. Model tests showed that the flow velocities near the bed, decrease due to these tetrahedrons (Waterloopkundig Laboratorium, 1968). These measures caused the least dangerous shape and length for the scour holes, meaning that the scour holes have the smallest chance at undermining the structure (Waterloopkundig Laboratorium, 1968).

The bed protection at the river side consists of 33.0 m reinforced concrete of 1.5 meter thick. Due to the weight of this thick layer, piles are not necessary. Against the concrete protection, rubble filter layers are placed. These are placed over a length of 126.5 meter.

2.1.3. Design of the sluices

The foundation of the Haringvliet sluices consists of circa 22,000 concrete foundation piles. These piles are bundled, which increases the total resistance (Ferguson, 1971). The floor is connected to the foundation piles and consists of a concrete slab which is 80 meter wide and several meters thick (Ferguson, 1971), Figure 2.1.



(a) The cross section of the sluice complex, with the seaside at the left and the riverside at the right, from Deltadienst (1970)

(b) Drawing of the connection and control mechanism of the sluice doors via the arm to the Nabla beam. Image from Ferguson (1971).

Figure 2.1: Drawings of the cross section of the Haringvliet sluices.

On top of this floor, 18 piers are built. Between these 18 piers, a beam is constructed. In between two piers, 22 prefab concrete girders were connected with each other, forming one large beam called the NABLA beam, see Figure 2.1a (the black triangle). This beam is the core of the design. The doors are connected with arms to this beam. Each opening is closed by two doors. One at the sea side and one at the Haringvliet side. The curved sluice doors at the sea and river side differ in height. When closed, the height of the doors reach to respectively NAP + 3.0 m and NAP + 5.0 m. The bottom of the sluice complex is installed at NAP - 5.5 m. The dynamic forces acting on the sea side doors are larger compared to straight doors. The curves at the river side are favourable concerning dynamic forces. Therefore, it was decided to use the sea side doors as wave breakers during extreme water levels and the river side doors to reduce the overtopping volumes. In Figure 2.1 the cross section of the sluices are shown.

2.2. Functions

In this section, the functions the Haringvliet area and the Haringvliet sluices fulfill, are described. This section answers the question which functions are influenced by the Haringvliet sluices. The functions are schematized in Figure 2.2. Some functions are of greater importance than others.The functional lifetime of the Haringvliet sluices is assessed on the functions the sluices fulfils. These requirements are presented in the program of requirements in Section 3.6.

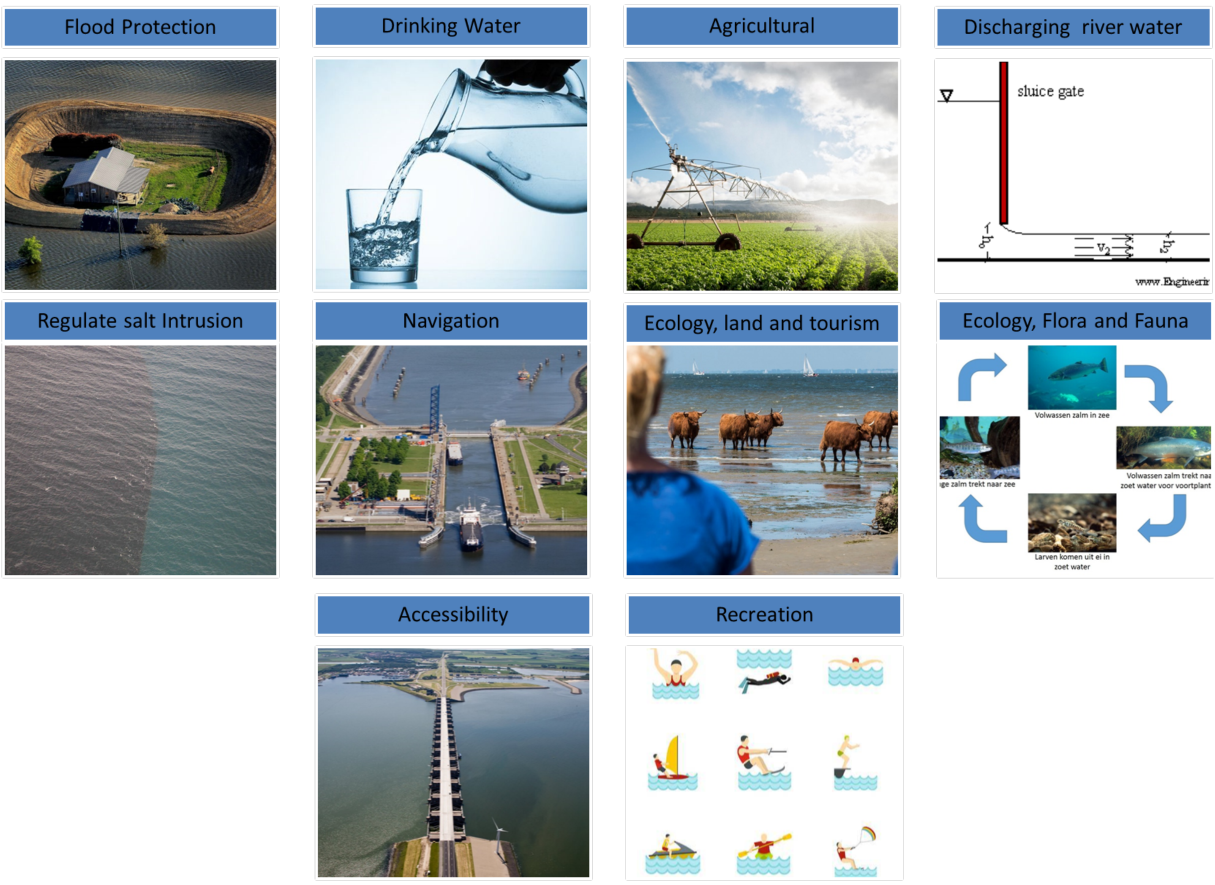


Figure 2.2: All functions of the Haringvliet area

The functions can be classified into three groups. Each row in Figure 2.2 can be seen as a group. The functions are classified based on the purpose of the sluices. For instance, the accessibility was an additional function the sluices could fulfil. The main purpose of building the Haringvliet is flood protection. The classifications from Figure 2.2 is as follows:

- Main functions, top row in Figure 2.2.
  - Flood protection
  - Fresh water availability for drinking water and agricultural purposes
  - Part of flood protection is to discharge river water to the sea.
- Functions to preserve, middle row in Figure 2.2.
  - Regulation of the salt intrusion for Haringvliet and Nieuwe Waterweg.
  - Navigation
  - Take care of the environment in and around the Haringvliet
  - Tourism
- Additional functions, bottom row in Figure 2.2.
  - Accessibility of the islands Voorne-Putten and Goerree-Overflakkee
  - Recreation

Some of the above mentioned functions were already present before the closure.

2.2.1. Flood Protection

The Haringvliet is closed off from the North-Sea to reduce the risk of flooding. In the South-Western delta, multiple water ways were in open connection with the North-Sea. The delta works decreased the length of primary dikes and dunes with about 700 km (Stichting Deltawerken, 2004).

The Delta Works protect the south western delta against high water levels. The Maeslantkering (and Hartelkering), the Oosterscheldekering and the Haringvliet sluices close if there is high a water at the North-Sea. When one of these works fail to close, the water is able to enter the connected waterway, meaning that dikes become the primary defence. Therefore, dikes are designed for water levels which take into account the probability of failure of the delta works. These dikes also protect the hinterland against high water levels from the rivers Rhine and Meuse. Therefore, dikes around the Haringvliet need to be able to withstand large water levels caused by both the North-Sea and large river Rhine and/or Meuse discharges.

2.2.2. Fresh Water availability and Salt Intrusion

A secondary function of the Haringvliet Delta Work was to create a fresh water basin (Ferguson, 1971). Before the construction of the Haringvliet dam and sluices, the Haringvliet was an estuary, where salty sea water and fresh river water mixed. With high tide and relatively low river discharges the salt water was able to reach till the Biesbosch (Wijsman et al., 2018). Due to the delta work, the salt water is not able to enter the Haringvliet any more. The Haringvliet became a fresh water basin over time.

Figure 2.3: Saline agricultural soils, from (Foundation, 2018).

The availability of fresh water in the area is of importance and is used for multiple purposes. It is extracted and used as drinking water and for agricultural purposes, see Figure 2.3. The fresh water is also used as cooling and process water for (harbour) industries. The basin turned fresh due to the incoming fresh discharges from the rivers Rhine and Meuse.

The water quality (temperature and concentrations of chloride or chemicals) is, due to the closure, mostly influenced by the incoming river water. When the quality is insufficient, the sluices ’flush’ this water to the North-Sea. The water could also become too salt due to the Kier or via salt intrusion through Het Spui. This could cause saline wells near the riverbed which need to be flushed fresh again to guarantee the quality of the water.

2.2.3. Ecology

The Haringvliet Delta Work caused a major impact on the ecology in the Haringvliet area. As mentioned, when designing and constructing the Haringvliet Delta Work, the effects on the nature was barely taken into account. The only ecological measures taken were fish passages through some pillars of the sluices (Ferguson, 1971). Kemper (1997) concluded that the sluices are mostly used during large discharges.

Hydrodynamic and morphodynamic processes play a considerable role in the ecology of the area. The interaction between processes, ecotopes and species are schematically shown in Figure 2.4.
Due to the closure, tides are not able to transport sediments in and out of the estuary of the Haringvliet any more. Before the closure, tidal flats established and disappeared due to the dynamic character of the Haringvliet estuary. Tidal flats were able to grow to such an extent that pioneers settled on these tidal flats. Growing of intertidal ecotopes caused positive feedback by reducing the flow velocities, causing sedimentation of fine sediments (Paalvast et al., 1998). Before closure, there was a dynamic balance. Because focussed is on the functional aspects of the Haringvliet the hydro-morphological changes are out of the scope of this thesis.

Brackish water species disappeared after the closure (Paalvast et al., 1998). Fish were barely able to migrate through the fish passages which were constructed in the piers. Therefore, the reproduction on the rivers decreased. The spawning areas for these migratory fish disappeared or became unreachable due to human interventions in the courses of water ways.

The discharge regime of the Haringvliet was regulated to keep the basin fresh (Rijkswaterstaat, 1984). There-

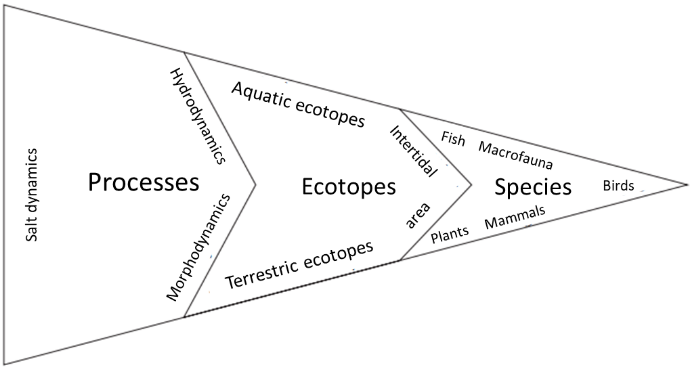


Figure 2.4: Hydrological and morphological processes (Processen) play an important role on ecoptopes (Ecotopen) which on its turn have large influence on the species (Soorten) which will be affected, Figure from Paalvast et al. (1998)

fore, only fresh water species are currently found at the Haringvliet. The hard boundary between fresh and salt water caused a difference in flora and fauna found both under as above the water level. Tidal flats became dry grounds and so drought preferable plants settled. Disappearance of the tidal flats also meant losing wading birds. To conclude, the biodiversity of the Haringvliet area decreased due to the closure (Paalvast et al., 1998). All species currently found along the Haringvliet need a fresh water environment. Before the closure, fresh and brackish water species were found.

With the new discharge regime, the Kierbesluit (Section 3.3.2), some brackish fish species could migrate again. Goal of the Kierbesluit is to create a brackish Haringvliet near the sluices. This could be reached by opening the sluice doors during high-tide. Main goal of the Kierbesluit is to stimulate the fish migration.

2.2.4. Navigation and Accessibility

The rivers Rhine and Meuse are not only used as fresh water sources. The rivers are important for the Netherlands when it comes to navigation. Multiple structures in branches of the Rhine and Meuse regulate the discharge distribution. With the discharge distribution the water levels in multiple branches are influenced. The Haringvliet sluice complex is one of the structures which regulates the water levels. The discharge distribution is regulated such that the salt intrusion lengths at the Nieuwe Waterweg are within limits, but also the navigational depths need to be met.

At the southern part of the Haringvliet dam, de *Goereese sluis* (lock) is built. This lock is used by smaller recreational boats and fishing ships. Larger intercontinental ships use the Nieuwe Waterweg to reach the harbour of Rotterdam. Ships entering the port of Rotterdam can ship their goods to smaller in-land vessels, which are able to sail through the Netherlands towards Germany, France and further into Europe, and vice versa. Therefore, sufficient draft and width of the waterways is necessary for the ships. To guarantee a certain depth at the Nieuwe Waterweg, the Haringvliet sluices will only discharge river water to the North-Sea when possible (Rijkswaterstaat, 1984), (Rijkswaterstaat, 2007) and (Rijkswaterstaat, 2015).

Another function created by the Haringvliet Delta Work is the accessibility and connectivity between Goeree-Overflakkee and Voorne-Putten. A national road, the N57, connects Goeree-Overflakkee and Voorne-Putten. The road consists of two driving lanes in each, northward and southward, direction. There is also a bike lane, which could also be used in both directions.

2.2.5. Recreation

The Haringvliet is used as a recreational lake. The recreational activities are for instance:

- (Recreational) sailing
- Watersports
- Beach recreation
- Fishing
- Attractive for tourists due to nature and wildlife.

The Haringvliet area is well known for its nature and wildlife diversity. Tourists visit the Haringvliet area for the islands in the Haringvliet-basin where nature and water activities can be enjoyed. However, the attractiveness for nature and wildlife decreased due to less ecological diversity, see Section 2.2.3.

2.3. Climate Change

Climate change has large influence on the lifetime of structures and therefore also on the Haringvliet sluices. Sea level rise and changes in river discharges of the river Rhine are consequences of climate change (Tank et al., 2015). All functions the sluices need to fulfil are influenced by climate change. The lifetime per function is expressed based on two KNMI2014 climate scenarios, scenarios W_H and G_L, as shown in Figure 2.5. The circumstances for which the sluices do not fulfil the requirements any more will be compared with these climate scenarios. During this thesis only the 50% percentiles of the scenarios are used to estimate the lifetime of the sluices.

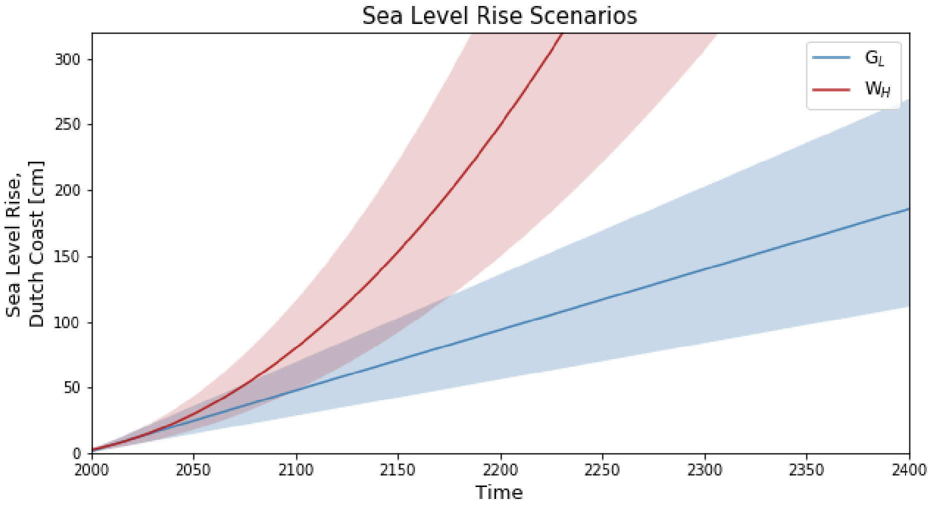


Figure 2.5: The sea level rise scenarios G_l and W_h from the KNMI2014. The G_l is extrapolated linearly from 2100 on. The W_h scenario is extrapolated exponentially from the year 2100 on.

The average water levels at the Dutch Coast till 2100 are obtained from Tank et al. (2015). The values are linearly extrapolated in scenario G_l. Scenario W_h is extrapolated exponentially from the year 2100 on. Eventually, the 50% percentiles of the sea level rise scenarios (thick lines in Figure 2.5a) are used to determine the lifetime of the sluices.

Baart (2018) shows that the sea level in the last century on average increased linearly. The 50% percentile line of the G_l scenario is comparable with the sea level rise trend found in Baart (2018). Therefore, the 50% percentile line of the scenario G_l is used in this thesis and is thought to be quite a conservative outcome.

Mechanisms which were not included in models predicting sea level rise can lead to accelerated sea level rise, as described in DeConto and Pollard (2016). With these accelerated sea level rise, the 50% percentile line in the W_h scenario is thought to be the upper limit scenario. This is due to the fact that the scenario W_h is extrapolated exponentially from 2100 onwards, which is quite a progressive approach. With these climate scenarios it is thought to have a bandwidth which realistically shows the lifetime of the Haringvliet sluices.
In case the change in discharge distribution over the year is the guiding parameter, the discharges shown in Figure 2.6 are extrapolated till a certain value/year. Expected is that climate change will grow till at least 2250, see Appendix C.

As already mentioned, climate change and especially water levels due to changing river discharges and water levels at sea can decrease the lifetime of structures. The average water levels at sea and monthly average river discharges are used for the assessment of the sluices because these play a large role on the effect of the functions of the sluices.

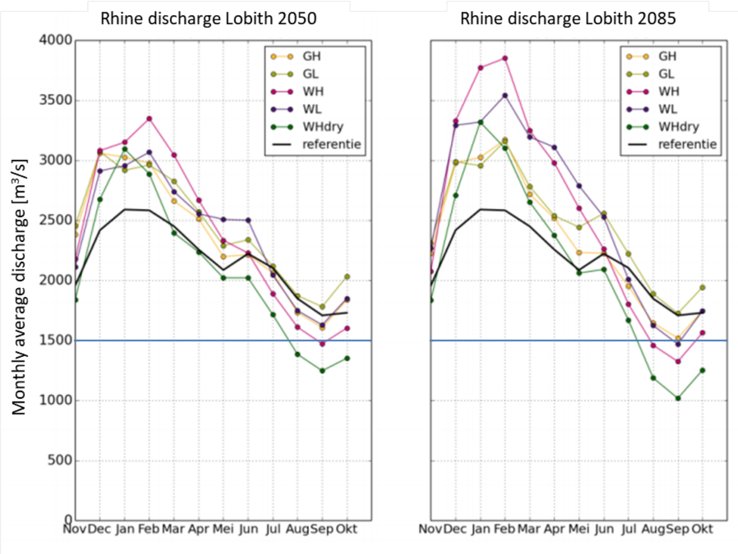


Figure 2.6: The expected average monthly discharges for all KNMI2014 climate scenarios. These are indicated for the years 2050 and 2085.

2.4. Stakeholder Analysis

In the previous sections multiple functions the Haringvliet area fulfils are described. These functions and their fulfilment are considered desirable by at least one single stakeholder. The stakeholder analysis is used to have a clear insight which functions are most important. With a stakeholder analysis the stakeholders are coupled to the functions in which they are mostly interested in. This gives insight in the most important functions and is used for the assessment of the sluices.

Stakeholders can be governments, companies, Non Governmental Organizations (NGO's), inhabitants and other persons or groups which have stakes in or for a certain function or area. In this case the Haringvliet and the south western delta are the locations of interest for the stakeholders. The influence and level of interest each stakeholder has, differs per stakeholder and per project (Donaldson and Preston, 1995).

Some stakeholders are more obvious than others. The Haringvliet sluices and dams are maintained and owned by Rijkswaterstaat and they protect parts of the provinces of Zuid-Holland, Noord-Brabant and Zeeland. Rijkswaterstaat and these provinces are therefore obvious stakeholders. However, the adjacent municipalities in these provinces and their inhabitants are stakeholders as well. Consultancy companies have stakes when it comes to work and projects. They want to get involved in projects which are executed in this area. Therefore, consultancy companies are stakeholder as well. Research and advice from consultancy companies can lead to changes which are against the wishes of other stakeholders.

The quality and quantity of water in the Netherlands is regulated and controlled by 21 Water Boards. All Water Boards need to regulate and control the quality and quantities in a certain area. However, water passes these borders causing Water Boards to collaborate closely. Water Board Hollandse Delta is responsible for the water quality and quantities in the Haringvliet area. The following Non Governmental Organisations (NGO): Natuurontwikkeling, Natuurmonumenten, Staatsbosbeheer, Sportvisserij Nederland, Vogelbescherming Nederland and World Wide Fund for Nature, have stakes concerning the water quality which needs to lead to a more diverse ecosystem. In the stakeholder analysis all these stakeholders are evaluated as one stakeholder called NGO.

The influence and interest of the stakeholders is visualised with a stakeholder map (Olander and Landin, 2005). On the vertical axis the parameter 'power' is expressed and on the horizontal axis the parameter 'interest' is expressed. When stating that the parameters are 'low' or 'high', the map can be divided into 4 blocks, as can be seen in Figure 2.7.

When evaluating each stakeholder, it becomes clear what the role of each stakeholder is. When both the level

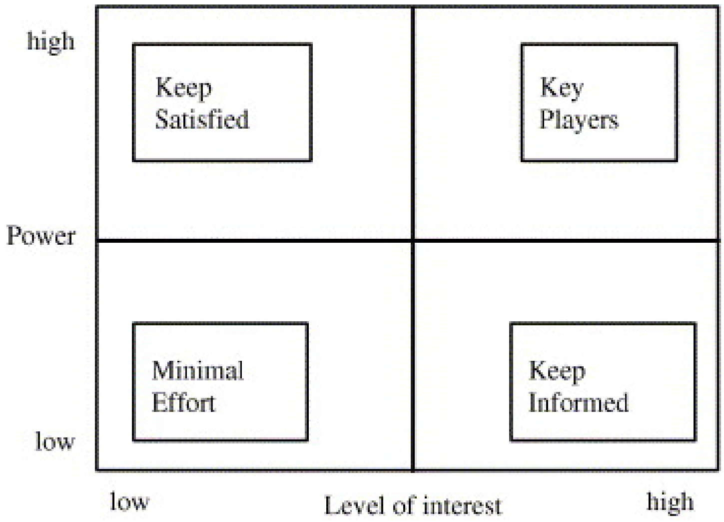


Figure 2.7: Stakeholder analysis describing the combination of power and interest of each stakeholder, from Olander and Landin (2005).

of interest and power are low, minimal effort is required. For high interest but low power, the stakeholder needs to be informed. The key players are stakeholders with high power and interest. When the power is high but the level of interest is low, the stakeholders needs to be kept satisfied. From Figure 2.7 it becomes clear what the function and/or goal is for each stakeholder.

With the stakeholders mentioned a stakeholder map is made, Figure 2.8, in which the power and interests are based on the functions flood protection, water quality and ecology, see Appendix B.

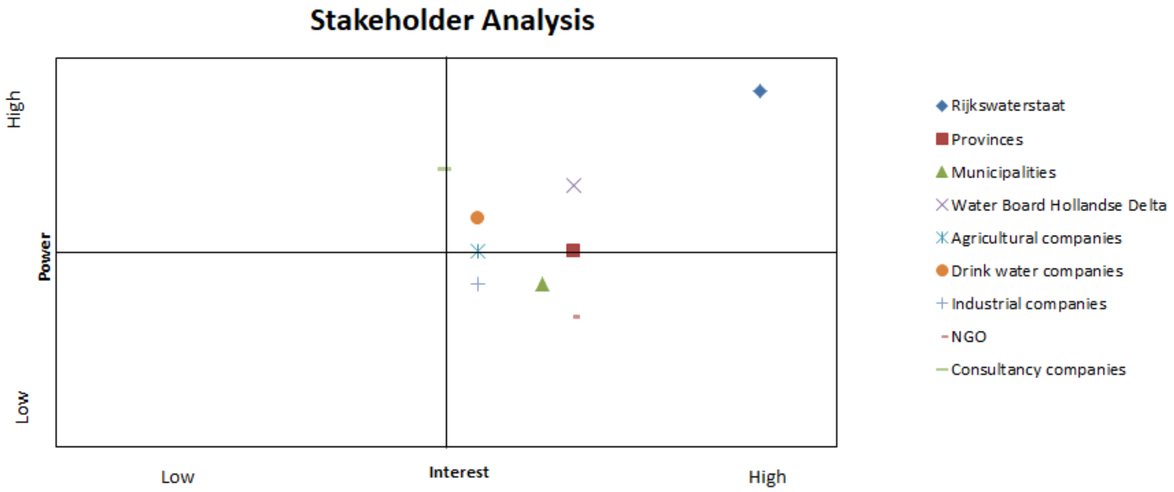


Figure 2.8: Stakeholder Analysis for the Haringvliet area.

In this thesis the focus is on the three main functions of the Haringvliet Sluices:

- Flood protection
- Water quality
- Preserve ecology, taking into account the Kier program.

The stakeholders in Figure 2.8 have interest in at least one of the above mentioned functions. The stakes of the stakeholders are used to come to a program of requirements. These requirements, based on the functions above, are given in Section 3.6. The criteria for the assessment of the current structure are given in section 3.6.3. In Table 2.1 these functions are combined for each stakeholder.

Table 2.1: Stakeholders and their interests, power not included.

Stakeholder	**Especially Interested in :**
Rijkswaterstaat	- Flood Protection - Water Quality
Provinces	- Flood Protection - Water Quality
Municipalities	- Flood Protection - Water Quality
Water Board Hollandse Delta	- Flood Protection - Water Quality
Agricultural companies	- Water Quality
Drink water companies	- Water Quality
Industrial companies	- Water Quality
NGO's	- Ecology
Consultancy companies	- Flood Protection - Water Quality - Ecology

2.5. Assessed Functions

In this subsection some theoretical background on which aspects can be considered during the assessment of the three main functions.

2.5.1. Flood Protection

The South Western Delta needs to be protected against flooding due to large river discharges and/or storms at the North-Sea. The defence against storms at the North-Sea is regulated by structures, dunes and dikes. The defence against large river discharges is regulated by dikes. The Dutch system for flood protection is based on the Risk that a certain area will flood. *Risk* is defined as *probability* times *consequence*. This is schematically shown in Figure 2.9, with the probabilities of a dike section failing schematically shown (left), the consequences of a flooding (middle) and the risk (right).

Figure 2.9: The probability of failure times the consequence, gives the risk shown in the last drawing, from (Rijkswaterstaat Projectbureau VNK, 2014). In the left figure the probabilities of failure are indicated by color, in which red stands for large probability, orange a moderate probability and green for small probability. In the middle figure the effect of a flooding is shown. The right figure indicates the combined effect of probability and effect and can be be expressed as economical loss or loss of life or a combination of both.

The consequences can be reduced by, for instance, moving a large number of inhabitants and valuable companies to higher grounds. However, reducing the consequences is another discipline and is out of the scope of this thesis. Focussed in this thesis is on the probabilities of failure and the assessment of the sluices.
The probability that a structure fails for a certain mechanism is dependent on the properties of the structure and the probability that a certain event happens, see the Example below.

Example

In this example the dike has only one failure mechanism: overflow. The probability that a dikes fails for overflow is dependent on the:

- Height of the dike
-Probability that the water level exceeds this dike height.

Suppose the dike height is 4.0 meters and the probability of the water level exceeding this water level is for instance 10^{-4}. With a water level of 4.0 meters, the volume overflowing the dike will be relatively low. The economical consequences for the event of overflowing for a water level of 4.0 meter are estimated to be relatively low, in this example 1 million Euro is assumed. The risk can now be calculated as:

$$10^{-4} \cdot 10^{6}\text{€} = 100\text{€}. \tag{2.1}$$

However, the probability that a 5.0 meter water level is reached is 10^{-5}, the economical consequences are now estimated to be 1 billion Euro. The risk can now be calculated as:

$$10^{-5} \cdot 10^{9}\text{€} = 10,000\text{€}. \tag{2.2}$$

Eventually, all these calculations can be added up, or in formula form:

$$R = \sum_{i=1}^{n} H(p_i) \cdot C(H_i) \tag{2.3}$$

With R the risk, H(p) the probability that the water level exceeds the dike height and C(H) the consequences based on the water level. The same calculation can be executed for individual and societal risk, which calculates the number of losses of life per year or per flooding.

The probability of flooding in the example above is only based on one failure mechanism. In reality, failure of a structure is determined by the probability of multiple failure mechanisms which are determined by the probabilities that certain hydraulic loads occur.

The failure probabilities in the Netherlands are defined by law (Ministerie van Binnenlandse Zaken, 2018). The dike sections in the South-Western delta are shown in Figure 2.10. Each section has an allowed failure probability which is based on the economical and societal risk. The Haringvliet delta work failure probability must at least equal to a probability of 1:1000 every year.

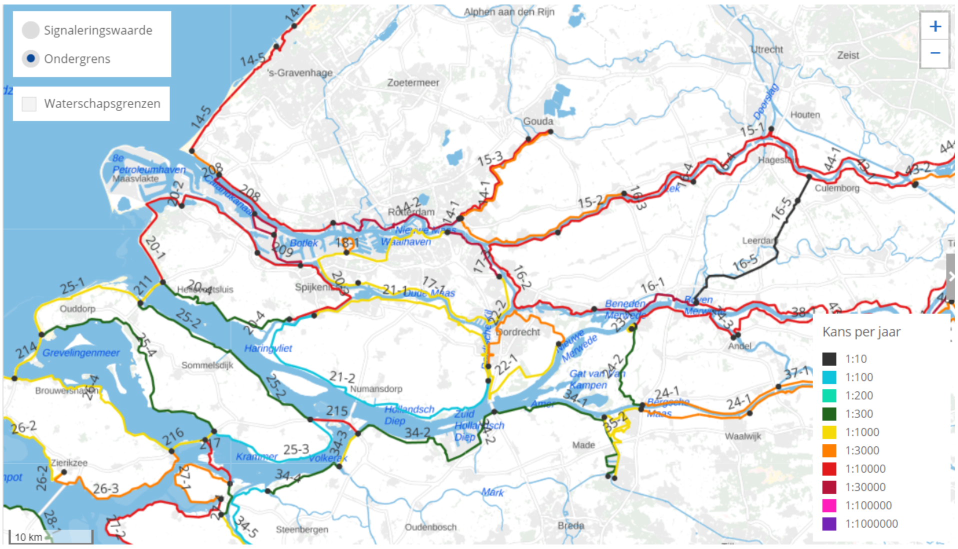


Figure 2.10: The norm trajectories in the South Western delta, from Rijkswaterstaat (2019).

The reason the sluices were built is to protect the hinterland against storms and the corresponding high waters on the North-Sea. The dimensions of the sluices were chosen based on the overtopping volumes and the strength the structure could withstand due to the wave forces (Ferguson, 1971). In the current assessment of the Haringvliet sluices the overtopping limits are not defined. It is assumed that the storage area of the Haringvliet can cope with the volumes overtopping and overflowing the structure. Following the WBI2017 standards, the retaining height of structures is based on the allowable overtopping criteria. This retaining height is calculated with a probabilistic calculation. It is thought that the hinterland can flood due to non closing doors during high sea water levels. The influence of the sluices not opening and not closing is examined and translated into the hydraulic load calculations for the hinterland.

The hinterland of the Haringvliet sluices, the dikes around the Haringvliet, can flood due to large river Rhine or Meuse discharges. If the river discharges are too large water overflows the dikes. It is thought that failure of the Haringvliet sluices or other structures influences the water levels. Large river discharges can not be discharged if the Haringvliet sluice doors fail. Therefore, the influence of the failure mechanisms of not closing and not opening is included in the assessment of the Haringvliet sluices, see Figure 2.11. The failure mechanisms differ for a structure or a dike section, see Figures 2.11 and 2.12.

Figure 2.11: Failure mechanisms for a (moving) structure (from left to right): overtopping and/or overflow, not closing/not opening of the structure, water flow under or past the structure and structural failure, from (Rijkswaterstaat Projectbureau VNK, 2014).

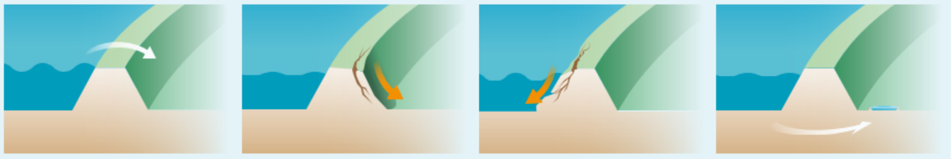


Figure 2.12: Failure mechanisms for dikes (from left to right): overtopping and/or overflow, instability of the dike, erosion of the revetment and piping, from (Rijkswaterstaat Projectbureau VNK, 2014).

The failure mechanisms examined in this thesis are overtopping and overflow, not closing of the sluices, not opening of the sluices and structural failure.

The failure mechanisms shown in Figures 2.11 and 2.12 can be translated to probabilities per failure mechanism. The probability of these failure mechanisms of a certain trajectory or structure is schematically shown in Figure 2.13.

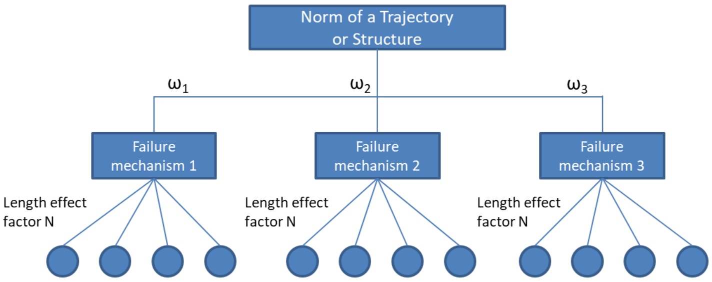


Figure 2.13: Schematization how to assess flood risk for a structure or dike section, from Rijkswaterstaat (2018).

The norms of a trajectory or structure are shown in Figure 2.10. In the WBI2017 the following formula is used to come to the failure probability per failure mechanism:

$$P_{\text{required,fm}} = \frac{P_{\text{required}}}{N} = \frac{P_{\max} \cdot \omega}{N} \tag{2.4}$$

$P_{\text{required,fm}}$ is the required failure probability this dike section or structure must have for a particular failure mechanism, while P_{required} is the failure probability norm of the dike ring or structure, as shown in Figure 2.10. ω and N are respectively a failure probability factor and a length factor. These values vary per dike segment and failure mechanism.

The failure mechanism of water flowing under or around the structure are not assessed in this thesis. The bottom protection of the sluices is thought to be large and strong enough to avoid large flows under the structure which could lead to failure. The failure mechanism of water flowing through the connection between the sluices and the dam are out of the scope of this thesis. Assumed is that the effect on the water levels at the Haringvliet of these flow-through volumes is negligible.

In the assessment of the dikes of the hinterland only the failure mechanisms of overtopping and overflow is taken into account. The other dike failure mechanisms, as shown in Figure 2.12, are largely dependent on soil conditions and duration of a storm or large river discharge. Because these other conditions are as important and not directly linked to the effect of failure of the Haringvliet sluices, only overflow and overtopping are used in the assessment.

2.5.2. Water Quality

Water at the Haringvliet mostly originates from the rivers Rhine and Meuse and due to a relatively new measure, a part of the water originates from the North-Sea.

This new measure is called the 'Kierbesluit' (Decision on the flow area of the sluices). Since November 2018 the Haringvliet sluices are opened during both low and high tide. This is the case if the river discharge at Lobith exceeds a certain discharge to avoid salt intrusion at the Nieuwe Waterweg and Haringvliet. Opening the sluices during high tide is, compared to the previous discharge regime, the largest difference. The Kierbesluit as described in Paalvast (2016), see Section 3.3.2, is used throughout this thesis. With the Kierbesluit the western part of the Haringvliet is allowed to become brackish. Goal of the Kierbesluit is to increase the fish migration and to create a more diverse ecosystem in the western part of the Haringvliet. However, the protection against floods and the availability of fresh water may not be compromised.

The quality of the water in the Haringvliet is also determined by the quality of the water from the rivers Rhine and Meuse. Multiple companies use the water from the rivers, as cooling water for example. This water is also discharged back into the rivers. Therefore, the water can contain multiple fabrics or the temperature can differ compared to the river temperature.

As mentioned, the water quality at the Haringvliet is influenced by multiple factors. The salt intrusion of the sea and the water quality of the river in which temperature changes, salt quantities and pollutants like metals, medicines and pesticides change over time. In this thesis the salt concentration is the only indicator used. The water quality from the rivers can not be influenced by the Haringvliet sluices. The only factor the Haringvliet sluices can control is the amount of salt incoming via the sluices.

2.5.3. Ecology

The Haringvliet area serves as an ecological place for flora and fauna. The value of nature and ecology is becoming more important in today's society. Therefore, it was decided to open the Haringvliet sluices during high tide, as mentioned before. It is thought that especially fish migration is stimulated with the Kierbesluit.

The ecological diversity around the Haringvliet and Hollands Diep need at least be preserved. Increasing the amount and diversity of fish migrating is the aim of the Kierbesluit.

The influence of the Kierbesluit with respect to ecology can not be concluded yet due to the short period that the Kierbesluit is operative. The ecological goals and their fulfilment is assessed by examining whether the Kierbesluit is preservable in the future. Each specie has its own migration period in which the specie can migrate from the sea to the Haringvliet. These periods are indicated, per fish specie, in the migration calender for the Haringvliet, see Figure 2.14.

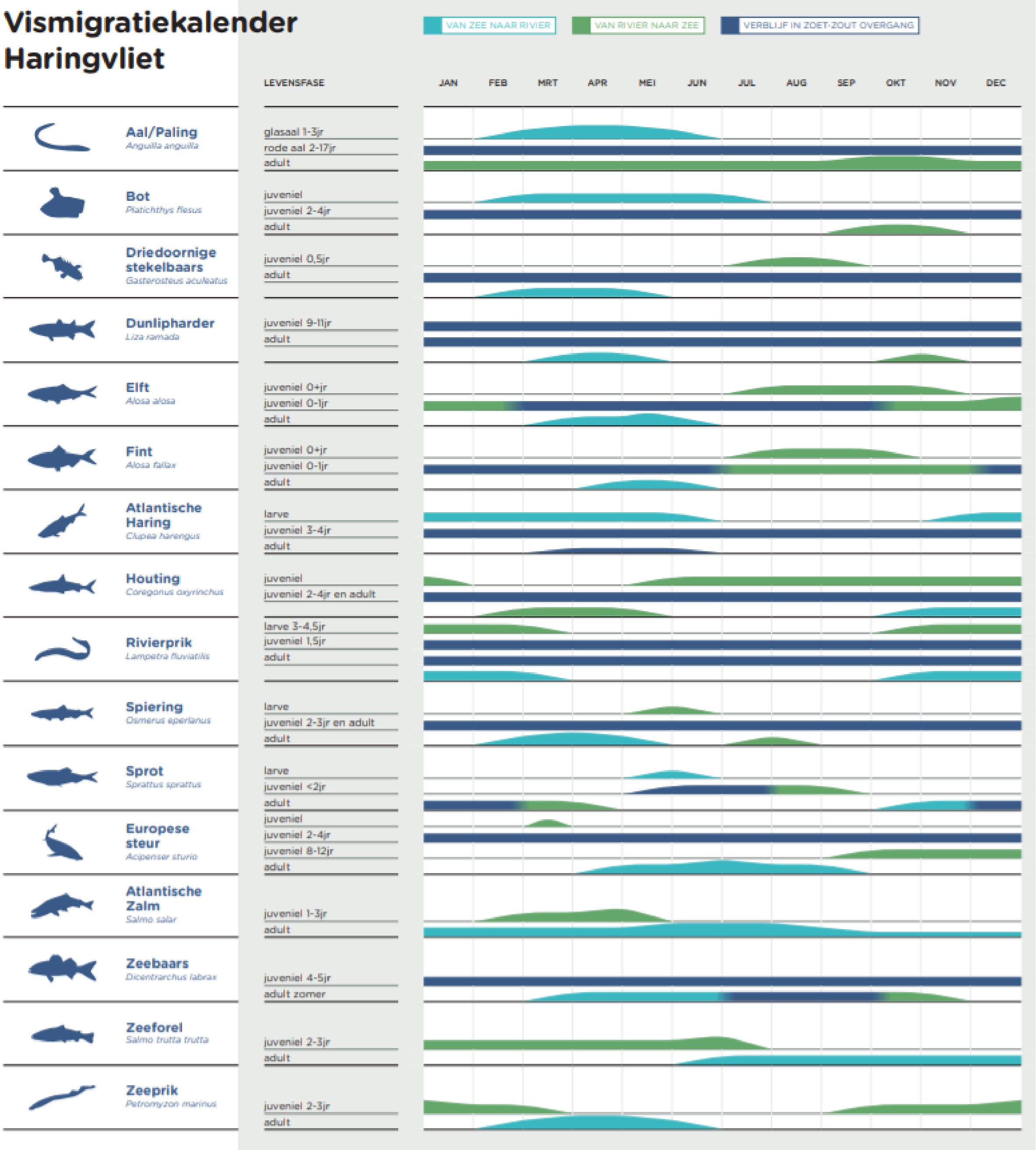


Figure 2.14: The fish migration calender for species important for the Haringvliet, from www.haringvliet.nu. The light-blue color shows fish the period in which the specie will travel from sea to river, green shows from river to sea and dark-blue is the time species stay in brackish water.

2.5.4. Assessment of the Sluices

Based on the description of the functions above, the answer can be given to the research question:
Which functions are taken into account for the assessment of the Haringvliet Sluices?

The assessment of the sluices is based on three main functions. These functions are flood risk, fresh water availability and ecology. These functions are most relevant for this research. The long term effect of the Kierbesluit in combination with climate change on the ecology is not known. Also, the effect of climate change on flood risk and fresh water availability is not known. The functions recreation, navigation and accessibility are not included in the assessment. In Section 2.4 the choice to assess the sluices for certain functions is described more elaborately.

3

Research Framework

In this chapter the tools and research method used to answer the research questions (Section 1.4.1) will be described in Sections 3.1 and 3.2. The literature, data, models and other methods used to answer the objectives are described in those sections. The methodology gives insight in this research and in the assessment of the current Haringvliet Sluices. All the information and results used and gathered during this thesis is analysed critically. In Section 3.3 the boundary conditions needed for the models will be described. In Section 3.4 the hydraulic model SOBEK-RE will be described. This section will also describe the changes made to the existing model and describe the boundary conditions used in the calculations. In Section 3.5 the probabilistic calculation model Hydra-BS will be described. The relevant failure mechanisms included in Hydra-BS and their failure probabilities will also be given. The last section, Section 3.6, will state the requirements for which the Haringvliet sluices do not fulfil their function any more.

3.1. Tools

In this section all the tools used in this research are described. To answer the research objectives, models, interviews and literature are used. For the design objectives mostly interviews and literature are used.

3.1.1. Literature

In the previous chapter background information about the design and structure of the sluices and functions the sluices fulfil are described. A literature study is conducted in which relevant information is gathered. The information gathered during the literature study is used for the assessment of the sluices. The literature contains information about the following topics:

- Flood Risk in the Netherlands
- Failure mechanisms of structures and dikes
- Climate change
- Effect of the Kierbesluit on ecology and fresh water availability
- Fresh water availability and usage
- Influence of structures on ecology

The relevant literature is obtained from Google (Scholar), the TU Delft Library, the HKV library or is obtained by contacting employees of Rijkswaterstaat, HKV or the TU Delft. The information conducted during the literature study is in combination with models, calculations and interviews, used for the assessment of the Haringvliet sluices.

3.1.2. Models

Models are useful in case of complex computations. Models are a schematization of the reality. Models can be used to validate theories or to calculate certain values needed. The use of models in combination with literature result in a reproducible research. In this thesis the models SOBEK-RE (Section 3.4), Hydra-BS (Section 3.5) and Hydra-NL (as comparison) will be used. With SOBEK-RE water levels will be calculated throughout the South-Western delta. Multiple failure mechanisms of the Haringvliet Sluices will be incorporated in the

SOBEK calculations. The results of the SOBEK calculations will be used to calculate the hydraulic loads statistically with the probabilistic program Hydra-BS. Hydra-BS is not part of the statutory assessment tool (WBI) software. Chosen is to use Hydra-BS because potential failure mechanisms of the Haringvliet sluices are included in the program. Hydra-NL, a similar probabilistic program is part of the WBI software. Research to the differences in results between Hydra-NL and Hydra-BS is carried out. The differences between Hydra-BS and Hydra-NL are used to assess the Haringvliet sluices conform the WBI guidelines. The calculations with Hydra-BS in combination with hand calculations are used to assess the effect of multiple failure mechanisms. Also the effect of climate change on the hydraulic loads is modelled.

3.1.3. Interviews

Multiple experts with different stakes and a different view on the future of the Haringvliet will be interviewed. The information gathered during these interviews will be helpful in all phases of writing this thesis. Multiple outcomes of models and literature study can be verified with expert judgement. Interviews with multiple persons of Rijkswaterstaat, WWF, Hollandse Delta and an interview by email with a member of the Delta Commission will be held.

3.2. Research Method

The assessment of the Haringvliet sluices focusses on three functional aspects: flood risk, fresh water availability and ecology. The structural assessment of the sluices is qualitatively taken into account. The effect of climate change on these functions is researched. The method for the assessment of the sluices is shown in Figure 3.1.

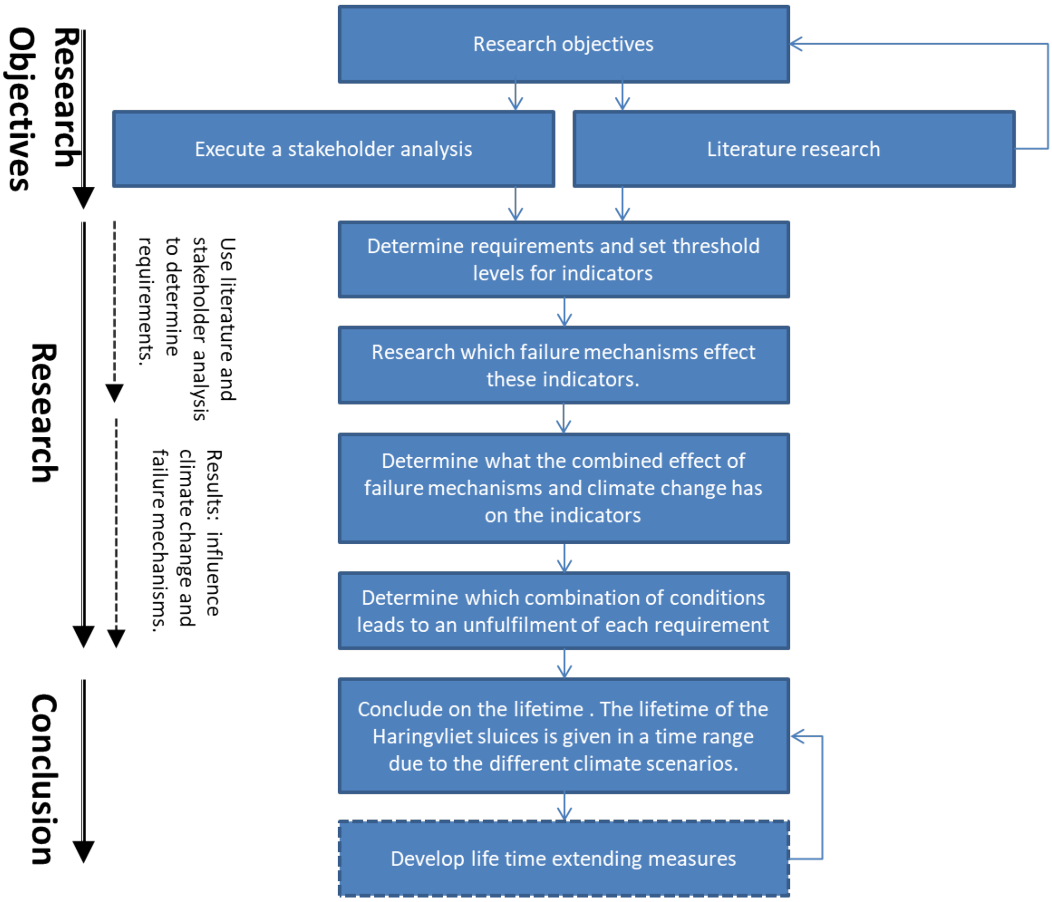


Figure 3.1: Research method in which the aim is to determine the lifetime of the Haringvliet Sluices.

The research objectives are given in Section 1.4.1. The stakeholder analysis is executed in Section 2.4. Multiple results from researches which are used throughout this thesis are described in the literature research in Chapter 2. With the information conducted from the literature research and the stakeholder analysis the requirements for which the Haringvliet sluices will be assessed are determined (Section 3.6). These are summarized in Section 3.6.3. In Chapter 4 the results of the calculations will be presented. The effect of some potential failure mechanisms of the sluices and the effect in combination with climate change are researched. With the results found from the calculations executed in Chapter 4, concluded is on the lifetime of the sluices depending on the climate scenario. The lifetime is dependent on which requirement is not met. Lifetime extending measures will be proposed and worked out. The lifetime extending measures will be described at the end of Chapter 4. The conclusion of the lifetime and the extending measures are used as starting point for the design phase.

3.3. Boundary Conditions

For finding the lifetime for which the Haringvliet sluices can fulfil the criteria which will be mentioned in Section 3.6.3, calculations with SOBEK-RE (from now called SOBEK) and Hydra-BS will be done. Most important boundary conditions for the SOBEK calculations are the: water levels at sea, wind speed and direction and river discharges. Some background information about the boundary conditions and the processes which influence these conditions are explained here. The boundary conditions are simplified for the models and are further described in Section 3.4.

3.3.1. Water Levels at the North Sea

The water level at the sea side of the Haringvliet sluices change over time and space. These variations are caused by tides, surgesand waves driven by wind, as schematically shown in Figure 3.2. The interaction with the structure is also an influence on the water level, which is schematized as wave run up in Figure 3.2.

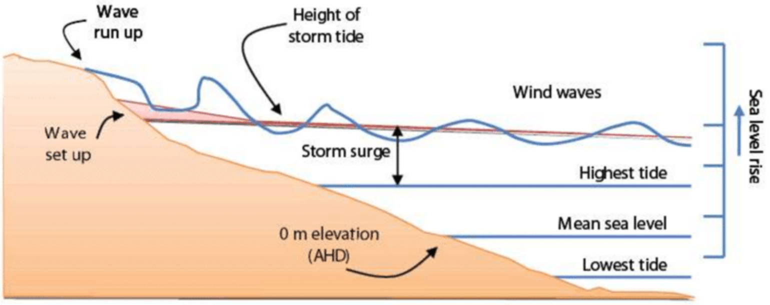


Figure 3.2: Wind, wave set-up and run-up, storm surge and tides all contribute to the actual water level, Figure from (Harty, 2011)

From all of the above mentioned processes, the tides can be predicted quite accurately. The tides are coming from the Atlantic ocean. The tides reach from NAP -1.0 till NAP +1.5 meter. surges and waves are variables which are mostly dependent on the wind (speed and direction) and parameters such as depth, fetch length and interference with a structure. For the Haringvliet, waves coming from the range south-west till north-west are thought to have largest influence.

For the assessment on the lifetime of the Haringvliet sluices, multiple water levels at the North-Sea boundary need to be used in the models. The height of the surges and waves is directly linked to the wind speed and direction and also to the local depth. The probabilities of occurrence of a certain event are incorporated in the statistics which are included in Hydra-BS. The simplified boundary conditions used for the calculations are given in Section 4.2.

3.3.2. River discharges in the Haringvliet

The boundary conditions needed at the east side of the Haringvliet, are river discharges coming from upstream. These discharges are mainly from the rivers Rhine and Meuse.

The river Rhine has its source in Switzerland and flows through Germany to the Netherlands, where it enters at Spijk, near Lobith. Here the water is discharged into the North Sea. The catchment area is around 170.000 km^2, see Figure 3.3. The origin of the river starts in the Swiss Alps and does not consist only of precipitated water, but of a combination of melt-water and precipitation. Therefore, always water is present in the river Rhine, in contrast to rain-rivers. This can be seen in the river discharge through the year in Figure 3.4.

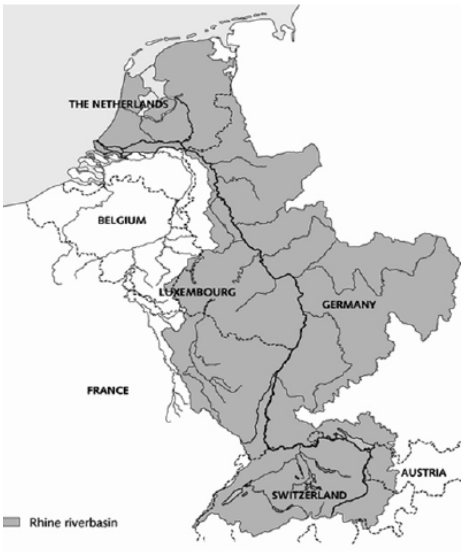


Figure 3.3: The catchment area of the river Rhine, from Frijters (2003)

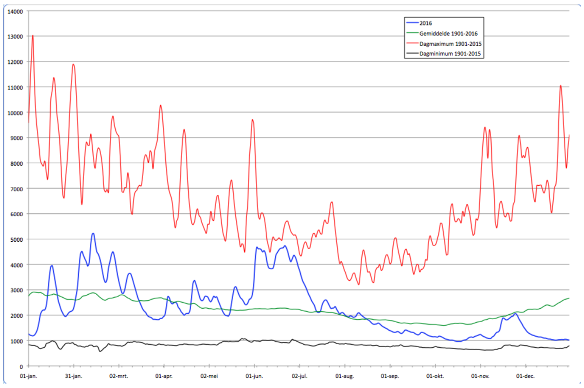


Figure 3.4: The discharge of the river Rhine for the years 1901-2016, including mean (green), day maxima (red), day minima (black), from Waterpeilen (2016).

The Meuse is a rain-river. The catchment area consists of parts of France, Belgium and the Netherlands and is around 33.000 km^2, Figure 3.5. Due to the fact that the Meuse is a rain river, the discharge changes more over the year, Figure 3.6. The Meuse enters the Netherlands at Maastricht.

Figure 3.5: The catchment area of the river Meuse, from Blogspot (2013)

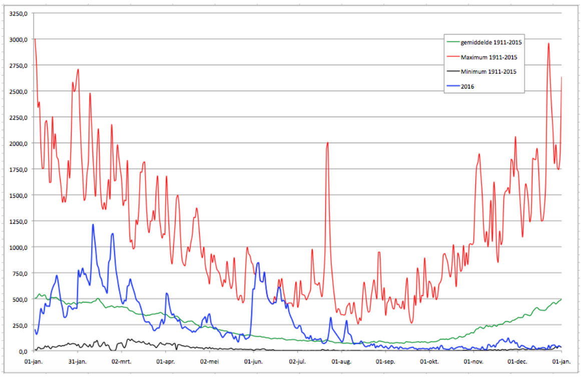


Figure 3.6: The discharge of the river Meuse for the years 1901-2016, including mean (green), day maxima (red), day minima (black), and 2016 (blue) from Waterpeilen (2016).

The incoming discharges of the rivers Rhine and Meuse are distributed into multiple tranches. The distribution of these discharges over the Netherlands are shown in Figure 3.7.
In Figure 3.7, the distribution of the annual river discharges, for the years 2000-2011, is shown. The discharge between the Rhine and Meuse are coupled. Which means in this case, that the discharge in the Meuse is equal to 0.113 times the discharge in the river Rhine. Figure 3.7 shows that in the period of 2000-2011, between 24.2 and 30.4 % of the discharge from the Rhine is discharged onto sea via the Haringvliet sluices (Dörrbecker, 2016). The discharge volume of the Haringvliet sluices depends on the river discharge of the Rhine at Lobith. Before November 2018, the gate height of the sluices of the Haringvliet was regulated by a program called 'Lozingsprogramma van de Haringvlietsluizen 1984' (LPH84). In this program, the sluices opened when the

Figure 3.7: Annual river distribution from the rivers Rhine and Meuse for the years 2000-2011, from Dörrbecker (2016).

discharge of the Rhine at Lobith was large enough. Discharged was only during low tide. As mentioned, nowadays, the Kierbesluit is used. Since November 2018 the sluices also open during high tide, depending on the discharge at Lobith. The Kierbesluit suggested in Paalvast (2016) and the LPH84 program are shown in Figure 3.8. This Kierbesluit is used for the assessment of the lifetime of the sluices.

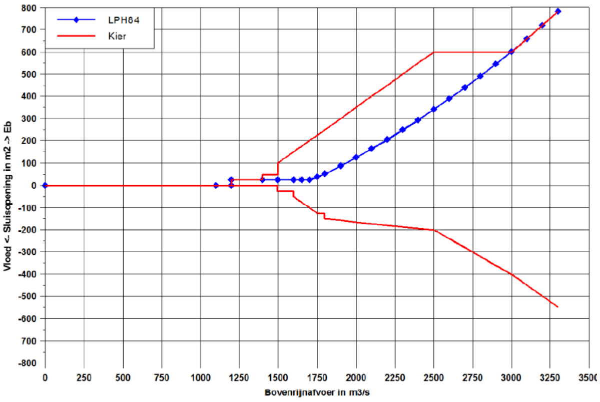


Figure 3.8: The old, LPH84 (blue), and introduced since November 2018, Kier (red), discharge regimes. In which the vertical axis shows the opening of the sluices in m^2 for low tide (eb) and high tide (vloed) and the horizontal axis shows the river Rhine discharge upstream in m^3. From Paalvast (2016).

The actual size of the openings of the sluices is determined by learning during implementation. Most important during this learning during implementation phase, is the salt intrusion length in the Haringvliet, which is measured by Rijkswaterstaat with buoys. With the measurements, the Kierbesluit can change to smaller or larger opening sizes during high tide.

3.4. SOBEK-RE

As mentioned, water level simulations are carried out with SOBEK-RE (WL | Delft Hydraulics, 2008) for the south-western delta. The part of interest is the transition area from river to sea, an estuary. Therefore, SOBEK-RE (River-Estuary) is chosen. An already existing model Delta Programma Rijnmond Drechtsteden (DPRD) (Slootjes et al., 2011), see Figure 3.9, is adjusted.

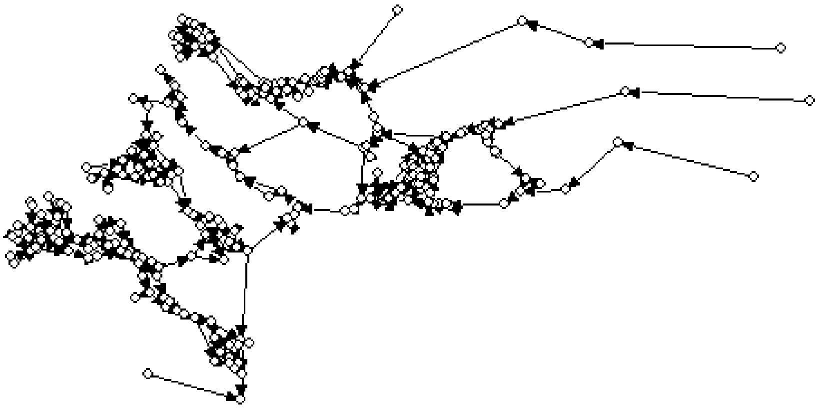


Figure 3.9: The SOBEK-RE DPRD model. All branches (arrows) and nodes (white dots) are shown, for which at some points initial and boundary conditions are given. Also structures are included. Movable structures are regulated based on triggers and controllers. These triggers could be based on time or on hydraulic conditions (relative) water level, river discharge, or flow direction.

SOBEK-RE is a hydraulic 1D model which calculates the water levels in all branches and nodes shown in Figure 3.9. Conditions are attached to each node and to some branches. These conditions can be sea levels, discharge distribution or the extraction of discharge can be described. With these (boundary) conditions, water levels at certain points in the branches are calculated. The water levels are also effected by structures in the Delta. In the SOBEK DPRD model multiple hydraulic structures are modelled (Slootjes et al., 2011). The condition of the structures is mostly dependent of water levels, river discharges or flow directions. The conditions of the structure can also be dependent on time. The hydraulic conditions for which a structure reacts are triggers. One or multiple triggers activate a controller. The controller activates or deactivate a structure and regulates the gate height at a certain time for example, see Figure 3.10.

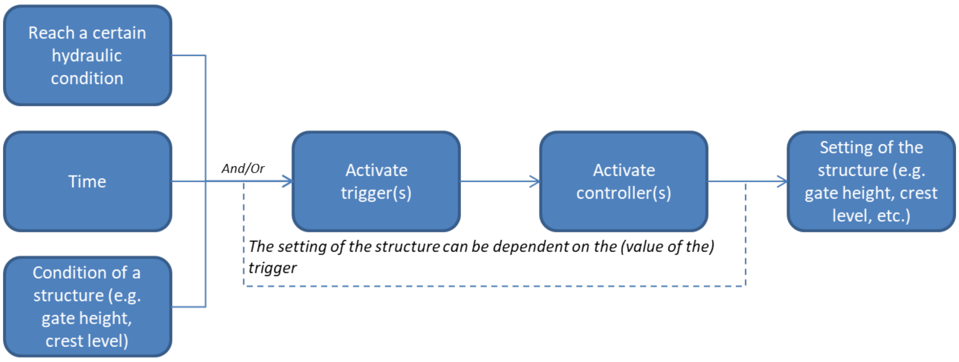


Figure 3.10: The structures in SOBEK are influenced by indicators as: hydraulic conditions, time and settings of other structures. If the indicators reach a certain value, a trigger can be turned on or off. This can be one or more indicators and differs per trigger. If one or multiple triggers are turned on or off a controller can be activated. The controller contains information about a certain setting of a structure (e.g. gate height). The controller changes this setting. This setting can on its turn be dependent on a hydraulic condition, time or state of another structure.

The triggers and controllers that regulate the 17 openings of the Haringvliet sluices are adjusted compared to the current DPRD model. In the current model, the Haringvliet sluices react on two triggers. One trigger becomes ’active’ if there is a *negative* head difference at Haringvliet sluice door number 1. This means that the water level at the sea side is larger than the water level at the Haringvliet side. The other trigger becomes ’active’ if the head difference is *positive* at sluice number 1. All the gates are closed if the ’negative’-trigger is active. The gate height of each door is dependent on the river discharge in branch ’Waal__ 2’ when the head difference is positive. In case of a positive head difference, a travel time of 86400 seconds (24 hours) is used because of the distance between the sluices and this branch. This travel time was already incorporated in the model and is also found in Geerse (2013). Due to this travel time, the controller uses the river discharge of 24 hours ago.

What must be noted is that the Haringvliet sluices in SOBEK are modelled by one door per opening. In reality, two doors per opening should fail before an opening will not be closed or opened. The doors are operated individually and independent of each other. Therefore, the results of the calculations executed in this research are quite conservative.

In the adjusted model, the sluices are opened if the head difference is negative in combination with a river discharge larger than 1500 m^3/s at Lobith. This is the implementation of the so called 'Kierbesluit'. Also two failure modes of the Haringvliet sluices are added in the model. In the execution of the computations the setting of the Haringvliet sluices can be as follows:

- The doors work.
- The sluice doors do not *open after* the storm.
- The sluice doors do not *close during* the storm.

To include the failure modes, triggers and controllers are added to the model. In the SOBEK model the time a storm occurs is known from the boundary conditions. Therefore, the triggers are based on time. The specifications of these triggers and controllers are described more elaborately in Appendix E. The sluice doors fail for 24 hours for both not opening and not closing. In case of failure the gate heights are 0.0 and +11.0 meter respectively for a fully closed and fully opened sluice.

To get fully insight in the effect of the failure mechanism of the Haringvliet, the effect of a failing Europoortkering (Hartelkering and Maeslantkering together) needs to be taken into account. For the Europoortkering only the failure mechanism of not closing is taken into account. All the other structures in the model function properly.

Multiple calculations are carried out to get full insight in the effect of the failure mechanism not opening and not closing of the Haringvliet sluices in combination with the failure mechanism of a not closing Maeslantkering. In Table 3.1 all variable parameters are shown. A python script that controls the input parameters for SOBEK is used. In total 4536 calculations are carried out. These calculations are carried out twice: in case 8 doors fail and in case that (all) 17 doors fail. Firstly the influence of 8 and 17 doors failing is investigated. When this turns out to have a significant influence on the hydraulic loads, further iteration is needed. The probabilities of failing doors and structures are described in the next section.
The discharge and water levels shown in Table 3.1 are as used in Botterhuis (2012). These discharges and water levels represent values of the whole spectrum for which hydraulic loads can be calculated. The probabilities of all these events are included in Hydra-BS. The probabilities of occurrence of the water levels at the North-Sea, Rhine discharges, wind directions and wind velocities at the North Sea can be found in Appendix F. These probabilities in combination with the results of the SOBEK calculations are used to calculate the water levels at all the locations in the delta.

The boundary conditions for the water levels at the North-Sea, as stated in Table 3.1, are shown in Figure 3.11. These water levels are the result of a storm surge and the tide. The components for a storm surge of H5 is shown in Figure 3.12. H1 is equal to the tide as shown in the top left figure in Figure 3.11. The storm surge increases for each boundary condition. The maximum water level increases with around one meter. In Figure 3.11 the boundary conditions are shown for the climate reference scenario, in which 0.07 meter sea level rise is included. An additional water level increase of 0.01 and 0.28 meter is added respectively for climate scenarios 1 and 2.

Table 3.1: All changing parameters and their options

Parameter	**Number of options per parameter**	**Parameter options**
Haringvlietsluizen	3	Works Does not close Does not open
Europoortkering	2	Closes Does not close
Water level [m]	6	6 different water levels (see Figure 3.11)
Discharge [m^3/s]	9	Q1 = 600 Q2 = 2000 Q3 = 4000 Q4 = 6000 Q5 = 8000 Q6 = 10,000 Q7 = 13,000 Q8 = 16,000 Q9 = 18,000
Wind direction [degrees]	7	sw = 225 sww = 247.5 w = 270 nww = 292.5 nw = 315 nnw = 337.5 n = 360
Climate Scenarios	2	Scenario 1/R2015 = +8 cm sea level rise Scenario 2/W2050 = +35 cm sea level rise
Number of calculations:	3 x 2 x 6 x 9 x 7 x 2 = 4536	[-]

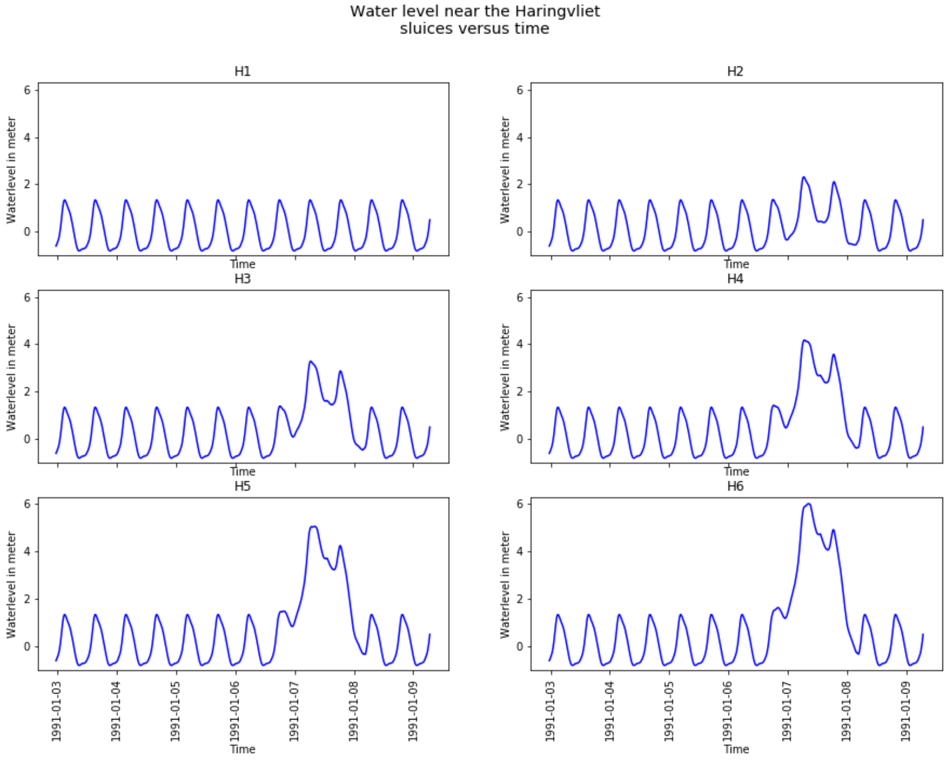


Figure 3.11: Water levels used as boundary condition at the sea side of the Haringvliet sluices. These water levels are increased by 0.01 m. for the sea level rise scenario R2015 and 0.28 m. for the scenario W2050.

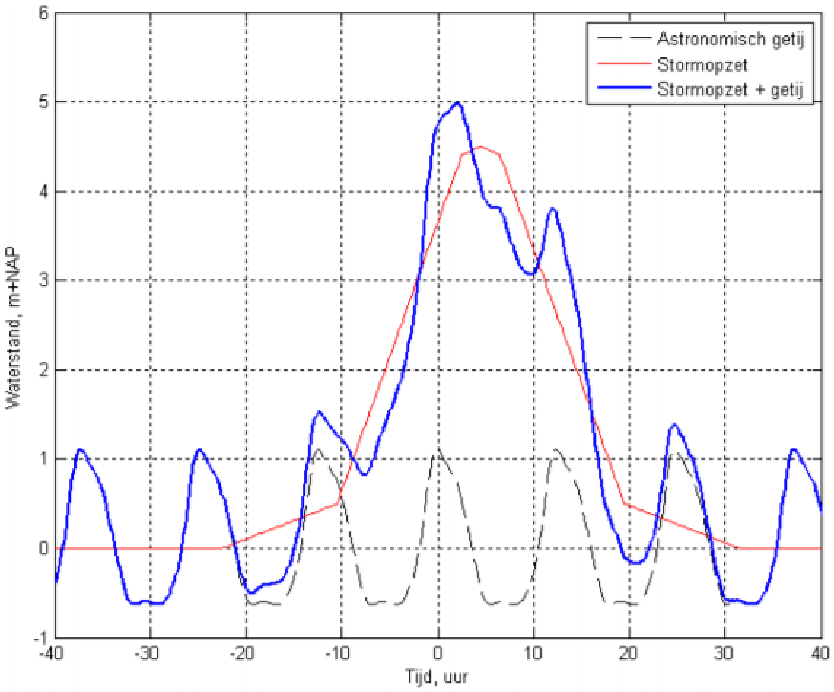


Figure 3.12: An example of the water level during a storm, in this case H5. In which the water levels due to astronomical tide (black), water level due to storm (red) are combined (blue) to the total water level at sea, from (Rijkswaterstaat, 2017a).

Intermezzo on the naming and use of the climate scenarios.

Sea level rise scenario 1 and R2015 are used interchangeably. Same holds for sea level rise scenario 2 and W2050. These are the sea level rise additions added in the computations. When there is stated, with the sea level rise of R2015, it means that in total 8 centimetre sea level rise is added. For W2050 this addition is 35 centimetre.

The sea level rise scenarios W_h and G_l are KNMI scenarios distracted from the RCP scenarios. The KNMI scenarios are used for the assessments to conclude on the final lifetime of a function. The Warm and W_h, and Gemiddeld and G_l are also used interchangeably.

New research of DeConto and Pollard (2016) shows that climate change and especially sea level rise may occur faster than previously thought. This has to do with mechanisms as cliff failure and hydro-fracturing, which is not accounted for in the current sea level rise scenarios, as described in Appendix C. These mechanisms can cause a larger sea level rise, but due to the fact that these mechanisms are not incorporated in the models, sea levels may rise faster.

The river discharges shown in Table 3.1, are the river discharges of the Rhine. The discharges of the Meuse are directly coupled to the discharges of the Rhine. The discharges at Lobith corresponding with the discharges at the Waal__2 branch are shown in Appendix E.

3.5. Hydra-BS

Hydra-BS is a program which calculates return periods for given water levels and vice versa. Hydra-BS uses a database in which the results of SOBEK are gathered. The probabilities of the discharges, wind directions, wind velocities and sea water levels are input files which are included in the Hydra-BS software. Hydra-BS calculates the hydraulic loads based on the results in the database and these statistics. Hydra-BS enables the user to include

Table 3.2: All *possible* failure mechanisms incorporated in Hydra-BS

Structure	**Failure mode(s)**
Europoortkering	Not closing Not opening
Haringvliet sluizen	Not closing Not opening
Volkeraksluizen	Not opening

the effect of certain failure mechanisms for the Maeslantkering, the Haringvliet sluices and the Volkerak-Zoommeer. The failure mechanisms that can be used for the Hydra-BS calculations can be found in Table 3.2. In the current Statutory Assessment Instrumentation (in Dutch: Wettelijk Beoordelings Instrument (WBI2017), see Appendix D, Hydra-NL and Ringtoets are used for the assessment of structures. However, the effect due to the failure mechanisms of the Haringvliet sluices are not included in Hydra-NL and Ringtoets. Therefore, Hydra-BS is used. A more elaborate description of the differences between Hydra-NL and Hydra-BS is described in Appendix F. Largest difference between Hydra-NL and Hydra-BS, and thus calculating via the WBI2017 standards, is the inclusion of model uncertainty. In Hydra-NL it is an option to calculate the hydraulic loads including model uncertainty which is not incorporated in the software of Hydra-BS. The effect due to this model uncertainty is calculated by comparing results between Hydra-BS and Hydra-NL.

In the SOBEK calculations, the failure modes of not opening for the Europoortkering and Volkeraksluizen are not incorporated. Therefore, the probability of failure is set to 0, meaning that the Europoortkering always opens and that the Volkeraksluizen always work. The probability and effect on the hydraulic loads due to not opening of the Europoortkering is relatively small and will therefore be neglected (Bijl, 2006).

The Volkeraksluizen are situated between the Hollands Diep and the Volkerak-Zoommeer. In case of large river Rhine discharges and a storm at sea, the Volkeraksluizen are opened and the Volkerak-Zoommeer is used as storage basin. The Volkerak-Zoommeer is able to store 200 million cubic meters of water and is only used if both the discharge and water level at sea are large. The Volkerak-Sluices are opened if the water level at Hoek van Holland reaches NAP + 3.0 m, which is the level for which the Europoortkering closes too. The Volkeraksluizen are opened and water from the Hollands Diep flows by gravity to the Volkerak-Zoommeer. Due to the large storage volume the water levels at the Haringvliet, Hollandsch Diep, Nieuwe Waterweg and multiple other waterways downstream of the Hollandsch Diep decrease compared to the situation without storage (Slootjes and Hesselink, 2005). The effect this storage volume has on the water levels in the South-Western delta is shown in Figure 3.13. The effect of the Volkeraksluizen not working have a significant effect on the water levels in the south western delta (Slootjes and Hesselink, 2005).

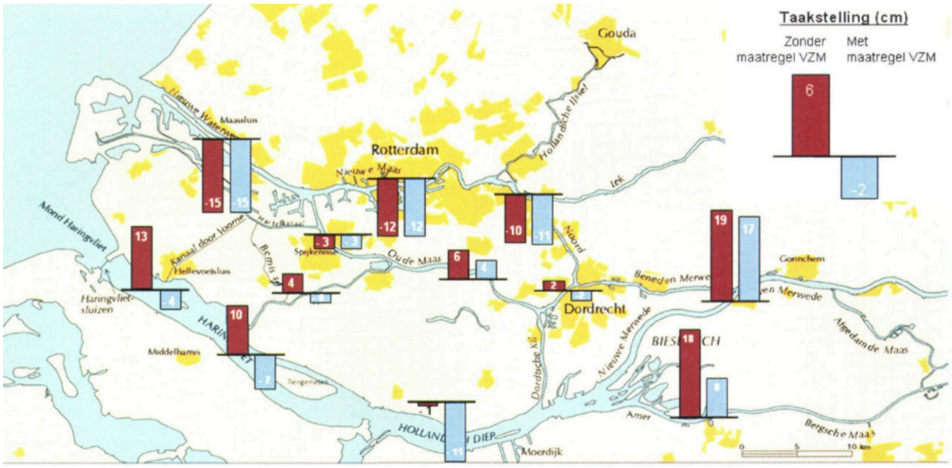


Figure 3.13: The effect on the water levels when the Volkerak-Zoommeer is used as storage in blue, and without Volkerak-Zoommeer as storage in red, from (Slootjes and Hesselink, 2005).

In the SOBEK calculations failure of the Volkeraksluizen is not included. The hydraulic loads calculated without the effect of the Volkerak-Zoommeer would be larger as shown in Figure 3.13. The calculations without including the failure of not opening of the sluices can be considered conservative.

The failure mechanism of a not closing Europoortkering and especially the Maeslantkering has a significant effect on the hydraulic load (Bijl, 2006). For the failure mechanism not closing of the Maeslantkering the required failure probability is extracted from Bijl (2006) and is once per 100 requests. For the Haringvliet sluices the actual failure probabilities are unknown. Therefore, the required probability of failure as stated in Goederen (2013) are used as actual failure probabilities for the Haringvliet sluices. The required failure probabilities in combination with the number of doors failing are stated in Tables 3.3 and 3.4, extracted from

Goederen (2013).

Table 3.3: Required failure probabilities for the Haringvliet sluices with respect to the failure mechanism not closing, from (Goederen, 2013). The failure probabilities are given per request.

Not Closing	
Number of failing doors	**Required Failure Probability**
1	5.0E-03
2	1.05E-03
3-5	1.0E-04
6-10	1.8E-05
11-17	2.0E-04

Table 3.4: Required failure probabilities for the Haringvliet sluices with respect to the failure mechanism not opening, from (Goederen, 2013). The failure probabilities are given per request.

Not Opening	
Number of failing doors	**Required Failure Probability**
1	0.5
2-5	0.1
6-10	0.01
11-17	1.0E-04

What must be noted is that the required failure probability for not closing, Table 3.3, of 6-10 doors is smaller than for 11-17 doors. The explanation given in Goederen (2013), is that there are barely failure mechanisms which cause 6-10 failing doors at the same time. As mentioned, taking the required probabilities as actual failure probabilities is an assumption. These probabilities are used for both climate scenarios and are assumed to remain constant. To have insight in the sensitivity of the probabilities, calculations without failure and with a probability 10 times larger than the required probability are executed.

The failure modes not opening for the Europoortkering and not working for the Volkeraksluizen are not incorporated in the fault tree for the calculations executed with Hydra-BS. The incorporated failure modes which are assessed with Hydra-BS are schematically shown in the fault tree shown in Figure 3.14. The probabilities included in the figure are extracted from Tables 3.3 and 3.4 in case 17 doors fail or function.

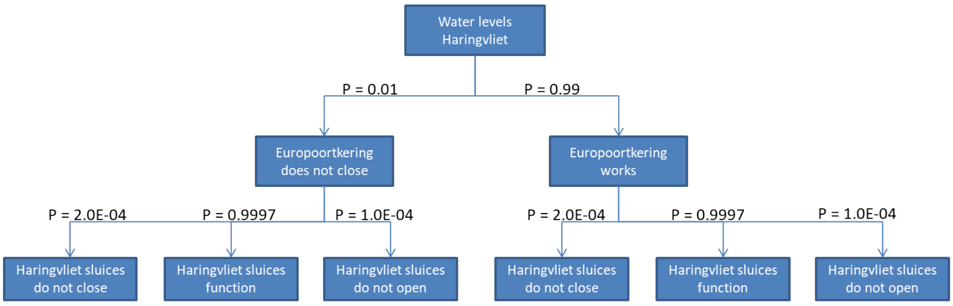


Figure 3.14: The fault tree as used in Hydra-BS with the probabilities in case all doors of the Haringvliet sluices fail. The probabilities for the Haringvliet sluices shown in this fault-tree are extracted from Goederen (2013). The probabilities for the Maeslantkering are extracted from Bijl (2006).

The probabilities as shown in Figure 3.14 are used in Hydra-BS to calculate the water levels at multiple locations. In Figure 3.15 the locations at which the calculations are executed are shown.

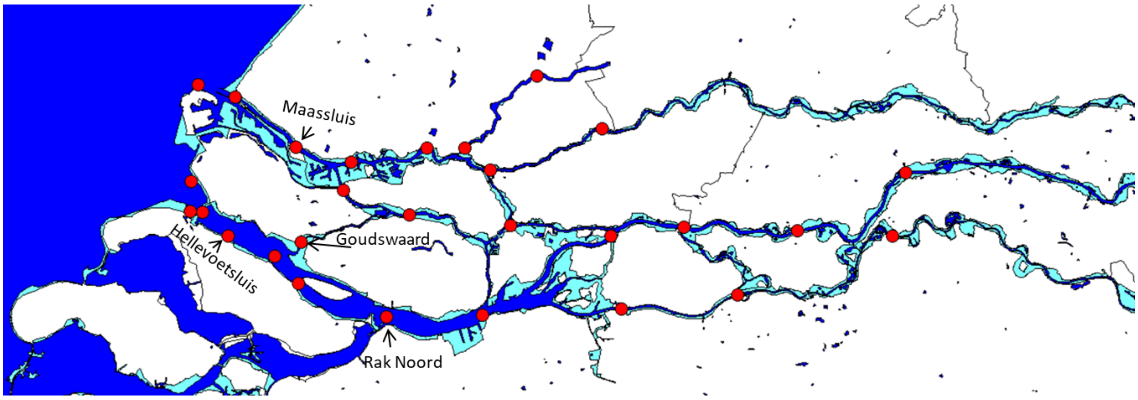


Figure 3.15: The red dots are the locations for which the water levels have been calculated with Hydra-BS.

3.6. Requirements

The program of requirements is important when designing a structure. The indicators are different for each requirement and are described here. During the lifetime of a structure the requirements can change due to new demands. In this section the program of requirements for the assessment of the current structure is given. The program of requirements is divided in functional and structural requirements. The focus in this research is at the functional requirements. The functional strategies proposed after the lifetime of the current structure is reached, have to fulfil a program of requirements which can differ due to other demands and criteria. This program of requirements will be given in Section 5.1.3.

3.6.1. Indicators and Threshold Levels

The research question: 'which indicators determine whether the functions can not be fulfilled any more?' is answered in this section for the three functions assessed. The question: 'what methods are used to, quantitatively and qualitatively, assess these indicators?' are answered in this subsection too.

Flood Protection

For the assessment of the Haringvliet sluices concerning flood protection three failure mechanisms are taken into account. The failure mechanisms are:

- Not opening or not closing of the sluices
- Overtopping/Overflow
- Constructive failure

Because a lack of information and data, the WBI2017 assessment method as shown in Figure 2.13, can not be followed. The *actual* failure probabilities of not opening and not closing are not known. Therefore, the **required** probabilities as stated in Goederen (2013) are used as **'actual'** probabilities in the calculations (Section 4.2.2). Also, there are no limits available concerning overtopping and overflow of the sluices. In Van der Meer (2008) a study to the overtopping and overflow volumes is executed. The overtopping volumes and effect on the hydraulic loads will be described in Section 4.2.3. The third failure mechanism used in the assessment of the Haringvliet sluices, is structural failure. The structural failure is assessed based on a semi structured interview, Section 4.1. The lifetime for structural failure is solely based on sea level rise. To retrieve the year for which the sluices fail structurally, the sea level rise amount for which the sluices fail structurally is compared with the sea level rise scenarios. This is described more elaborately in Section 3.6.2.

The effects on the water levels due to not opening and not closing and overtopping and overflow are used to assess the retaining dikes inside the delta. The dikes at the hinterland are only assessed for the failure mechanisms overtopping and overflow (Ministerie van Binnenlandse Zaken, 2018). The failure mechanisms instability, erosion of the revetments and piping, are out of scope of this thesis because these failure mechanisms are not only dependent on large water levels but also on other circumstances, e.g. soil type, the type of revetment. These circumstances are not treated in this thesis. The failure probabilities per failure mechanism per dike ring are stated in Rijkswaterstaat Projectbureau VNK (2014). It becomes clear that other failure mechanisms than overtopping and overflow have larger probabilities, see Appendix G.

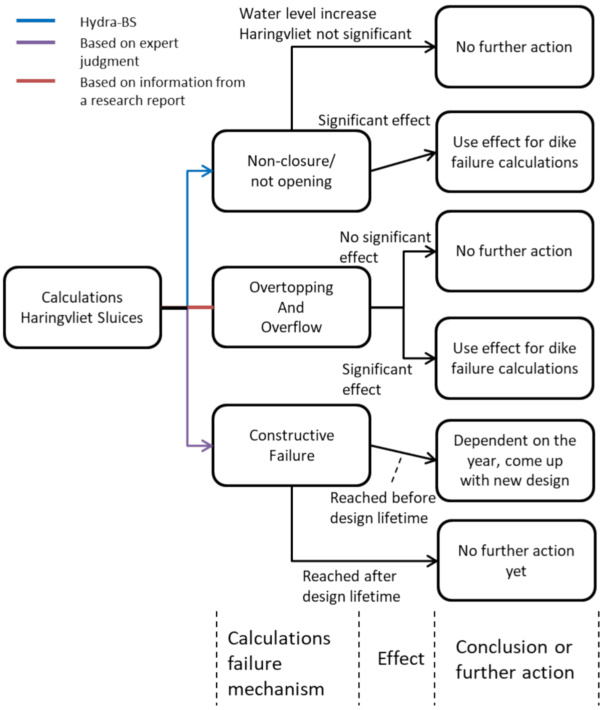


Figure 3.16: The calculations to follow for protection against flooding. Each failure mechanisms is assessed with another method, as shown with the coloured lines.

The effects used to decide on the lifetime concerning protection against flooding is based on three failure mechanisms. The failure mechanisms and method used to assess for each failure mechanism is schematized in Figure 3.16.

Failure mechanism 1
The first failure mechanism assessed is the failure of not opening and not closing of the sluices, see Figure 3.16. The effect of the failure mechanisms not opening and not closing on the hydraulic loads is thought to be significant if at the average return period of 10^3 years, the water level increase is in the order of centimetres. The increase is compared to the results of calculations in which the sluices always function. The return period of 10^3 years is chosen based on the failure probabilities allowed for the Haringvliet sluices and the dike sections around the Haringvliet from Ministerie van Binnenlandse Zaken (2018).

It is not yet known if there will be an effect on the hydraulic loads of the hinterland due to the inclusion of the failure mechanism. Therefore, the probabilities of failure for the dike sections of the hinterland effected by the failure mechanisms of the sluices will be mentioned during the assessment of the dike sections. For the effected dike segments, the probabilities as stated in Ministerie van Binnenlandse Zaken (2018) needs to be used.

The effect of the failure mechanisms is calculated with the models SOBEK and Hydra-BS as previously mentioned. The probabilistic program Hydra-BS calculates frequency lines. Hydra-BS includes the probability of not opening and not closing of the Haringvliet sluices. Other structures which can be included in the calculation are the Maeslantkering and the Volkerak Sluices. The input file is a database containing information of the hydraulic boundary conditions, the state of a structure and the water levels at multiple locations. The database is extracted from the results of multiple SOBEK calculations. These SOBEK-RE computations include two sea level rise scenarios. All variables and boundary conditions used are descried in Section 4.2.1. The simplified boundary conditions used for the SOBEK computations are as described in WBI2017. The boundary conditions are described in Section 3.3.

Compared to the current assessment of the Haringvliet sluices, two failure mechanisms are added to the SOBEK and Hydra-BS calculations. These mechanisms are not closing and not opening of the sluices. The failure mechanism that is expected to have the largest effect on the hydraulic loads is failure of all the doors (17 doors). However, it is also known that the probability of failure of all doors has the lowest probability (Goederen, 2013). Therefore the effect of failure of 9 doors, for which the probability is larger, is also assessed. The **required** probabilities from Goederen (2013) are used to calculate the effect of failing doors. Firstly the results of 9 and 17 doors failing will be investigated. If the effect on the hydraulic loads turn out to be significant large, the effect of less failing doors can be investigated.

The database made from the SOBEK calculations is compared with the already existing WBI2017 databases. The WBI2017 database is only suitable for the program Hydra-NL. As prior mentioned, Hydra-BS is no official WBI2017 software. The self made databases with SOBEK are only suitable for Hydra-BS. The current WBI-2017 assessments incorporate model uncertainty, which is not included in Hydra-BS. The possible effect of this model uncertainty is, when significant, added to the hydraulic loads.

Failure mechanism 2

The second failure mechanism is Overtopping and Overflow, see Figure 3.16. The failure mechanism of overtopping and overflow over the sluices are based on the research of Van der Meer (2008). The increase of the water level at the Haringvliet due to the overtop-and overflow volumes over the sluices is calculated. Overtopping and overflow was included during the design of the sluices. The effect of the overtopping and overflow volumes was thought to be insignificant. With sea level rise these volumes will increase. The overtopping and overflow volumes due to sea level rise are set to be significant if this increases the water level at the Haringvliet in the order of decimetres. This increase in water level is used to assess the dikes at the hinterland for the failure mechanism overtopping and overflow.

Failure mechanism 3

Structural failure, see Figure 3.16, is the failure mechanism for which the sluices can not fulfil the requirements concerning strength and stability. Structural failure of the Haringvliet sluices is based on a semi structured interview with ir. Frank Spaargaren. This failure mechanism is qualitatively considered. Climate change is thought to lead to larger forces on the structure which leads to structural failure of the sluices. The estimation for which sea level rise the sluices fail is based on ir. Frank Spaargaren his experience and knowledge gained during the design of the sluices. The amount of sea level rise that will lead to structural failure is compared to the climate scenarios of the KNMI2014, G_l and W_h. A range for which the lifetime concerning structural failure can be given.

Assessment concerning flood risk

The final assessment concerning flood risk is based on the failure mechanisms overtopping and overflow at dike segments of the hinterland influenced by the failure mechanisms described above. The hydraulic loads are calculated for the allowable overtopping quantities of 1 and 10 l/s/m. When it turns out that with the sea level rise scenarios included in the computations the dike segments do not fail concerning overtopping and overflow, the results will be extrapolated till failure is reached. Failure concerning overtopping and overflow of the dikes at the hinterland is reached when multiple dike sections need to be reinforced with a certain height. The lifetime of the Haringvliet sluices is reached if **2 dike segments** need to be reinforced by at least **0.2 meter**. These numbers are based on costs, available space and safety of the hinterland.

The calculated sea level rise which lead to failure is compared with the 50% percentiles of the scenarios G_l and W_h, for which the final lifetime is concluded, Figure 2.5.

Water Quality

The lifetime of the sluices concerning fresh water availability will be assessed qualitatively. Multiple researches and measurements from Rijkswaterstaat will be used to come to a conclusion on the lifetime.

Water at the Haringvliet must always be of such quality that it is usable as drink water and can be used for agricultural purposes and as industrial water. This means that the water may not contain more than 300 mg chloride per litre. Water containing less than 300 mg/litre is classified as fresh-brackish water (Stuyfzand, 1986). If water at the intake locations contains more than 300 mg chloride per litre the agricultural fields become too salty. Also, the intake of water to produce qualitative drinking water is stopped if the concentration is larger than 300 mg chloride per litre. The implementation of the Kierbesluit caused a relocation of multiple fresh water intake locations. The intake locations are all moved upstream of the imaginary line between Middelharnis and Spui in the past four years before the Kierbesluit was introduced in November 2018 (Wijsman et al., 2018; WSHD, 2019). All measures taken, are shown in Figure 3.17.

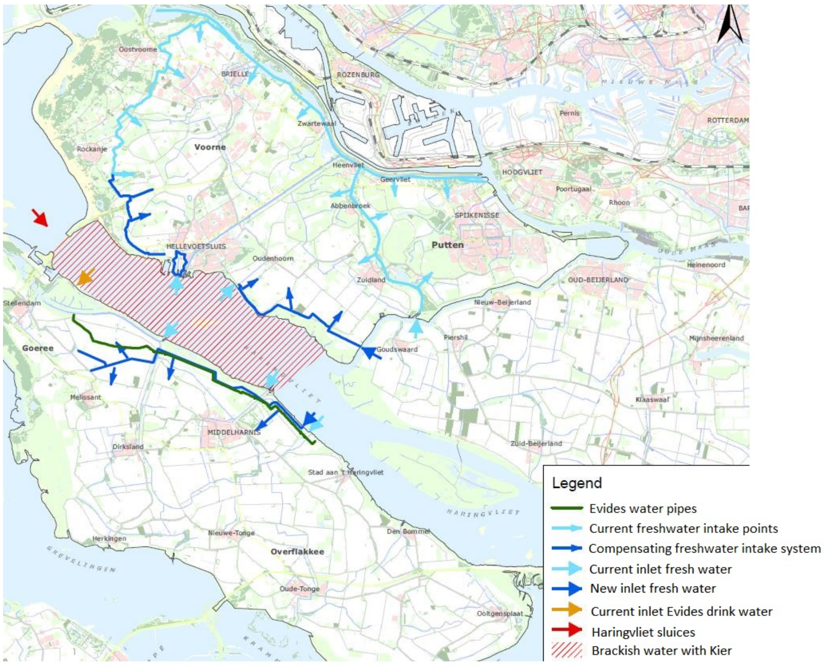


Figure 3.17: All measures taken for the Kier besluit, from (WSHD, 2019)

The parameters which influence the intrusion length are investigated in Jacobs et al. (2003). The effect of climate change on the influencing parameters will be investigated. The combination of parameters for which the salt concentration exceeds the limit of 300 mg/l chloride, is used to assess the lifetime of the fresh water availability. The parameter combination leading to an exceedance of the limit is compared to the climate scenarios of KNMI2014 (G_l and W_h) as described in Section 2.3. It is thought that the fresh water availability is largely influenced by the sea level rise and the monthly average discharge distribution of the Rhine, Figure 2.5. The assessment is based on qualitative information from multiple researches and measurements carried out in 1997 which are described in Jacobs et al. (2003).

Ecology

The lifetime of the sluices concerning ecology is based on the time each specie can migrate. It is thought that each specie needs at least 50% of the time as indicated at the migration calender. As an example: if a fish specie can migrate from sea to Haringvliet during the months June till October (4 months), but due to climate change the sluices can only be opened in the month June (1 month), the lifetime for ecology is reached (25%). Another requirement is that the sluices may not be closed for 50 consecutive days or more. It is thought that with a closure of 50 days or more, the species have found another way to migrate upstream or will not migrate at all.

It is expected that due to climate change the sluices need to be closed more frequently and for longer periods. The lifetime concerning ecology is based on multiple reports in which simulations are carried out (Noordhuis, 2017). The simulations result in frequencies for which the sluices can be opened during both low or high tide. With climate change the frequencies the sluices can be opened are thought to decrease. The four main sources used to asses the sluices concerning ecology are described below.

First of all the consequences climate change has on the average river discharge per month over the year and on the sea level rise is used. Secondly, the fish migration calender is used. This calender indicates in which periods each fish specie is able to migrate from sea to river. Thirdly, the Kierbesluit as described in Paalvast

(2016) is used for the assessment concerning ecology. And the fourth source used are the results and simulations as described in Noordhuis (2017). The results in Noordhuis (2017) are obtained by using data that includes Rhine discharges and water levels from the north sea. With this data it is calculated which days the sluices could have been opened with the Kierbesluit as described in Paalvast (2016). With these sources the lifetime concerning ecology is estimated.

The indicator in this thesis concerning ecology is the migration time of all the fish species mentioned in the Haringvliet migration calender. Preserving or increasing the biodiversity will be measured by analysing and evaluating the time fish species can migrate from the sea to the Haringvliet. This time is thought to decrease due to the effects of climate change.

3.6.2. Structural Requirements

For all (hydraulic) structures, multiple structural requirements must be fulfilled. The most important structural requirements in new designs have to do with:

- Stability
- Strength
- Constructibility
- Maintainability
- Adaptability

For the assessment of the current structure the strength and stability of the most important parts of the sluices are researched. Expert judgement is used to assess the stability and strength. This assessment is solely based on sea level rise scenarios causing an increase in the external forcing. This can cause stability and strength issues for the structure.

The elevation of the sea level for which the Haringvliet sluices can not meet the structural requirements any more will be compared with the sea level rise scenarios as shown in Section 2.3. This gives a range of years in which the lifetime with respect to the structural requirements can not be met.

The latter three, constructibility, maintainability and adaptability are requirements which are not used for the assessment for the current structure. These requirements can be used as criteria for the new strategies. In this thesis functional designs are looked into for which the constructibility is thought to be less relevant. The lifetime of the current structure can be extended with adaptation or maintainability measures. Adapting the structure can be an option. However, this is dependent on the lifetime of all the functions, the costs and the increase in lifetime reached with these measures. With rapidly rising sea levels the lifetime enlarging time is smaller..

Design Lifetime

Most Civil structures are designed for a lifetime of 50 or 100 years. The Haringvliet Sluices are designed for a lifetime of 250 years (Ferguson, 1971). The design lifetime can be seen as a requirement and is used as ultimate limit concerning the lifetime of the structure, as shown in Figure 1.4. The lifetime for which the sluices are designed for is the year 2230.

3.6.3. Summary of the Functional Requirements

The criteria researched for the assessment of the current structure are coming from the functions: safety against flooding, water quality and ecology. The requirements concerning safety against flooding is based on the failure mechanisms of the sluices and the hydraulic loads on the hinterland. The requirement for water quality is based on the salt intrusion due to the Kierbesluit. The requirements for the ecological function is based on the fish migration calender and the Kierbesluit. For all requirements the influence of climate change is investigated. The indicators and requirements are already mentioned in Section 2.5. The requirements and their indicators are summarized below and answer one of the research questions as described in Section 1.4: **Which requirements need to be fulfilled by the Haringvliet sluices and which indicators show that the requirements are not fulfilled any more?**

- The effect of the failure modes not opening and not closing of the Haringvliet sluices needs to be taken into account if the water level increase (at the Haringvliet) is in the order of centimetres for the return periods as specified in the Ministerie van Binnenlandse Zaken (2018). The failure mechanisms need to be included in the assessment of the dikes of the hinterland.

- The effect of the failure mode overtopping for the Haringvliet sluices needs to be taken into account for the assessment of the dikes at the hinterland if the water level increase is in the order of decimetres.
- The effected dike segments at the hinterland are assessed for the failure mechanism overtopping. The overtopping quantities for multiple dike segments need to be calculated and must remain under the limits stated in the Ministerie van Binnenlandse Zaken (2018). The limits differ per dike segment. If two dike segments need to be elevated with 0.2 meters or more due to the failure mechanism overtopping, the lifetime concerning flood risk is reached.
- The frequency the sluices can be opened during high-tide reduces significantly compared to the current situation, the amount of fish that can and will migrate will become insufficient. Each fish specie must be able during at least 50% of the time of the period indicated at the Haringvliet fish-migration calender. If the migratory fish have half the time to migrate compared to the current situation, the requirement is not met. Another requirement is that the sluices may not be closed for 50 consecutive days.
- The Haringvliet sluices need to guarantee the stability and strength at all time.
- The water from the Haringvliet is used as drink water and for agricultural and industrial purposes. Therefore, water at the imaginary line Spui-Middelharnis may not contain more than 300 mg chloride per litre.

4

Results

In this chapter the Delta Work is assessed. Therefore, the two main aspects as described in Chapter 2, is focussed on. First aspect is the functional lifetime and the second is the structural lifetime. The design lifetime is thought to be the limit lifetime for the sluices. The assessment of the sluices is based on the requirements (Section 3.6.3). When the requirements are not met the lifetime is reached. Each requirement belongs to a certain function, meaning that a certain function can not be fulfilled any more. In Sections 4.1 to 4.4 the lifetime of the Haringvliet sluices concerning strength and stability, flood protection, fresh water availability and ecology respectively will be researched. In Section 4.5 the lifetime of the Haringvliet sluices for the assessed functions will be given. The final section of this chapter, Section 4.6, will treat the possible life time extending measures.

4.1. Lifetime Concerning: Strength and Stability

The structural assessment is based on expert judgement obtained by an interview of ir. F (Frank) Spaargaren. Mr.Spaargaren was involved at the design and the closure of the Oosterschelde and Haringvliet and worked at the Deltadienst Rijkswaterstaat. Mr.Spaargaren mentions during the interview that the design of the Haringvliet sluice doors have been adjusted while the construction of the sluices already started. The adjustments on the doors were necessary due to new insights on the forces due to wind waves. During tests in a 100 meter long basin, the forces on the originally designed sea side door of NAP +5.0 m, became too large. Therefore, it was decided to reduce the height of these sea side doors until NAP +3.0 m. Due to the unfavourable curvature of the sea doors a retention basin, which is a shallow basin in front of the doors, was necessary to reduce the impact of the waves. These dynamic wave forces would not only be too large for the sluice doors, but also for the NABLA-beam, which takes up the forces acting on the doors, see Section 2.1.3 for the design of the sluices. In conclusion: the design was changed in such a way, that the door at the sea side now acts as a wave breaker during extreme conditions at sea. More information about the design is stated in Section 2.1 and Appendix A.

For the structural assessment, the focus will be on failure of the NABLA-beam and the influence of the sluice doors. The NABLA-beam is the core of the structure and is not replaceable. The NABLA-beam eventually absorbs all the hydraulic forces. Because the NABLA-beam is irreplaceable and almost all the other (moving) parts of the sluices are replaceable, focus is on the NABLA-beam. However, replacing the sluice doors will be very costly and need great engineering skills due to the specific dimensions. Increasing the height of the doors will probably increase their weight. The extra weight must be carried by the NABLA-beam. Also larger hydro forces will act on larger doors, while the forces on the NABLA-beam are already around their design limits.

The doors at the river side are NAP + 5.0 meter and have to resist the static forces due to water level differences between the Haringvliet and the water level between the doors. The doors also have to resist the forces due to waves from the Haringvliet and during storms from the North-sea. To keep the forces at the river-side door at a minimum, overtopping was allowed. The volumes which overtopped the sluices were thought to be acceptable, meaning that the increase of the water level at the Haringvliet would be limited. The forces on the river doors are also absorbed by the NABLA beam. The combination of the forces from the sea and-river side doors at the NABLA-beam were calculated to almost reach the maximum values the NABLA-beam can resist during stormy weather.

The design of the Haringvliet sluices is accounted for 0.5 metres sea level rise for the design lifetime of 250 years. Recent research shows that the sea level rose on average with 1.86 mm/year in the last century (Baart, 2018). Therefore, since the design of the Haringvliet sluices was finished in 1955, the sea level rose with 11.90 centimetres (2019).

With the sea level rise as found in the last 110 years in Baart (2018), 1.86 mm/year or 0.186 m/century, the included sea level rise of 0.2 metres per century in the design of the sluices will be sufficient. However, if the sea level rises faster the structural safety can not be guaranteed.

In the semi-structured interview with Mr. Spaargaren, he expects that one meter sea level rise is an absolute maximum the Haringvliet sluices can withstand regarding structural safety. The explanation given is that sea level rise cause a larger gradient over the sluices. This is due to the fact that the water level in the Haringvliet does not rise with the same amount as the sea level does. This larger gradient causes larger static forces on the doors which on its turn has an effect on the forces on the NABLA-beam.

The hydraulic forces increase due to the effect of sea level rise. The forces due to waves and their impact on structures depends on a large number of parameters. When assuming the sea bottom, the tidal flats and also the enlarged Maasvlakte do not change in the future, the water level at the North-Sea increses. Meaning that waves contain more energy and reach further or with more energy to the coast. These waves are generated due to high wind velocities at the North-Sea. The energy spectrum due to the larger depth changes. The energy spectrum will shift to a spectrum containing more energy. This means that the wave height and period reaching the coast enlarges. When the waves break at the sea door, the transmission coefficient, as mentioned before, remains quite large. The energy in the waves will therefore apply a larger force on both doors. These forces will at a certain point become to large for the NABLA-beam.

Another problem which could occur due to larger waves and the sea water splashing against the NABLA-beam, is that the concrete will corrode faster. This will decrease the strength of the NABLA-beam. Question is of the concrete NABLA-beam and piers, which is concrete produced in the years 1960-1970, is of good enough quality to withstand this sea water splash water.

From the semi-structured interview with ir. Frank Spaargaren it is concluded that the NABLA-beam is thought not to withstand a sea level rise of 1.0 meter. In the design only 0.20 meter sea level rise per century is included. This means that 0.5 meter of sea level rise (250 years design lifetime) is included in the design. Concluded is that the final lifetime of the Haringvliet sluices concerning strength is reached for a sea level rise of 0.8 meter. This is illustrated in Figure 4.1.

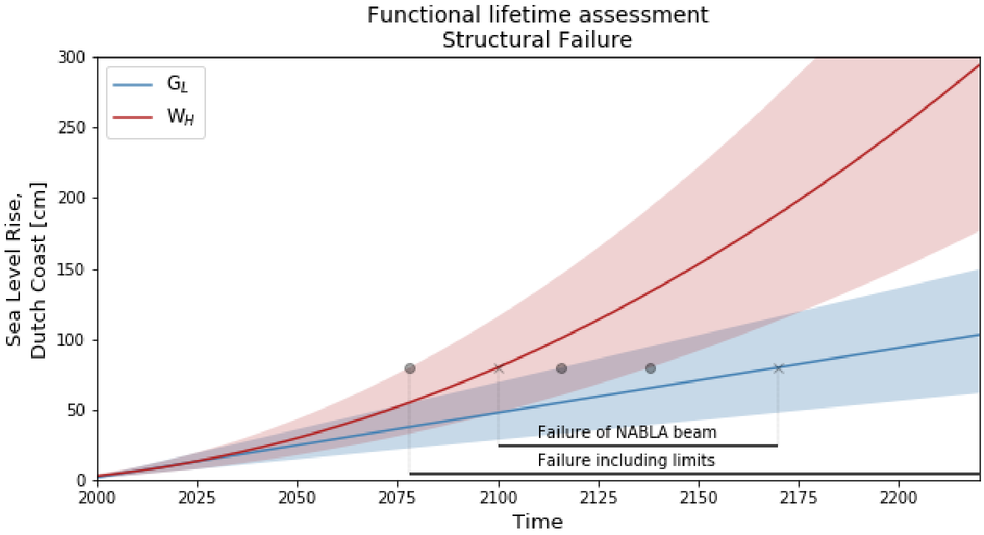


Figure 4.1: The structural lifetime of the Haringvliet is found for a sea level rise of 0.8 meter. Comparing the 50% precentiles (thick lines) of the sea level rise scenarios with 0.8 meter sea level rise, the lifetime is reached between 2100 and 2170.

4.2. Lifetime Concerning: Flood Protection

The effect of the failure mechanisms not opening and not closing is modelled with SOBEK-RE and Hydra-BS. The water levels for the South-Western delta are calculated with SOBEK (WL | Delft Hydraulics, 2008). Three failure mechanisms are included in the SOBEK calculations which are described in Section 4.2.1. Multiple boundary conditions, as described in 3.3, are used for the SOBEK calculations. The (simplified) boundary conditions used for the calculations are described in Section 4.2.1. With the results of the calculations a database is filled which is used as an input file for Hydra-BS (HKV Lijn in Water, 2013). Hydra-BS calculates water levels and their corresponding return periods. Hydra-BS is able to include the effect of certain failure mechanisms of the Haringvliet Sluices, the Europoortkering and the Volkerak-Zoommeer, on the hydraulic loads. This is described more elaborately in Section 4.2.2. The effect on the water levels at the Haringvliet due to the failure mechanism overflow and overtopping of the Haringvliet sluices is described in Section 4.2.3. The hydraulic loads due to the failure mechanism of not opening and not closing on the hinterland are calculated and described in Section 4.2.4. This section ends with a conclusion on the lifetime concerning flood protection in Section 4.2.5.

4.2.1. Results SOBEK-RE calculations

The results of the SOBEK calculations for a single location at the Haringvliet sluice entrance are shown in Figures 4.2, 4.3 and 4.4. The figures zoom in at the time the storm occurs. From these figures, the influence of the boundary conditions and failure mechanisms can be seen.

In the plots in Figures 4.2, 4.3 and 4.4 different water levels and/or river discharges were used at the boundaries. In each subfigure the results of 3 scenarios are plotted: 17 functioning sluice doors, 17 sluice doors which do not close and 17 sluice doors which do not open. The wind direction, climate scenario and configuration of the Europoortkering (closed) are the same for all calculations. The influence of the North-Sea boundary condition is found when comparing the images horizontally (discharge remains the same). When looking vertically through the three images, the influence due to different discharge boundary conditions can be seen (same water level boundary condition).

The influence of not opening and not closing can be seen in these figures. The water level at the entrance of the Haringvliet increases mostly due to the combination of two conditions: the first combination is that the discharge is relatively large and the Haringvliet sluices do not open, the second combination is that the storm is relatively large combined with non closing Haringvliet sluice doors.

The Haringvliet sluices react based on time triggers. If a certain time is reached, the doors are closed or opened immediately, depending on the calculation. For the failure mechanism: 'doors do not open', there is

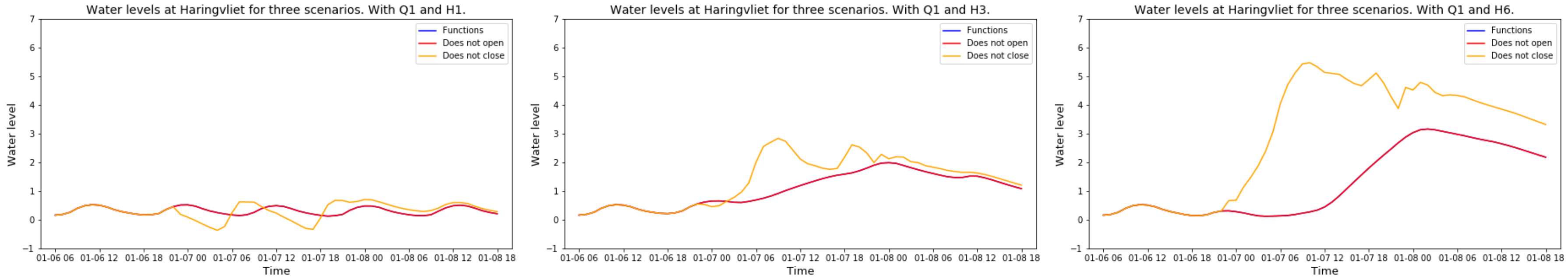


Figure 4.2: River discharge Q1 and waterlevels H1, H3 and H6.

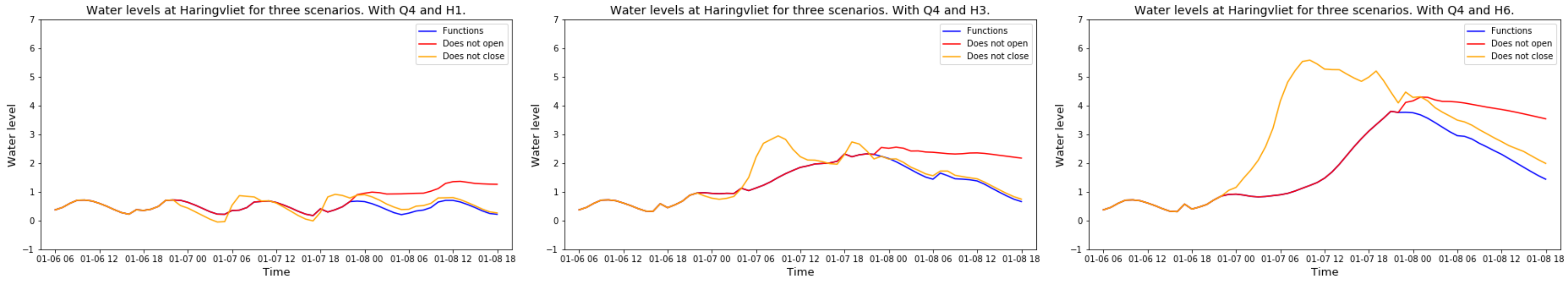


Figure 4.3: River discharge Q4 and waterlevels H1, H3 and H6.

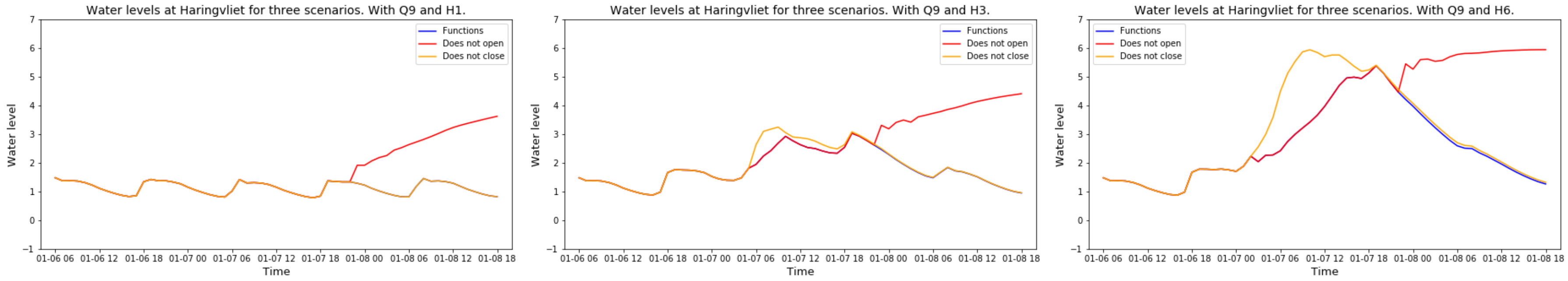


Figure 4.4: River discharge Q9 and waterlevels H1, H3 and H6.

a short period at which the doors open just after the storm (around 01-08 00). Therefore, a sudden drop in the water level is found. The larger the discharge, the more influence this has on the water level. It is thought that the water levels will be slightly larger in case the sluices do not open.

The results of the SOBEK calculations are used to create four databases. The results are split into four databases. The first two databases contain the results from the SOBEK calculations with the climate scenario R2015. The difference between the databases are the number of failing doors, which are respectively 8 and 17. The other two databases contain the SOBEK results with the W2050 scenario with also 8 and 17 failing doors. These databases contain all information needed to execute probabilistic calculations with Hydra-BS. An example of a database is shown in Appendix F.2.

4.2.2. Results Hydra-BS Calculations

As mentioned, the results of the SOBEK-RE calculations are stored in a database. This database is used as input model. The effect on the return periods for water levels in the Haringvliet, the Nieuwe Waterweg, Spui and Hollands Diep are shown by plotting the frequency curves for the locations Hellevoetsluis, Rak Noord, Goudswaard and Maassluis as indicated in Figure 3.15.

To have good insight in the effect of the failure probabilities, three frequency curves are plotted per location. First, the probability for not closing and not opening is set to zero (Faalkans0). Faalkans0 corresponds with the current WBI2017 calculation method. Secondly the probabilities (Faalkans) as can be found in Figure 3.14 are used to calculate the water levels. Third, the failure probabilities of the failure mechanisms of the Haringvliet as shown in Figure 3.14 are multiplied with a factor 10 (Faalkansx10). The frequency lines for the locations indicated in Figure 3.15 are plotted in Figures 4.5 until 4.8. These figures are plotted for the case all the doors (17) work or fail.

Figure 4.5: The return period curves for the location Goudswaard with all sluices failing and the climate scenario R2015.

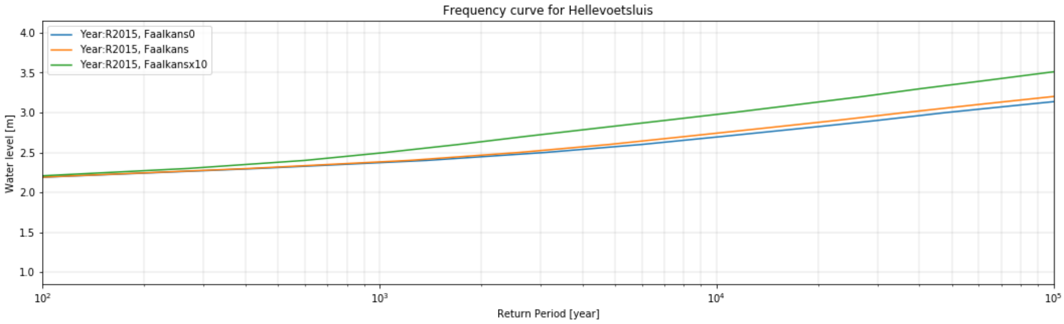


Figure 4.6: The return period curves for the location Hellevoetsluis with all sluices failing and the climate scenario R2015.

Concluded from Figures 4.5 until 4.8, is that the influence of failing sluices only effects the Haringvliet, Spui and Hollandsch Diep. In Appendix F.3 calculations for the scenario with 8 failing doors is shown. When multiplying the required probability with a factor 10, the increase of water level is relatively large from the return period of 10^3 on.

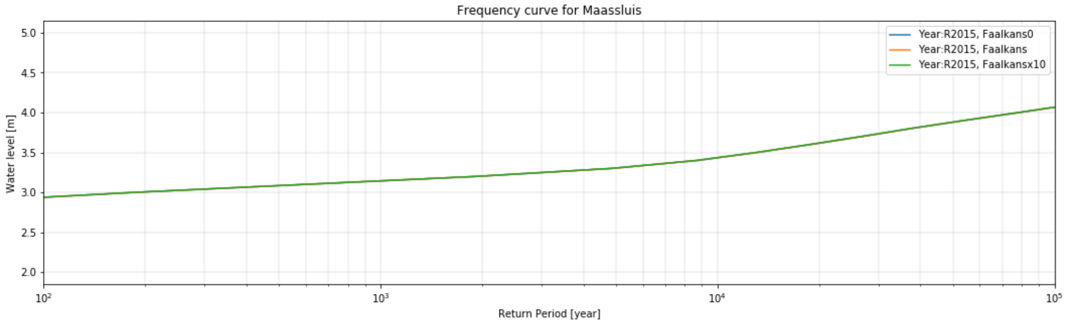


Figure 4.7: The return period curves for the location Maassluis with all sluices failing and the climate scenario R2015.

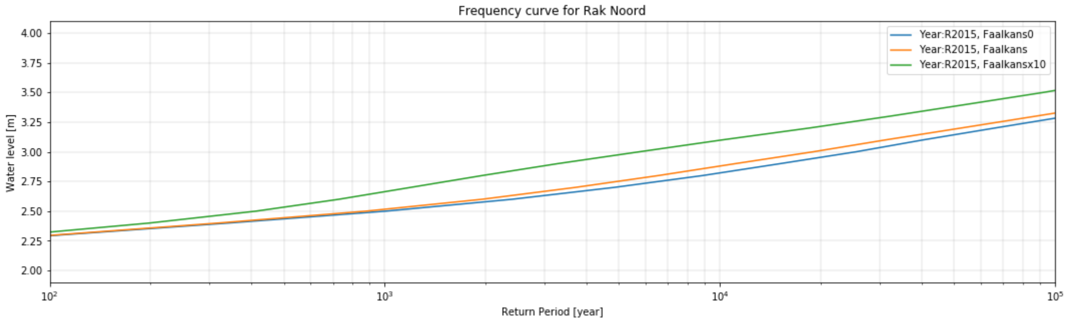
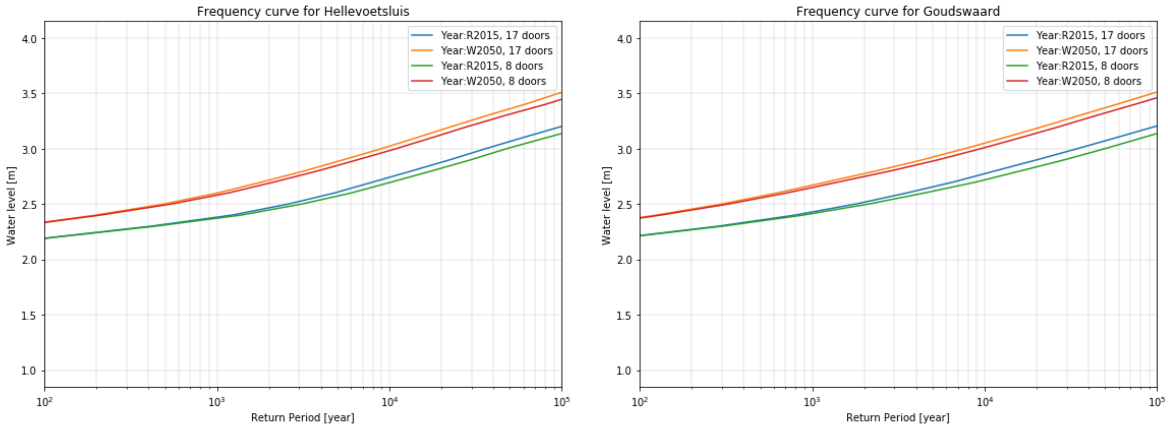


Figure 4.8: The return period curves for the location Rak Noord with all sluices failing and the climate scenario R2015.

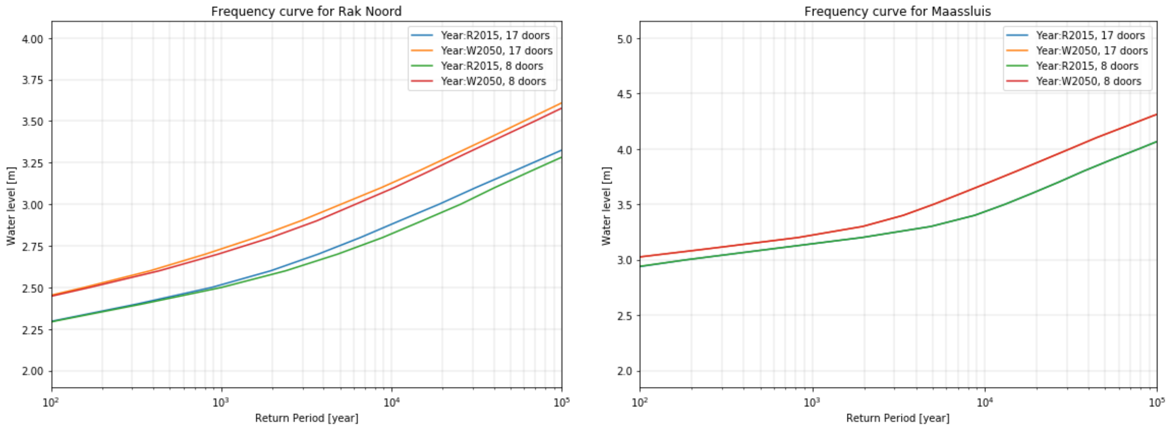
In Goederen (2013) it is concluded that the failure of 1 until 10 doors has a negligible effect on the hydraulic loads. The calculations executed with SOBEK and Hydra-BS confirm this. This can be explained by the required failure probabilities used in the calculations. The failure probability in case of not closing for 6-10 doors (Table 3.3) is smaller than for 11-17 doors, while the effect of 11-17 doors failing is larger. Therefore, the effect on the water levels is mostly influenced by 11 until 17 failing doors.

The water levels and return periods for the same locations as shown in Figure 3.15 calculated with sea level rise scenario 2 can be found in Appendix F.3. The boundary conditions at the North Sea differ with 0.27 meter between scenarios R2015 and W2050 respectively. The water levels including the failure probabilities for the Haringvliet sluices, Tables 3.3 and 3.4, and the failure probability of once per 100 requests for the Maeslantkering with the climate scenarios 1 and 2 are illustrated in Figure 4.9. The differences of each line are the climate scenario and number of failing doors used in the calculation.
In Figure 4.9 the influence of sea level rise and the effect of the failure mechanisms can be found. For the smaller return periods (between 100 and 1000 years), the R2015 and W2050 lines are almost parallel and the 8 and 17 doors failing lines are similar. This means that the failure mechanisms barely influences the water levels and that the differences are caused by the climate change scenarios. The effect of failing doors can be seen for return periods larger than 1000 years. The differences between the red and orange, and green and blue lines show that water levels with 17 failing doors are larger compared to those with 8 failing doors. In case 8 sluice doors possibly fail, the frequency lines remain almost the same compared to a failure probability of 0 as can be found in the previous figures and in Appendix F.3. The effect on the water levels in the south western delta in case 8 doors fail is negligible and is therefore not used further in this thesis. It is therefore also not necessary to iterate further and investigate the effect of less than 8 failing doors.

As mentioned, Hydra-BS does not include model uncertainty. To correspond with WBI2017, model uncertainty needs to be included. Calculations carried out with Hydra-NL including and excluding model uncertainty are compared with Hydra-BS calculations. In the comparison between Hydra-BS and Hydra-NL two factors influence the results. First, there is statistical difference. This means that the input files containing the statistics concerning river discharges, wind directions, wind speeds and other parameters differ for Hydra-NL and Hydra-BS. The statistical difference for the river discharge of the river Rhine are shown in Figure 4.10. The second difference in the calculations method are the databases used for the Hydra-BS and Hydra-NL



(a) Hellevoetsluis (b) Goudswaard



(c) Rak Noord (d) Maassluis

Figure 4.9: Frequency curves generated at four places. Calculated with the required probability of failures from Tables 3.3 and 3.4. The effect on the frequency lines due to the addition of sea level rise (scenarios R2015 and W2050), in combination with failure of 8 or 17 doors.

calculations. The database for Hydra-BS is created from the SOBEK calculations used in this thesis while for Hydra-NL the WBI2017 database is used. More results and differences between Hydra-NL and Hydra-BS can be found in Appendix F.2.

When comparing the Hydra-BS results (the failure mechanisms of the Haringvliet sluices are not taken into account) with the results of Hydra-NL in which model uncertainty is excluded, the results are quite similar. Hydra-NL calculates slightly larger water levels, in the order of centimetres, for return periods smaller than 1000 years. Hydra-BS calculates slightly larger water levels for return periods larger than 1000 years. For return periods larger than 1000 years, the statistical differences of the river discharges, as can be seen in Figure 4.10 could cause these different outcomes.

From Figure 4.10 it becomes clear that the exceedance frequency for large water levels is smaller for Hydra-BS than for Hydra-NL. This results in slightly larger water levels through the south western delta from 1000 years and larger with Hydra-BS.

Concluded from the calculations is that the failure mechanisms not opening and not closing only effect the water level at the hinterland in case all 17 doors fail. The effect on the frequency curves is relatively small and in the order of 2 to 5 centimetre for a return period of 10^{3}. The effect of model uncertainty on the water level is multiple times larger than the effect of the failure mechanism not opening and not closing. Also the influence of sea level rise

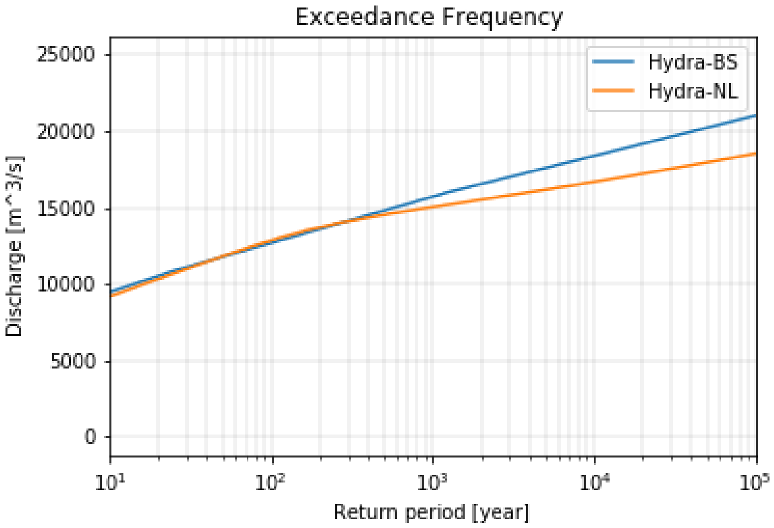


Figure 4.10: Difference of the exceedance frequencies for river discharges of the Rhine which are used for the calculations in Hydra-BS and Hydra-NL.

4.2.3. Overflow and Overtopping of the Haringvliet Sluices

The failure mechanism overtopping and overflow of the sluices is dependent on the water level and waves at the North-Sea and of the height of the sluice doors. The sluice doors at the sea and river side reach until respectively NAP +3.0 and +5.0 meters. The horizontal distance between the doors is circa 50 meters. In Van der Meer (2008) a study is done to the overflow and overtopping volumes of the Haringvliet sluices. Due to the fact that the sea door is NAP +3.0 meter, overtopping and overflow volumes with water levels smaller than NAP +3.0 meter are neglected. The height for which overflow occurs is NAP +5.0 meter with a physical maximum of NAP +6.0 meter due to the bottom of the NABLA-beam (Van der Meer, 2008). However, the energy reduction due to hitting this NABLA-beam is thought to be small and is therefore neglected in the calculations in Van der Meer (2008). It is assumed that when the water level is NAP +3.0 meter or larger the water level between the doors is equal to this water level at sea. In conclusion, the influence of water levels smaller than NAP +3.0 meter are neglected, water levels between NAP +3.0 meter and NAP +5.0 meter can cause overtopping and water levels larger than NAP +5.0 meter cause both, overtopping and overflow.

The sluice doors are designed such that the energy of the waves is reduced by the sea doors. The remaining energy of the waves can reach the retaining doors at the Haringvliet side. The total energy of a wave that reaches the river door is the energy reached at the sea door multiplied with a so called transmission coefficient K_t. The wave height and period used in the following research are respectively 2.5 m and 5.6 seconds. In Van der Meer (2008) the calculations concerning the wave energy, transmission and the effects on overflow and overtopping are executed. A recap with the most important findings are described in Appendix H. The result of the calculations in Van der Meer (2008) is plotted in Figure 4.11.
The red line in Figure 4.11 is a fit through the calculated points and is written as a function of the water level at sea. The equations of the fitted functions are given in Equations 4.1 and 4.2.

wl < 5.0 meter:

$$q = 1.25 \cdot 10^{-6} \cdot wl^{8.5} \tag{4.1}$$

wl >= 5.0 meter:

$$q = 1.25 \cdot 10^{-6} \cdot 5^{7.5} \cdot wl \tag{4.2}$$

In which q is the overtopping quantity (m^3/s/m) and wl is the water level (m).

With formulas 4.1 and 4.2 the overtopping quantities during storms is calculated. Assumed is that the overtopping and overflowing quantities over the whole length of the Haringvliet sluices are equal. The storms as

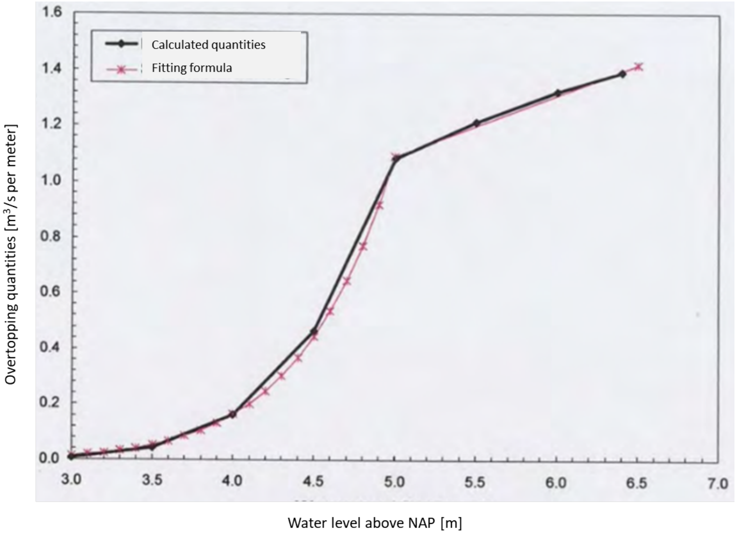


Figure 4.11: Overtopping quantities for the calculated dots (black) and a fitted formula (red), from Van der Meer (2008)

schematized for the SOBEK calculations are used to calculate the total volume overtopping and overflowing the sluices. Assumed is that the influence of the tide levels out and therefore only the water levels of the storms are used (see Figure 3.12 for the schematization of a storm). Further, it is assumed that the overtopping volumes are equally and solely stored at the Haringvliet and do not reach other waterways.

Assuming an equal distribution of the overtopping volume over the Haringvliet the water level increase, Δ h, can be calculated with Formula 4.3.

$$\Delta h = q * B * T / A \tag{4.3}$$

In which:

- B is the width of the sluices, which in this case is the length of all sluice doors together. This is equal to $17 \cdot 56.5 = 960.5$ meters.
- T is the duration that the storm is larger than NAP +3.0 meters [seconds].
- A is the effective storage area of the Haringvliet which is estimated to be 78.21 km^2.

With Formulas 4.1, 4.2 and 4.3 the overtopping quantities and elevation of the water level at the Haringvliet are calculated per storm.

Overflow only occurs for water levels larger than +NAP 5.0 meter. The overflow values are calculated with formula 5.20 from Van der Meer et al. (2018), which is the formula for broad crested structures:

$$q_{\text{overflow}} = 0.54 \cdot \sqrt{g \cdot \left|-R_c^3\right|} \tag{4.4}$$

The storms are schematized as can be seen in Figures 4.12 until 4.19.

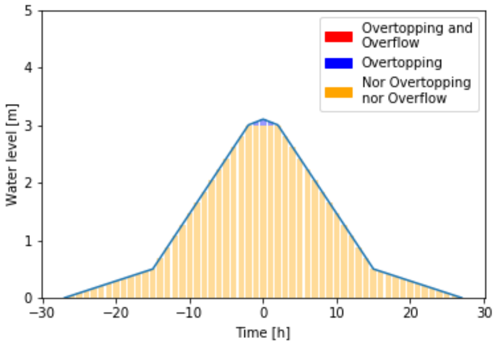


Figure 4.12: Storm of 3.0 meter

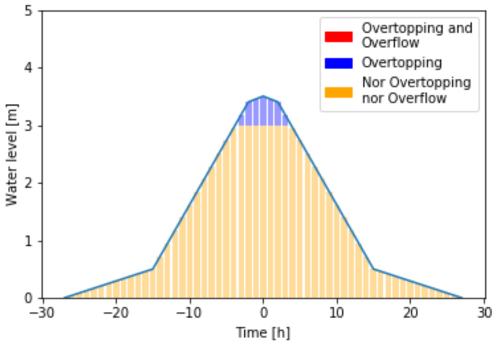


Figure 4.13: Storm of 3.5 meter

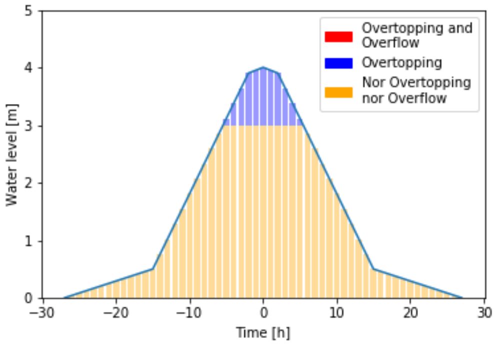


Figure 4.14: Storm of 4.0 meter

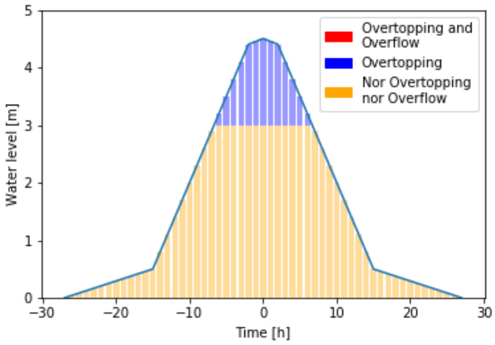


Figure 4.15: Storm of 4.5 meter

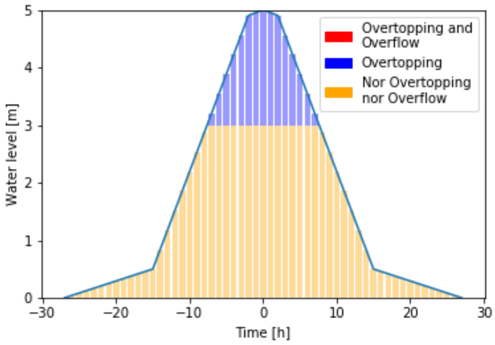


Figure 4.16: Storm of 5.0 meter

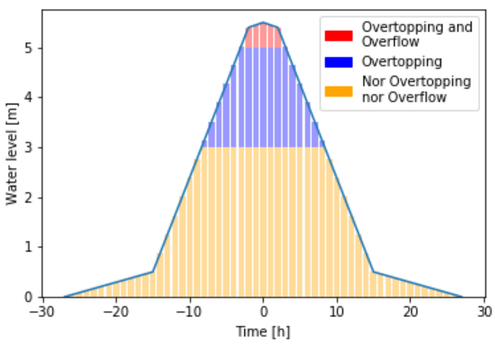


Figure 4.17: Storm of 5.5 meter

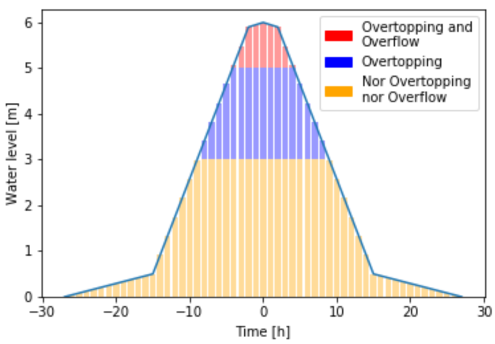


Figure 4.18: Storm of 6.0 meter

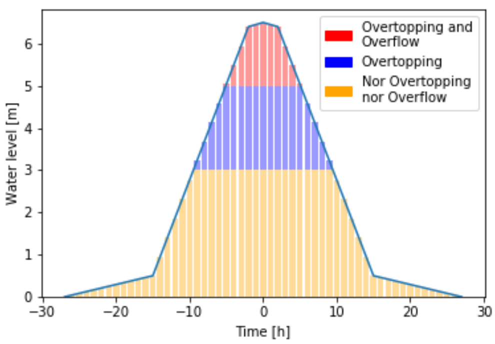


Figure 4.19: Storm of 6.5 meter

The outcome of the overtopping and overflow quantities are shown in Table 4.1.

Table 4.1: Overtopping quantities and elevation of the Haringvliet water level.

Water level NAP +m	Overtopping q [$m^3/s/m$]	Overtopping total [m^3 for storm]	Overflow total [m^3 for storm]	Elevation Haringvliet due to overtopping and overflow volume[m]
3.0	0.006	8.30E+04	0.00E+00	0.0011
3.5	0.039	5.39E+05	0.00E+00	0.0069
4.0	0.155	2.14E+06	0.00E+00	0.0274
4.5	0.448	6.20E+06	0.00E+00	0.0792
5.0	1.057	1.46E+07	0.00E+00	0.1869
5.5	1.182	1.63E+07	8.27E+06	0.3148
6.0	1.286	1.78E+07	2.34E+07	0.5265
6.5	1.351	1.87E+07	4.30E+07	0.7884

If the overtopping volumes increase the hydraulic loads on the is dependent on the water level of the Haringvliet. Overtopping and overflow occur with water levels larger than NAP +2.9 meters. This means that the Maeslantkering and Haringvliet sluices need to be closed. The structures are closed before the storm actually reaches the coast. The water levels at the Haringvliet are therefore mostly effected by the river Rhine and Meuse discharges, the overtopping and overflow volumes over the Haringvliet sluices and by sea water which leaks through the Maeslantkering and Haringvliet sluices. For the Haringvliet sluices, leakage through the doors is neglected because it is assumed to be small. In the SOBEK model, leakage through the Maeslantkering is taken into account and is therefore already included in the Hydra-BS calculations. In the Intermezzo on the next page it is shown what correlation is between the possibility of a large river Rhine discharge and a storm at sea. There is a weak relationship between large river discharges and large sea levels, meaning that the probability that the water level at the Haringvliet increases relatively fast during a storm is relatively small. If the water levels at the Haringvliet are relatively large the elevation of the water level due to overtopping and overflow could lead to flooding.

In Table 4.1 it is shown that $q_{overflow}$ and $q_{overtopping}$ can lead to a large water level increase (Δh) of the Haringvliet. However, the probability that a certain water level is reached is not known yet. For each of the water levels shown in Table 4.1 the return period is calculated and can be seen in Table 4.2. These return periods decrease if the sea level rises.

Table 4.2: Water levels at sea and the return periods for the scenarios R2015 and W2050

Water level, NAP +m	Return Period [year] R2015	Return Period [year] W2050
3.0	10.5	3.3
3.5	64.5	22.8
4.0	382	143
4.5	1,974	799
5.0	9,443	3973
5.5	40,710	18,150
6.0	176,704	77,468
6.5	683,212	405,629

With the return periods as shown in 4.2 and the return period limits of most dike segments around the Haringvliet (1:300 years), assumed is that the overtopping quantities for NAP + 5.0 meters can be seen as guiding. The increase in water level will directly be added to the hydraulic loads. This is a quite conservative approach. Therefore, it is assumed that with larger sea level rise scenarios the addition of 0.187 meter (the elevation due to overtopping and overflow for water levels of 5 meter) is a valid assumption. In the next section this increase is used for the calculation of the overtopping and overflow volumes of the dike segments effected which are the segments around the Haringvliet, Spui and the Hollandsch Diep.

Intermezzo on the correlation between storms at the North-Sea and large river discharges

Questioned is if there is a correlation between the discharge of the river Rhine and the water levels at sea. If there is a positive relation, and the water levels at the Haringvliet are large during a storm, the effect of the overtopping and overflow volumes could lead to floods.

The water level at the Haringvliet is depending on the river discharge and water level at sea. The co-incidence between storm surges and extreme discharges for the Rhine-Meuse Delta is researched in Klerk et al. (2015) and Geerse (2013). It turned out that for a time lag of 6 days between Lobith and Hoek van Holland, the dependency between storm surges and river discharges is largest. The relative discharge for multiple climate scenarios was between 1.1 and 1.35 for respectively 5 and 95 % confidence intervals (Klerk et al., 2015). However, the case without time lag gives a weak relationship. Meaning that a storm and large discharge at the south-western delta are almost independent. Therefore, it is assumed that during a storm Rhine discharges are average (2200 m^3/s*). Therefore, it is assumed that the water levels in the Haringvliet before the storms arrive are normal.*

What must be noted, is that the increase of 18.7 centimetres is quite conservative. Also, taking the increase linearly and adding this directly as a load is a quite conservative approach. It is unlikely that for both, the sluices and the dike segments, the most unfavourable conditions occur at the same time. The most unfavourable wind direction leading to largest overtopping volumes is for the sluices is not the most unfavourable wind direction for most dikes segments. In the following section the hydraulic loads of the dike segments effected are calculated. It is assumed that dike segments allow 1 l/s/m. In some cases dike segments could withstand 10 l/s/m or larger. However, 1 l/s/m is more conservative and will therefore be used in the hydraulic load calculations.

4.2.4. Overflow and Overtopping of dikes around the Haringvliet

The effect of not opening and not closing is only visible in the frequency lines for the area around the Haringvliet, Hollandsch Diep and Spui. A new databases containing all the locations at the edges of these waters is made, as shown in Figure 4.20.

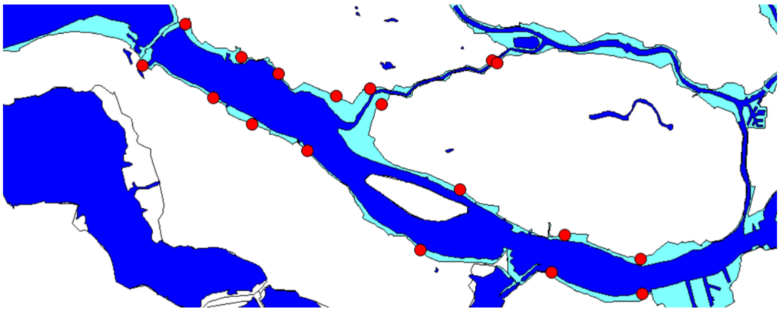


Figure 4.20: Locations used to calculate the hydraulic loads and the corresponding height for the dike bodies

Compared to the water level calculations made in the previous sections, these databases contain depths and fetch lengths for all directions. Also dike segments are coupled based on their location. The dike profiles used for the assessment of overtopping and overflow are VNK profiles. To have good insight in the effect of sea level rise and the effect of failing sluices it is assumed that the locations as shown in Figure 4.20 represent the whole area. The locations shown are all part of dike rings 20, 21, 25 or 34.

The overtopping calculations are carried out with the following failure probabilities of the structures:

- Probability of not closing Maeslantkering: 1/100
- Probability of not closing Haringvliet Sluices: 1/5,000
- Probability of not opening Haringvliet Sluices: 1/10,000

These are consistent with the probabilities of not closing of all 17 sluice doors (Section 4.2.2).

The only failure mechanism assessed is the failure mechanism of overtopping and overflow. This is in fact not the only mechanism which could lead to failure of the effected dike rings, 20, 21, 25 and 34. The potential failure mechanisms and their probabilities are shown in Appendix G. While the other failure mechanism have larger probabilities, chosen is to only assess the dikes on height for overtopping and overflow. Failure of the Haringvliet sluices leads to larger hydraulic loads. Other failure mechanisms such as piping and instability are not assessed because it is thought that for these failure mechanisms the effect of larger hydraulic loads is not the only factor causing failure. These mechanisms occur if certain revetment types or certain soil conditions are available. In further research the effect of the Haringvliet sluices on these failure mechanisms needs to be looked into.

In the calculation with Hydra-BS only the failure mechanisms overtopping and overflow are incorporated directly. The influence of model uncertainty and the effect of overflow and overtopping of the sluices are not incorporated in the Hydra-BS calculations. Therefore, the hydraulic loads calculated with Hydra-BS are transferred to a spreadsheet in which the hydraulic loads are increased due to the effect of model uncertainty and overtopping and overflow. The outcomes of the spreadsheet calculations can be found in Appendix F. Concluded is that the dike assessment concerning overtopping and overflow for all locations shown in Figure 4.20 are all satisfied for both 1 and 10 l/s/m as allowable overtopping quantities. All locations satisfy concerning overtopping and overflow for both R2015 and W2050 and for both 1 and 10 l/s/m.

With a sea level rise of 35 centimetres the requirements concerning flood risk are still fulfilled. Therefore, the results are extrapolated until a certain amount of sea level rise for which the requirements are not fulfilled any more. The effect of sea level rise and the failure mechanisms of the Haringvliet sluices is calculated. For each location a ratio is calculated what the influence of 1 centimetre sea level rise has on the hydraulic load. This ratio is used to calculate for which sea level rise amount two segments need to be increased with 0.2 meter. In Appendix F the outcomes are shown. It turned out that with a sea level rise of 0.87 meter 2 dike segments need to be reinforced with 0.2 meter. This result is found by trial and error.

4.2.5. Conclusions Hydraulic Loads and Failure Mechanisms

From the frequency curves in Figures 4.5 until 4.8 it can be concluded that the failure mechanisms not closing and not opening of the Haringvliet sluices do not influence the water levels at the Nieuwe Waterweg.

At the other locations, the lines (Faalkans) compared to no failure (Faalkans0) differ slightly from a return period of 1000 years and larger. The differences are relatively small and in the order of centimetres. For a failure probability 10 times larger than required (Faalkansx10), the effect compared to 'Faalkans' is visible from a return period of 100 years and larger. Here the effect is in the order of decimetres. This means that the probabilities, for a large number of failing doors, have quite an influence on the hydraulic loads.

The current probability requirements for not opening and not closing of the Haringvliet sluices lead to a small increase of water levels, especially for return periods larger than 1000 years. If the probabilities for not opening and not closing turn out to be larger, the effect increases in the order of decimetres.

The effected dike rings, 20, 21, 25 and 34 are assessed for overtopping and overflow, for the scenarios R2015 and W2050. In these calculations, the overflow and overtopping volume over the Haringvliet sluices is also taken into account. All the assessments were positive, meaning that for the climate scenarios R2015 and W2050, including the failure mechanism not opening and not closing and overtopping over the sluices, the dike heights are sufficient concerning the failure mechanism overtopping and overflow. See Appendix F.4 for the calculations.

With the current sea level rises in the SOBEK and Hydra-BS calculations, the final lifetime is not reached. To assess on the final lifetime, the hydraulic loads are extrapolated, including larger sea level rise levels. With trial and error, it is found that for a sea level rise of 0.87 meter the requirements are not met any more, see Appendix F.4. In this calculation assumed is that all the other parameters are kept constant. When extrapolating to the requirement that two dike segments should be 0.2 meter too low, the sea level should rise with 0.87 meter. For the overtopping volumes of 1 and 10 l/s/m respectively 0 and 5 of the 18 dike sections will not meet the dike height needed. From the five segments not meeting the requirements 2 dike segments need to be increased by 20 centimetre or more.

With the 0.87 centimetre sea level rise and both, the W_h, and G_l sea level rise scenarios, the remaining lifetime including the bandwidth for these scenarios, is shown in Figure 4.21.

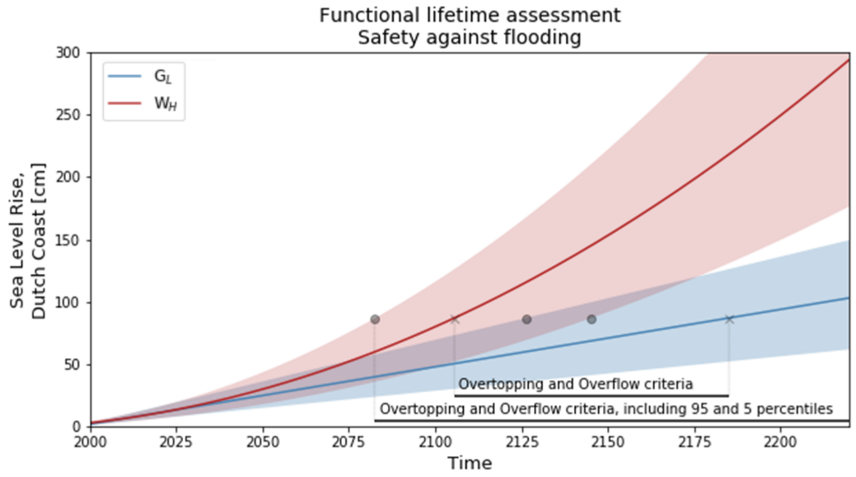


Figure 4.21: The functional lifetime assessment for the function of flood risk is based on the KNMI-2014 scenarios G_l and W_h which are derived for the Netherlands. The intersection of the 50% percentile lines of G_l and W_h with a sea level rise of 0.87 meter is respectively in the years 2185 and 2106. This concludes the lifetime concerning flood risk due to the failure mechanisms and the influence of sea level rise for the Haringvliet Sluices.

4.3. Lifetime Concerning: Fresh Water Availability

The intrusion of salt water via the sluices can become problematic for the fresh water availability as already mentioned. The Kierbesluit as shown in Paalvast (2016) and the KNMI2014 climate scenarios are used to assess the Haringvliet sluices on the function of fresh water availability. The assessment is based on historic data, research to the Kierbesluit and results from available measurements and simulations. The currently available models which model salt (intrusion length) concentrations show relatively large differences compared to measurements. The well-working models are expensive, relatively complex and hard to calibrate. Due to a lack of sources chosen is to assess the lifetime concerning the fresh water availability qualitatively.

Multiple water intake locations are relocated to make it possible to open the sluices during high tide. With the Kierbesluit, the west-side of the Haringvliet may become saline. The requirement concerning water quality, is that water eastwards of the imaginary line Middelharnis-Spui may not contain 300 mg/l chloride or more. The water quality of the rivers Rhine and Meuse are not included in the assessment. The Kierbesluit is based on Paalvast (2016) and results from measurements as described in Jacobs et al. (2003). Adjustments can be made, because the actual Kier is based with a 'learning on the job' method.

Properties influencing the salt intrusion length via the sluices are described in the literature study in Section 4.3.1. The influence of climate change on the salt intrusion length via the Haringvliet Sluices is based on logical reasoning and a literature research. The results are described in Section 4.3.2. Another potential mechanism which could lead to a long time exceeding the 300 mg/l chloride limit, is backward salt intrusion. Backward salt intrusion is intrusion via the Nieuwe Waterweg which reaches the Haringvliet via the Spui. This phenomena is treated and explained in Section 4.3.3. The conclusion on the lifetime is based on the requirement as mentioned above and is described in Section 4.3.4.

4.3.1. Theory Salt Intrusion

The quantities of salt water flowing into the Haringvliet is dependent on multiple properties. The most obvious properties are: the flow area (summation of all the flow areas under all the doors) and the water level difference between the Haringvliet and sea. Therefore, the boundary condition of the river discharges upstream are of importance too. I In the next section some theory concerning discharge, salt intrusion and velocities are given.

The equation to calculate discharge is written as:

$$Q = B \cdot h * v \tag{4.5}$$

With the conservation of energy, the discharge under the gate is described with the submerged underflow equation, as shown in Equation 4.6.

$$\mathrm{Q_t} = \mathrm{B} \cdot \mu \cdot \mathrm{a}\sqrt{2.\mathrm{g} \cdot \Delta \mathrm{h}} \tag{4.6}$$

With Q_t the total discharge per opening [m^3/s], B the width of the sluice opening [m], a the height of the opening of the door [m], Δ h the water level difference between the North Sea and Haringvliet [m] and μ the discharge coefficient [-]. This discharge coefficient is dependent on the flow regime under the doors. This coefficient is used as a constant and is not further researched in this thesis.

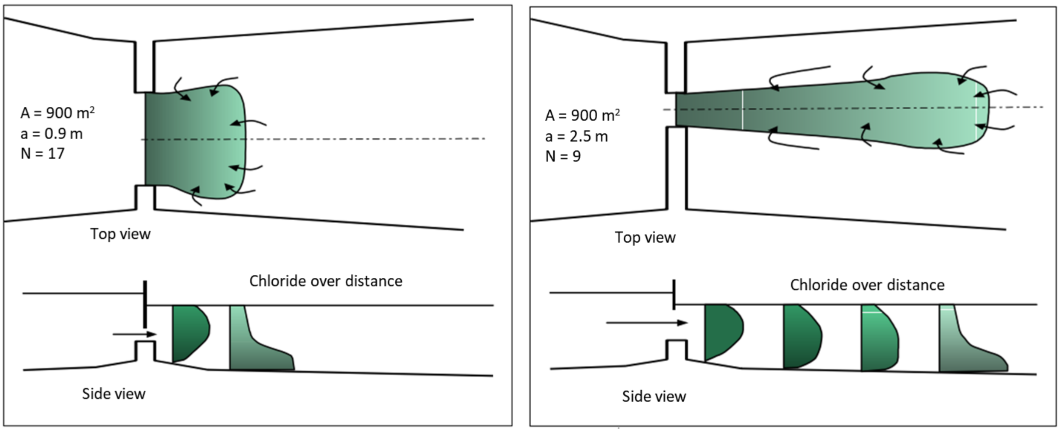
The average flow velocity under the door, v_{sluice} [m/s], can now be written as $\sqrt{2 \cdot g \cdot \Delta h}$ from Equation 4.6 (Jacobs et al., 2003). From the continuity equation, the velocity further upstream (in the direction of the Haringvliet) can be calculated. The discharge in the Haringvliet, not affected by the door any more, can be written as shown in Equation 4.7.

$$Q = B \cdot h_{Haringvliet} \cdot v_{upstream} \tag{4.7}$$

When equalling Equation 4.6 and 4.7(assuming the discharge remains the same), the velocity upstream can be expressed as shown in Equation 4.8.

$$v_{upstream} = \left(\frac{\mu . a}{h_{Haringvliet}}\right) \cdot \sqrt{2 \cdot g \cdot \Delta h} \tag{4.8}$$

Concluded can be from Equation 4.8 that the velocity upstream of the sluices is linearly dependent on the height of the sluice opening. Meaning that the more a certain door is opened, the further the salt will intrude. In Figure 4.22 this is schematically shown. The flow areas of the sluices are the same, but the height of the doors differs per opening. Less openings with larger height leads to further intrusion lengths.



(a) Small opening per door, 17 doors are opened.

(b) Large openings per door, 9 doors are opened.

Figure 4.22: The effects on the number of sluices and their opening schematically shown. Also over the depth and length the chloride concentration, from (Jacobs et al., 2003).

However, in the analysis above, multiple mechanisms which play a role in the salt water distribution are not taken into account yet. Density differences, river discharge, flow velocity, the tides and other diffusion phenomena are not taken into account. Depth variations are also not been accounted for, which is an important parameter for salt intrusion (Wijsman et al., 2018).

It is known that the salt water is heavier than fresh water. In Figure 4.22 the bottom images show the chloride concentration over the water column. Because the flow velocity at the Haringvliet side is in downstream direction (to the left) and the sea water is flowing in an upstream direction (to the right), the lighter fresh water flows over the heavier salt water. In between the fresh and salt water a mixing zone forms. In the mixing zone the density is larger than fresh water but smaller than salt water. At a certain point the forces due to density differences and flow velocity reach an equilibrium. Due to the relatively fast changing river discharge and water level difference due to the tide, the intrusion length changes constantly.

In March 1997, measurements to velocities and chloride concentrations have been carried out. Multiple configurations and openings of the sluices were tested as described in Jacobs et al. (2003). The measurements were carried out during 9 tide periods. The sluices were constantly opened with an opening of 900 m^2. The tide at the Haringvliet from the North-Sea is characterized with periods of high and low tide of respectively 4 and 8 hours per tide-period.

The river discharge, tides and configuration of the Haringvliet sluices during these measurements are shown in Figure 4.23.

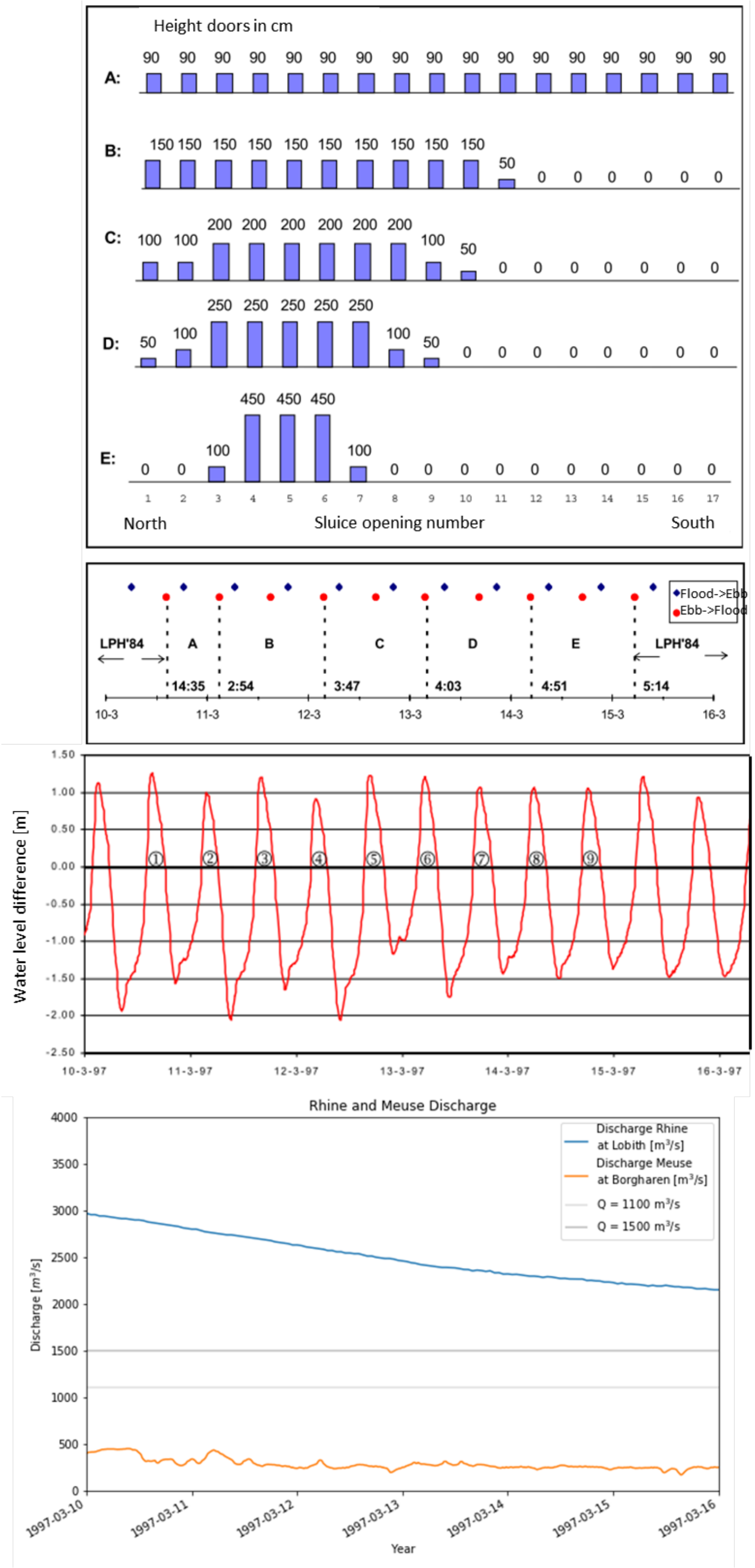


Figure 4.23: The conditions during the measurements, figures from (Jacobs et al., 2003) and data from (Rijkswaterstaat, 2017c). The top figure shows the height of each door, shown from North to south. The second figure shows which sluice regime (A-E) was used during each period. The third figure shows the water level **difference** between the Haringvliet and the Sea (positive means sea level is larger compared to Haringvliet). The last image shows the river discharges over the period of time, retrieved from (Rijkswaterstaat, 2017c).

Concluded in Jacobs et al. (2003) from the field measurements is that with the discharges and water levels during the tests, the velocity near the bottom is larger during low tide than during high tide. The maximum velocities are found for larger sluice openings and are largest during the high-tide-periods. Maximum velocity measured at the sluices during low tide and high tide are respectively 1.5 and 3.6 m/s for an opening of 4.5 meter of the sluice doors. The maximum height the doors were opened was 4.5 meter as shown in Figure 4.23. These velocities were measured when the water level differences were largest (Jacobs et al., 2003). In Appendix I a more elaborate description about the measurements and results found in Jacobs et al. (2003) is given.

The chloride concentrations were measured during 9 tide periods. The measurement locations are shown in Appendix I. There are no measurement found at the entrance at Spui. Closest measurement to the imaginary line between Middelharnis and Spui are buoys 3 Noord and South and Poles 5 North and South. The results of the measurements of poles 5 are not given in Jacobs et al. (2003). From the measurements of buoys 3 can be concluded that the salt water intrudes further with less openings with a greater height of the door, as shown in Figure 4.22b. The salt concentration exceeds the 300 mg/l chloride limit the last day of the measurements. The limit is exceeded at a water level of NAP -1.0 meter which is in the top of the water column. At larger depths, from NAP -9.0 meter, the concentration exceeds the limit constantly since the 13th of March, (Jacobs et al., 2003). That the concentrations are exceeded can be explained by the fact that the doors are constantly open for multiple days. Another explanation is that at the 13th of March the configuration of the sluices leads to the largest intrusion lengths. The influence of the river discharge can be significant. The larger the discharge, the more pressure acts on the sea water intruding into the delta. The discharge of the river Rhine decreased from 2900 to 2200 m^3/s during the tests. This means that less pressure against the incoming North-Sea was given. The salt intrusion length is measured and shown in Table 4.3.

Table 4.3: The intrusion lengths measured during the measurements as in Jacobs et al. (2003).

Date	**Intrusion Length measured at North side of Haringvliet [km]**	**Intrusion Length measured at South side of Haringvliet [km]**
March 10 1997	3	2
March 11 1997	11	6
March 12 1997	12	8
March 13 1997	12	10
March 14 1997	13	10

With the distance from the Sluices to the line Middelharnis-Spui being respectively 13 and 12 kilometre at the north and south bound, the chloride limit is exceeded at the North bound at the 14th of March. From this research it is concluded that with large openings of a small number of sluices leads to relatively large intrusion lengths. The influence of the river discharge can also be seen in the results of Table 4.3 in combination with Figure 4.23. About the relative water level not too much can be said, because the conditions were quite during the measurements.

To conclude on the fresh water availability, information about the frequency the sluices can be opened is needed. In Paalvast (2016) the percentages the Haringvliet sluices can be opened per month is calculated. This is shown in Figure 4.24. The opening of the sluices is solely based on the river discharge of the Rhine. To open the sluices, the discharge must be equal or larger than 1200 and 1500 m^3/s during low and high tide respectively (Noordhuis, 2017).

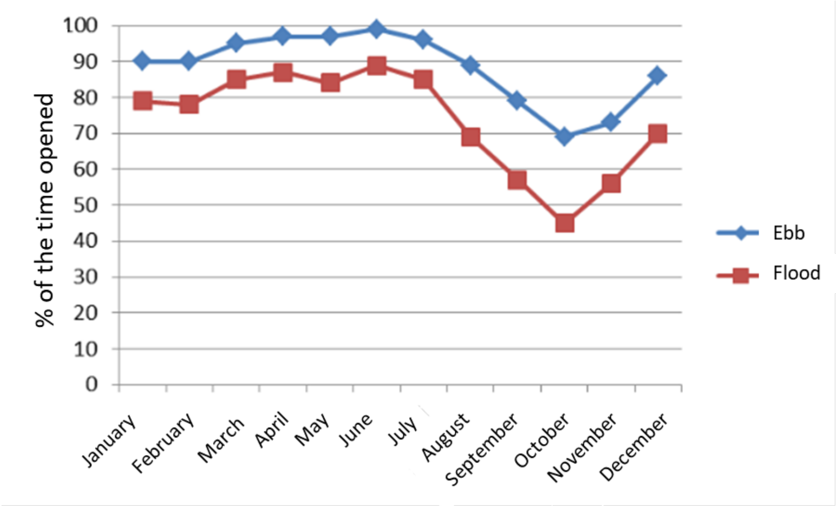


Figure 4.24: The percentages per month for which the sluices can be opened during low tide and high tide for a discharge of respectively 1200 m^3/s and 1500 ^{3}/s. Translated from (Paalvast, 2016)

The probability that the sluices can be opened is largest in the first 6 months of the year, until July. This is due to larger river discharges in the beginning of the year. In the months from July until October the average discharge reduces and thus the probability that the sluices can be opened reduce too. The data in Figure 4.24 is obtained by analysing a simulation on river discharges from 1900- 2010, Figure 4.25.

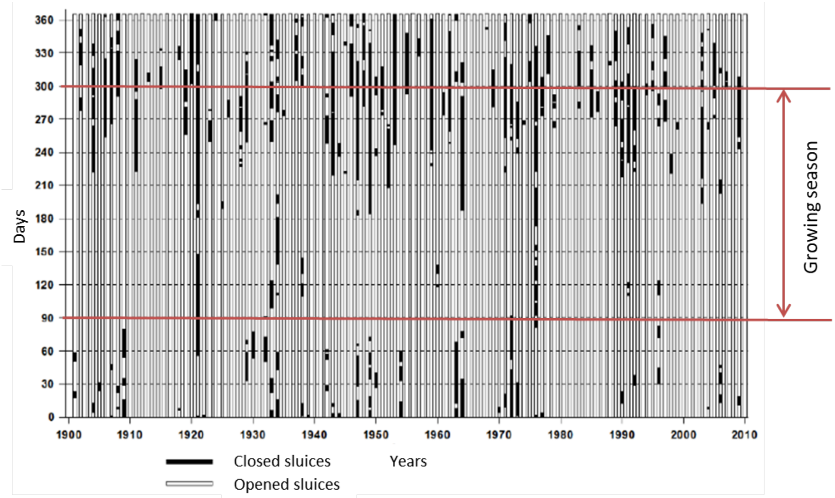


Figure 4.25: Simulation when the sluices could be opened based on historic river discharges and low tide and high tide. The sluices can be opened during low tide if the discharge is larger than 1100 m^3/s and during high tide if larger than 1500 m^3/s. In this figure the growing season is said to be from April until the beginning of November. Translated from (Noordhuis, 2017).

In Figure 4.25 it is shown that there are large periods for which the sluices can not be opened. On average, the daily average discharge at Lobith is lower than 1500 m^3/s 5 times per year with an average duration of 20 days (Noordhuis, 2017). It can be concluded that during those periods the discharge was smaller than 1100 m^3/s. Otherwise the sluices could have been opened during low tide.

As a check, zoomed in is at the Rhine discharge of the years 1920-1925. In Figure 4.25 it becomes clear that the sluices were closed for a long time in the year 1921. With discharge data obtained from Rijkswaterstaat (2017c), ^{3}/s, it can be concluded that the Rhine discharge in the year 1921 was most of the time smaller than 1500 m^3/s and also lots of time smaller than 1100^3/s. The simulation carried out gives a good indication of the frequency the sluices can be opened with the Kierbesluit.

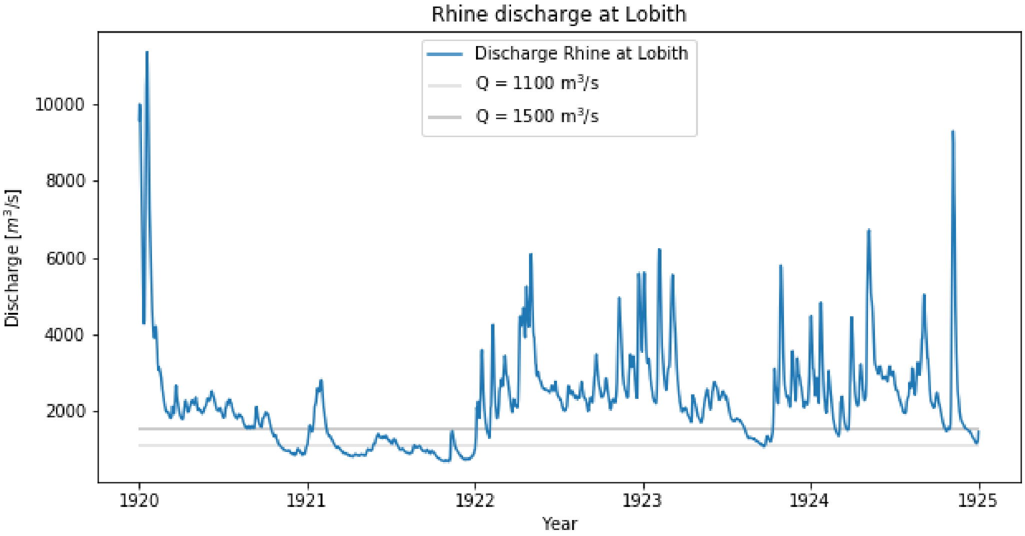


Figure 4.26: Rhine discharges between 1920 and 1925, obtained with data from Rijkswaterstaat (2017c).

4.3.2. Expected Lifetime due to Salt Intrusion

The effect of climate change on the frequency the sluices can be opened and the effect on salt intrusion is not investigated in Noordhuis (2017) and Paalvast (2016). Climate change is expected to effect the discharge distribution of the river Rhine (IKSR et al., 2015). It is expected that Rhine discharges will become more extreme. Meaning larger discharges in the hydrological winter and smaller discharges in the hydrological summer. The lower discharges in the hydrological summers lead to more frequent closed sluices during both low and high tide. Larger discharges in the winter increases the frequency of both low and high tide. However, the average discharge in the winter is currently around 2900 m^3/s which means that the sluices would already be opened (Bruggeman and Dammers, 2013). From the researches of Paalvast (2016), Noordhuis (2017) and Jacobs et al. (2003) in combination with climate change, the following can be concluded:

- Due to climate change and the expected change in river discharge over the year, expected is that the percentage the doors may be opened reduces compared to the percentages shown in Figure 4.24.
- Following from the conclusion above, it is expected that during hydrological summers the consecutive time the sluices must remain closed, increases.
- The water level difference over the sluices increases the intrusion length. Sea level rise will lead to larger intrusion lengths.

Intermezzo: Assumptions

The above is all concluded by assuming that the sluice doors are directly triggered by the river discharge at Lobith and the condition (low tide or high tide) at the North Sea. In reality, the decision about the opening is more complex. The water level at sea (not only if it is low tide or high tide), the water level at the Haringvliet and the intrusion length at the Nieuwe waterweg play a role in the actual flow area chosen. Therefore, the regime can be chosen such, that the salt intrusion lengths for both the Nieuwe Waterweg and Haringvliet will be within limits.

When following the Kierbesluit as shown in Figure 3.8 which is used in Noordhuis (2017, 2018); Paalvast (2016); Wijsman et al. (2018), it is expected that with the current Kierbesluit, the limit of 300 mg/L chloride at Middelharnis-Spui can be guaranteed. With a changing discharge over the year, the frequency and in which period the sluices remain closed will change. However, the chloride limit at Spui-Middelharnis will not be exceeded due to another discharge distribution over the year.

The only parameter influencing the salt intrusion length is the larger water level difference over the sluices. Sea level rise leads to larger water levels at sea. The water levels at the South-Western delta will increase with percentages of 40 until 100 % of this sea level rise. For the Haringvliet until Middelharnis, the sea level rise is followed with a percentage of about 50%. This means that for every centimetre sea level rise the difference over the sluices increases with about 0.5 cm. Therefore, a relatively large amount of sea level rise is needed to exceed the chloride limit with the current Kierbesluit.

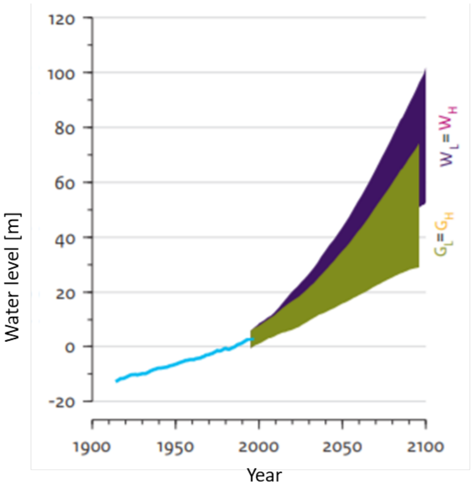


Figure 4.27: The KNMI14 scenarios G and W. From (Tank et al., 2015)

A combination which could cause the salt concentrations to exceed is:
A relatively large (negative) water level difference when the sluices are opened. The sluices remain open for a certain amount of time (e.g. days), the water levels at sea are relatively large, with a wind coming from the north-west, and a relatively small Rhine discharge (larger than 1500 m^3/s, otherwise the sluices will be closed).

An estimation on the lifetime is made, based on the measurements and conclusions mentioned. It is assumed that with a **sea level rise of 1.0 to 1.5 meter**, the salt intrusion lengths will become too large for the current Kierbesluit and chloride limit. Expected is that the intrusion length will be reached under the following conditions:

- Sea level rise of 1.0 to 1.5 meter
- Relatively long period of Rhine discharge between 1500 and 2000 m^3/s.

4.3.3. Backward Salt Intrusion

In the analysis above, only salt intrusion via the Haringvliet sluices is taken into account. The Haringvliet sluices (and other structures upstream) regulate the discharge distribution between the Nieuwe Waterweg and Haringvliet. If the discharge at the Nieuwe Waterweg is too small and the water level at sea is relatively large, it is possible that salt intrudes the Nieuwe Waterweg and will reach the Haringvliet via the Spui.

The influence of a different discharge distribution during the year and sea level rise cause that salt is able to intrude further into the Nieuwe Waterweg (Huismans, 2016). Backward salt intrusion into the Haringvliet is caused by low river discharges, relatively large water levels at the coast due to winds (Huismans, 2016). Backward intrusion via the Nieuwe Waterweg occurred several times between 1990 and 2005 as shown in Huismans (2016). From these events shown in Huismans (2016) it can be concluded that closing the Haringvliet sluices does not avoid backward salt intrusion. As a rule of thumb, the hydraulic properties that cause backward intrusion is as follows (Huismans, 2016):

- Water level at Hoek van Holland > NAP +1.5 m.
- $Q_{\text{Rhine upstream}} < 1500\ m^3/s$
- Water level difference between Hoek van Holland and Moerdijk > 1.0 m.
- Water level during high tide at Hoek van Holland must be 0.3 m larger compared to the previous high tide.

For both, salt intrusion via the sluices and backward salt intrusion, climate change will lead to a (more) frequent exceeding of the chloride limit. In the analysis coming from Huismans (2016) and the report of Haasnoot et al. (2018) the measurements and models show that the influence of sea level rise leads to larger chloride intrusion lengths. The measurements and models show the results for the concentration of 500 mg/l. In the models an average river discharge of 2200 m^3/s is included. For the 300 mg/l limit and lower discharges during hydrological summers, the intrusion length increases significantly. With the current Kierbesluit and looking at future sea level rise and river discharges, it is estimated that with a **sea level rise of 0.5 meter**, backward salt intrusion will become a structural problem every year during the summers. When considering the

50% probability lines for sea level rise scenarios for the Netherlands (thick lines in Figure 4.28) 0.5 m. sea level rise is reached between 2073 and 2104.

However, backward salt intrusion can not be avoided by another regime of the Haringvliet sluices and will therefore not be taken into account during the assessment and decision on the final lifetime of the Haringvliet Sluices.

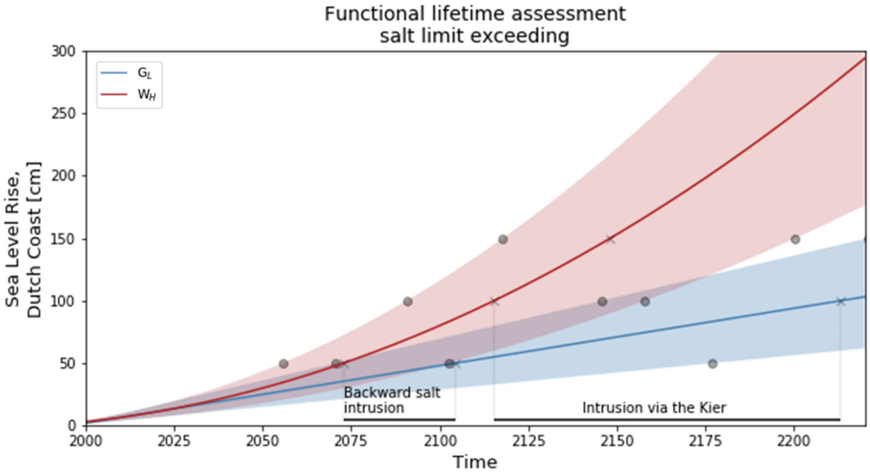


Figure 4.28: The functional lifetime assessment for the function of fresh water availability. The assessment is based on the KNMI scenarios W_h and G_l, which are derived for the Netherlands. Both scenarios are extrapolated until 2200.

Salt intrusion through the sluices will probably occur with a sea level rise of 1.0 to 1.5 meters for the current Kierbesluit. For the sea level rise scenarios chosen, the function of fresh water availability will be lost between 2115 and 2210, see Figure 4.28.

4.3.4. Conclusion: fresh water availability

The Haringvliet sluices are not able to avoid backward salt intrusion. The requirements may not be met, but this is not due to the failure of the Haringvliet sluices. It is therefore chosen to take only the assessment of salt intrusion via the Haringvliet sluices itself into account. The final lifetime for salt intrusion is estimated to happen with a sea level rise of 1.0 to 1.5 meters and will therefore be reached between 2115 and 2213. Considering new strategies, backward salt intrusion should be taken into account.

4.4. Lifetime Concerning: Ecology

The Haringvliet sluices are designed and built in a period in which most ecological processes were not considered during the design phase. In the Haringvliet sluice design some fish passages have been built. These passages are built through the piers of the sluices. It turned out that these fishing passages are mostly used by fresh water fish which swim to the sea without returning (Kemper, 1997).

In the reports (Noordhuis, 2018) and (Wijsman et al., 2018) multiple possibilities on how to use the Haringvliet sluices beneficially for the ecology are suggested. Multiple discharging programs are suggested. The effect of the previous LPH'86 program, the current Kierbesluit and other programs are investigated. These other programs are:

- Larger openings of the sluices which creates a tidal effect of 80 centimeter on the Haringvliet.
- Use the Haringvliet sluices as storm surge barrier (SSB).

In Noordhuis (2018) prognoses are given for the Kierbesluit and the effect on the fish migration. Almost all fish species profit from the Kierbesluit, except the fresh water species. Some fish species only profit from the Kierbesluit if there is a larger tidal effect on the Haringvliet. The tidal effect will not significantly change due to the Kierbesluit and thus concluded is that the Kierbesluit functions as a corridor for migratory fish from sea to river (Noordhuis, 2018).

In Noordhuis (2018) it is also concluded that with tidal effects fish will be able to create spawning areas, living areas and growing areas at the Haringvliet and further upstream. The other variants suggested create a tidal effect which will be beneficial for some a larger range of fish species. In this section the corridor function will be assessed. The effect climate change has on the frequency the sluices can be opened is investigated. These frequencies are compared with species which use the Kier for migrating from sea to the Haringvliet.

Most mentioned goal of the Kierbesluit by Rijkswaterstaat is to attract species like the salmon (zalm) and sea-trout (zeeforel) to the Haringvliet. However, in Reeze et al. (2017), a research of WWF, all migratory fish specified at the migratory calender benefit from the Kierbesluit. In this thesis investigated is which fish species from the calender benefit from the Kierbesluit. Started is with the ones mentioned above.

When looking at the fish migratory calender, see Appendix I, most fish migrate from sea to the Haringvliet in the first six months of the year. The time a fish specie wants to migrate from the Haringvliet to the sea differs per specie. Looking at the fish migratory calender some species need brackish water to migrate. With the current Kierbesluit this brackish water is flushed to the sea during low tide and therefore these species can not survive. Also other species at the bottom, which can not adapt to the large concentration differences over the year, can not survive. Species preferring brackish water are therefore not assessed.

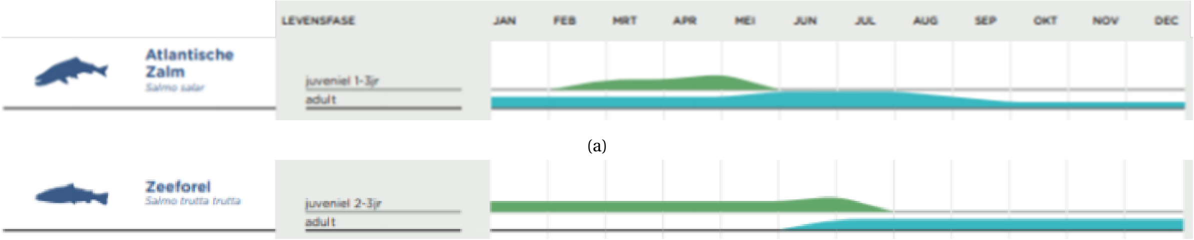
The time a fish species can migrate is compared to the percentage of time the sluices can be opened each month. From Figure 4.24 it can be seen that with the Kierbesluit the percentage of time the sluices can be opened, is relatively large during the winter. In the hydrological summer the sluices will be closed for a larger amount of time. This is due to the river Rhine discharge which changes over the year.

During low tide the species migrate from the Haringvliet to the North sea and during high tide vice versa. Fish are not able to swim against the relatively large flow velocities under the sluices. The percentages the sluices can be opened during high tide are therefore used when fish species want to migrate from the North Sea to the Haringvliet and the percentages the sluices can be opened during low tide are used for the migration to the North-Sea.

First the fish species mentioned by Rijkswaterstaat are assessed. The sea-trout (Zeeforel) is able to migrate from river to sea in the first 7 months of the year (green) and from sea to river in the last 7 months of a year (light-blue), see Figure 4.29b. Comparing the frequency the Haringvliet sluices can be open, Figure 4.24, with the times the sea-trout wants to migrate, Figure 4.29b, the sea-trout is able to migrate in both directions throughout the whole year. The percentages the sluices are closed in the summer are relatively large during high tide but the sea-trout largely benefits from the Kierbesluit and is most of the time able to migrate upstream. Concluded is that the Kierbesluit with the river discharge distribution and water levels over the last century are beneficial for the sea-trout.

The atlantic-salmon (Atlantische Zalm) is able to migrate seawards in the period February-May (green) and the upstream migration period is all year round (blue), see Figure 4.29a. The migration seawards is mostly dependent on the percentage the Haringvliet sluices can be opened during low tide. When looking at the months February until May in Figure 4.24, the sluices can be opened between 90 and 98% of the time during low tide. Concluded is that the Kierbesluit with the river discharge distribution and water levels over the last century are beneficial for the atlantic-salmon.
When comparing migration times of other species (see migration calender from Reeze et al. (2017) in Appendix I), with the frequencies the sluices can be opened (Figure 4.24), the migration towards the Haringvliet (during high tide) in the months August until December are most critical. The white fish (houting), sprat (sprot), river lamprey (rivierprik) and the atlantic herring (atlantische haring) are migrating fish which migrate during (a period of) August until December. The effect climate change has on the distribution of the river discharge of the Rhine throughout the year will influence the frequency the sluices can be opened.

The percentages the sluices can be opened in Figure 4.24 is extracted from a simulation in which 110 years of river Rhine discharges are used. The 110 years of river Rhine data corresponds to the reference ('Referentie') scenario as plotted in Figure 4.30. In this figure the expected monthly average river discharges of the Rhine is



(a)

(b)

Figure 4.29: The fish migration calender for the salmon and sea trout. With green the migrating months from river to sea and light-blue from sea to river. From www.haringvliet.nu .

plotted for multiple KNMI2014 scenarios. It can be seen that for 2050 and 2085 the average discharges at Lobith in the months November until May remain the same or increase compared to the reference situation for all KNMI2014 scenarios. In the months June until October the average discharge mostly decreases compared to the reference situation. Except for the G_l scenario, here the discharge remains almost the same. From these scenarios it can be concluded that the percentages the sluices can be opened will change. However, it is unknown with what quantities the lines as shown in Figure 4.24 will change.

When looking at the scenario W_H, the river discharges in the month September (2050) and September and August (2085) will on average be lower than 1500 m^3/s. For the scenario G_l the monthly average discharge does not fall below 1500 m^3/s. 1500 m^3/s can be seen as the critical discharge for which the sluices can be opened during high tide.

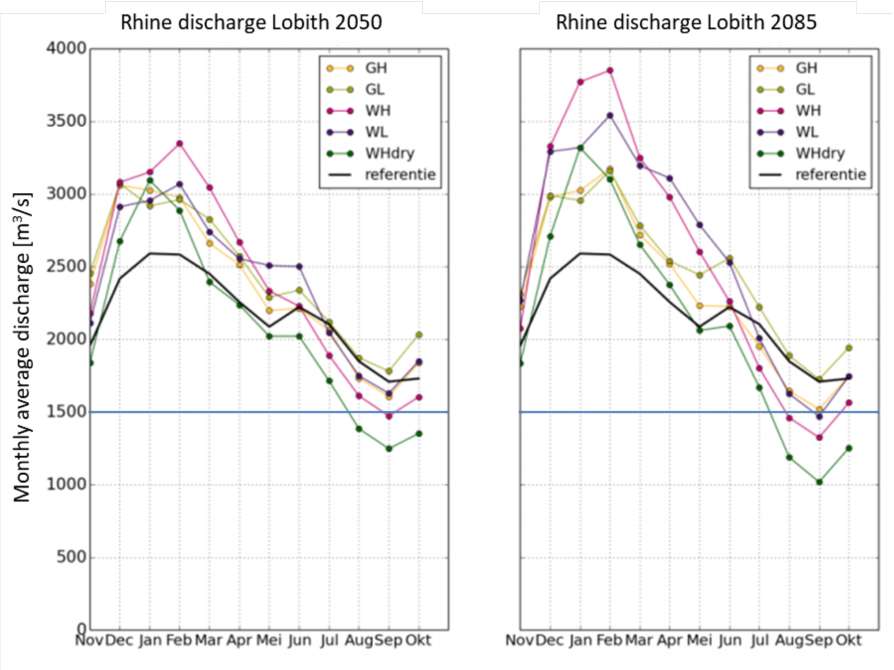


Figure 4.30: Expected average river discharge per month for the year 2050 and 2085, from (Klein et al., 2015).

When assessing ecology based on the mean river discharges per month as shown in Figure 4.30. This is used in combination with the research of Noordhuis (2017). In Noordhuis (2017) it is concluded that the discharge at Lobith is on average 5 times per year lower than 1500 m^3/s with an average period of 20 days. The longest closure simulated found in the simulation is 49 days (Figure 4.25).

The average monthly discharge scenarios as shown in Figure 4.30 are used to assess if species could migrate during the periods these fish species want to migrate. These periods are shown in the migration calender. The reference scenario is the current situation. Combining this with the fish migration calender, the migrating species can migrate in the months as can be seen in Table 4.4 for the most extreme climate scenario.

Table 4.4: Fish Migrating calender with the current Kierbesluit. Comparing the Rhine discharges with the frequencies the Haringvliet sluices could Kier for the scenario WHdry. For the GL scenario the results of this table would be the same in the years 2120 and 2160.

Specie	**Months to migrate Current situation**	**Potential months to migrate Future situation, 2050. Most extreme situation**	**Potential months to migrate Future situation, 2085. Most extreme situation**	**Decrease in months**	
				2050	**2085**
Atlantic Salmon	All year round	All year, except: August until November	November until July	12 to 9	12 to 8
Sea Trout	June until January	June, July, November and December	June, November and December	7 to 4	7 to 3
White fish	October until January	November and December	November and December	3 to 2	3 to 2
Sprat Larve **Sprat Adult**	May and June October and November	May and June November	May and June November	- 2 to 1	- 2 to 1
River Lamprey	October until April	November until April	November until April	6 to 5	6 to 5
Atlantic Herring	November until July	November until July	November until July	-	-

The function the Haringvliet sluices fulfil concerning preserving and stimulating the migration of fish can not be fulfilled for all migratory fish any more in case of the most extreme climate scenario as can be seen in Table 4.4. First of all, it is very likely that the sluices can not be opened for 50 consecutive days every year in case of the more extreme climate scenarios. Second, in case of the extreme scenarios, not all species are able to migrate upstream for at least 50 % of the time as indicated in the migration calender. The results in Table 4.4 show that the time sea-trout and sprat (adult) can migrate decreased with at least 50% of the months compared to the current situation. The requirements concerning ecology will not be met in case of the most extreme scenario, around 2050. When extrapolating the trend the river discharge scenario G_l follows, the average discharges in the summers become slightly lower and the average discharges in the winters will increase significantly. Assuming that this trend continues linearly, which based on the expected global warming as shown in Appendix C is a valid assumption, it is estimated that around the year 2160 (GL) the criteria concerning ecology can not be fulfilled any more. In Figure 4.31 the time line is shown when the function of Ecology can not be fulfilled any more.

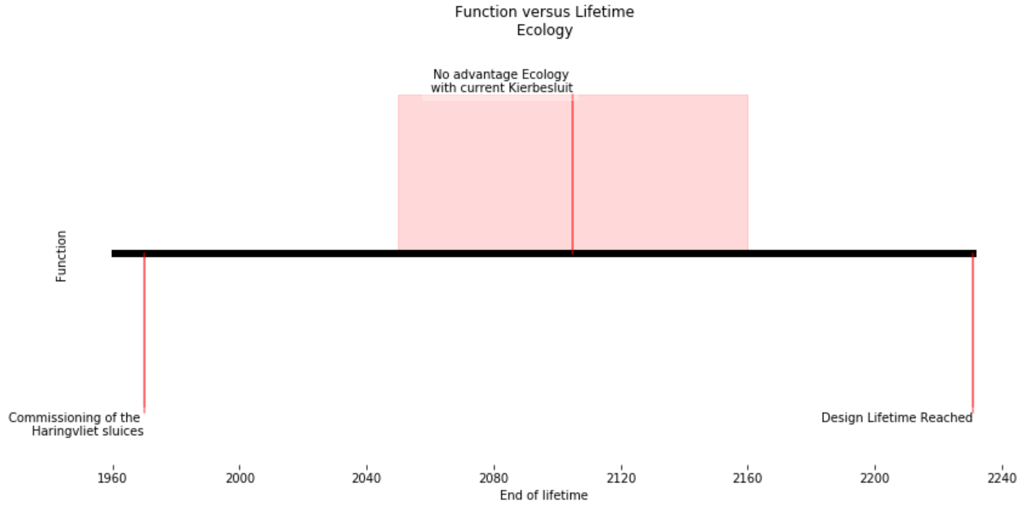


Figure 4.31: The ecological function of the Haringvliet will be lost in the period of time as shown in this time line.

4.5. Final lifetime assessment

From the assessments carried out, the research question: **which (failure) mechanisms or requirements from the stakeholders is firstly not met?** is answered. The time-line in Figure 4.32 summarizes all the outcomes of the analysis from the previous sections. It turns out that the advantage for the ecology and structural failure can occur in this century in case of an extreme climate change scenario. The ecological function is lost first in case of both, extreme and mild, climate scenarios. Another research question is also answered by the time line as shown in Figure 4.32. The question: **when will the Haringvliet sluices be at the end of its lifetime for the climate scenarios chosen?** is answered as shown in both Figure 4.32 and Table 4.5. The lifetime per function and climate scenario is shown and indicates the end of the lifetime of the Haringvliet sluices.

Table 4.5: The Haringvliet Sluice lifetime per climate scenario and function.

Function **Climate scenario**	**No Advantage Ecology**	**Fresh Water Availability**	**Flood Protection**	**Structural Failure**
$\mathbf{W_h}$	2050	2115	2105	2100
Average	**2105**	**2165**	**2145**	**2135**
$\mathbf{G_l}$	2160	2210	2185	2170

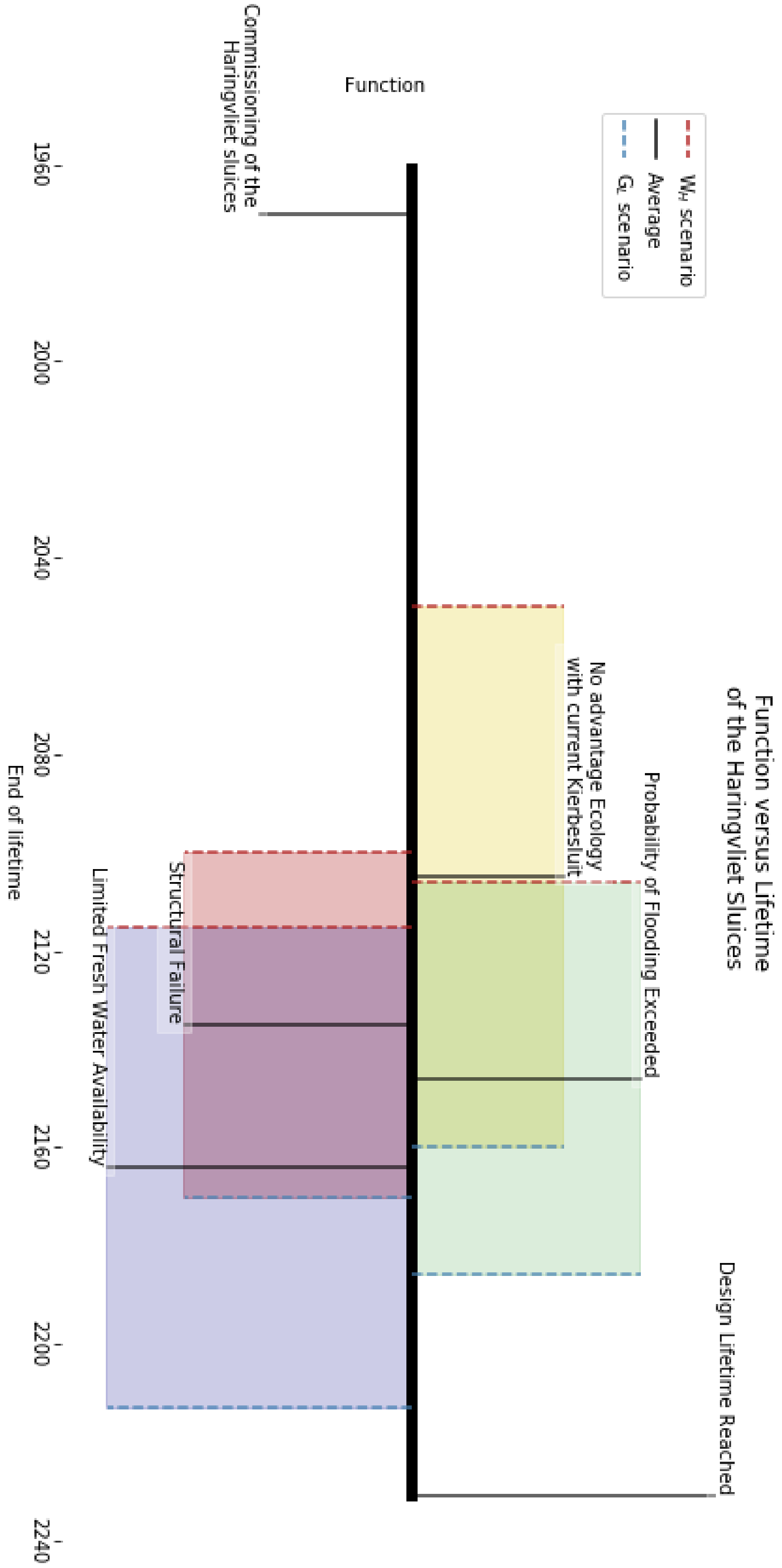


Figure 4.32: All the functions and their estimated lifetime based on climate scenarios plotted in a time line. With the black lines being the average of the 50% percentiles for the sea level rise function for each function.

4.6. Life Time Extending Measures

With the current Kierbesluit the sluices will not meet the requirements for stimulating the fish migration in the Haringvliet around the year 2050 in case of the W_h scenario. Research question to answer is: which measures can be implemented to extend the lifetime of the sluices? To extend the lifetime, the ecological requirements must be met again. An option to extend the lifetime is to optimize the Kierbesluit. Because the fresh water availability requirements and ecological requirements thrive with opposite conditions it is assumed that with an optimized Kierbesluit the lifetime concerning fresh water availability reduces inversely proportional to the increase of the lifetime concerning ecology. This is schematically shown in Figure 4.33.

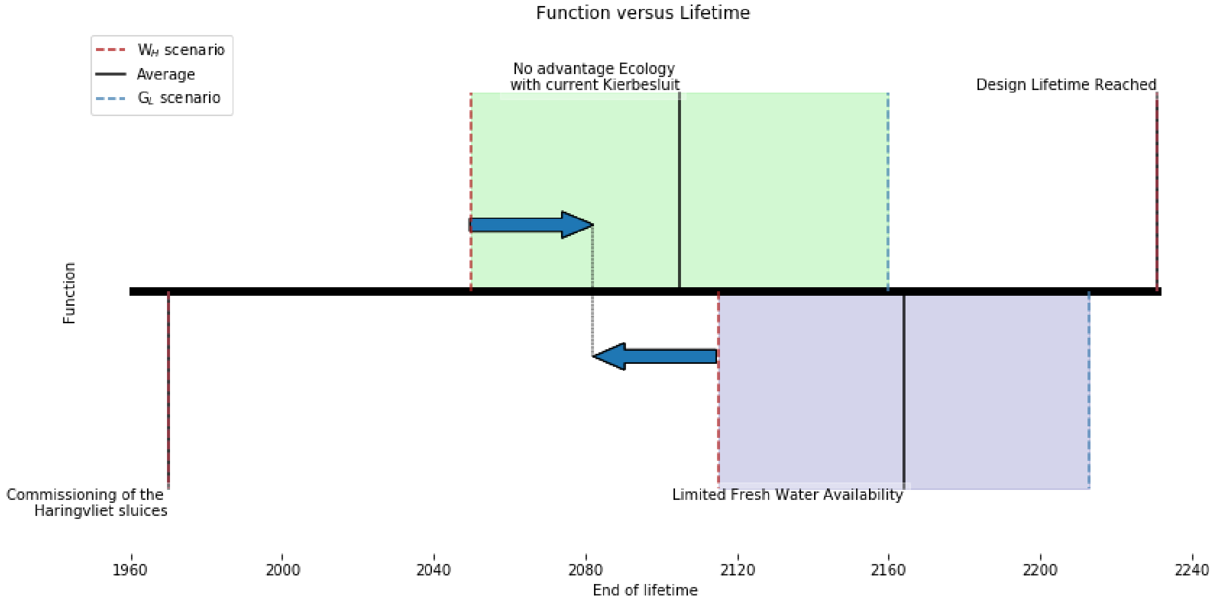


Figure 4.33: Schematically shown of the enlargement of the lifetime for ecological purposes, which will decrease the lifetime of the fresh water availability.

The proposed strategy to extend the lifetime is to change the current Kierbesluit. The best way to open the sluices is not known. With the measurements which are currently done at the Haringvliet, the Kierbesluit can be optimised. The Kierbesluit must be adjusted such that during high tide the sluices open for smaller discharges compared to the current threshold level of 1500 m^3/s. This results in a longer periods for which the species (see Table 4.4) are able to migrate. The sluices need to be closed during storms to avoid too large intrusion lengths. When opening the sluices for a smaller river discharge it is also expected that the sluices will not be closed for 50 consecutive days.

However, in case of the most extreme climate scenario the chloride concentration at the water intake points at Spui-Middelharnis will sometimes exceed the limit during hydrological summers due to backward intrusion. With the old program for which the sluices were closed during high tide, backward intrusion occurred several times. It is therefore not likely that the Haringvliet sluices are able to decrease the backward intrusion frequency. For a certain sea level rise, expected is in the order of 1 meter (Haasnoot et al., 2018), backward salt intrusion will reach the Haringvliet yearly.

With a new Kierbesluit as mentioned above the lifetime of the sluices becomes as shown in Figure 4.34. This time line is guiding from now on.

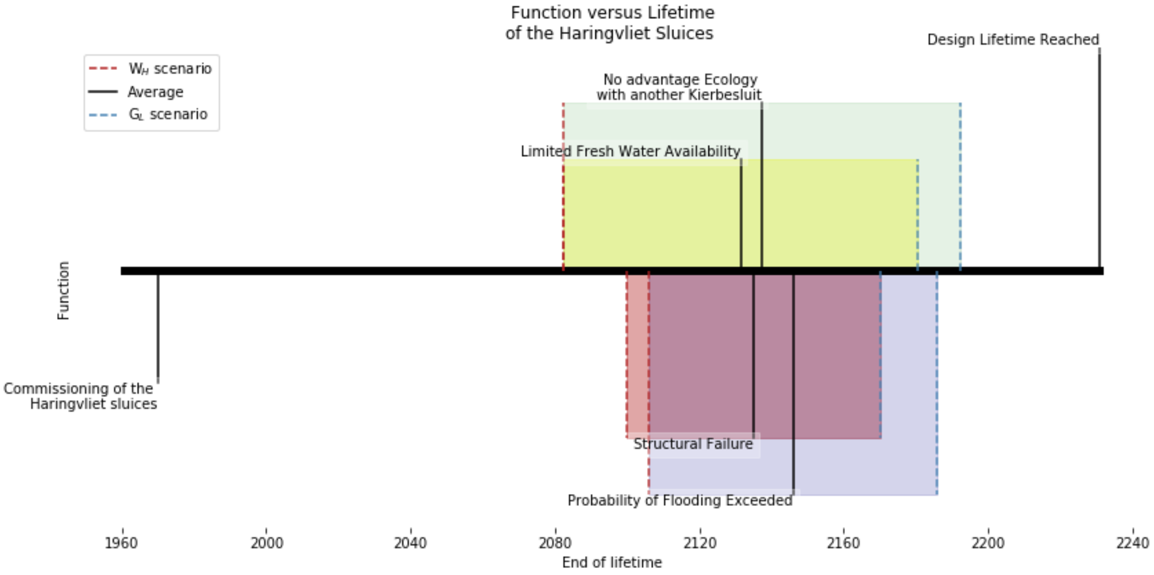


Figure 4.34: Expected life time of the Haringvliet sluices with an optimized Kierbesluit. The function for the availability of fresh water decreases due to a larger intrusion length and thus a larger probability the chloride limit is exceeded.

From Figure 4.34 the following objective is answered:

Which (failure) mechanisms or requirements from the stakeholders are not met after applying lifetime extending measures?

With an optimised Kierbesluit the fresh water availability and ecology still fail first for the scenario W_h. To extend the lifetime, multiple other measures can be taken. These measures can be of social or engineering nature. Examples of lifetime extending measures are:

- Remove the fresh water intake points more upstream.
- Create a fish passage or fish sluices at the Haringvliet and use the old discharge program (closed during high tide)
- From a social point: chosen can be to have no ecological benefits or to use water that contains more chloride which is used to create drink water or is used for the agricultural and industrial businesses.

In case of an average climate scenario, the black line in Figure 4.34, it can be seen that all failure mechanisms are accumulated around the year 2140. In that case, the sluices also fail structurally. It is therefore necessary to come up with new strategies for which the Haringvliet sluices will be replaced by another structure, removed or closed of. For these new strategies, the effect on the whole south-western delta must be thought of.

5

Strategies for the Haringvliet

In this chapter functional strategies for the Haringvliet are developed. In the first section the new boundary conditions, functions and requirements which new functional strategies must fulfil are described. In the section following, Section 5.2, multiple functional strategies are developed. The developed strategies will be verified. The verified strategies will be evaluated and eventually a conclusion on the final proposed functional strategy are described. This is described in Sections 5.2 until 5.5.

5.1. Boundary Conditions, Functions and Requirements

In the first subsection the boundary conditions which the functional strategies have to deal with are described. A description of the functions the conceptual designs have to deal with is given in the second subsection. This section ends with a requirement description.

5.1.1. Boundary Conditions

The boundary conditions for the functional strategies are different compared to the current boundary conditions. In the most extreme scenario the final life time is reached for the functions ecology and fresh water availability around the year 2080, see Figure 4.34. Structural failure occurs 20 years later, around 2100, in case of this most extreme climate scenario. Multiple solutions can be thought of to overcome these 20 years as described in Section 4.6. Questioned is if this is economically beneficial.

The lifetimes for all the functions in case of the average climate scenario are not met in a clustered time span between the years 2130 and 2150, see Figure 4.34. This includes the failure mechanisms of structural failure. Therefore, the starting point for the functional strategies is that the sluices need to be replaced or removed. Because all functions are lost, measures to extend the lifetime are not considered. This also includes the structural lifetime. Extending the lifetime is thought to be economically not feasible in case all functions are lost. Also, structural failure leads to failure of the NABLA-beam which is unrepairable.

The year 2130 is taken as starting year for the functional strategies. In case a new structure is built, it is assumed that this structure has a design lifetime of 100 years. Therefore, the boundary conditions should include the conditions which are relevant for the year 2230. Because this is more than 200 years from now, it is hard to imagine what the boundary conditions will be. This long term brings large uncertainties within these boundary conditions. The variants $\mathrm{G_l}$ and $\mathrm{W_h}$ show in 2230 a sea level rise of 1.1 and 3.2 meter respectively compared to the current situation.

For the river discharge of the river Rhine and Meuse no predictions for the years further than 2100 are found. Using the river Rhine predictions for the year 2100, the average discharge will almost remain the same (Lenderink et al., 2007). In case of the most extreme scenario, the discharge in the summers decreases with 30% while the discharge in the winters increases with 40% (Lenderink et al., 2007; Klein et al., 2015). This is largely due to global warming. Expected is that these values will respectively decrease and increase even more in the future.

Considering the global warming scenarios as found by the IPCC, see Appendix C, global warming increases until the year 2150 for scenarios RCP4.5 and RCP6.0. For the IPCC scenarios RCP2.6 and RCP8.5 global warming continues until the years 2060 and 2250 respectively. Therefore, it is expected that the river Rhine discharges in the year 2230 are even more extreme compared to the KNMI'14 scenarios as shown in Figure 4.30. When extrapolating the monthly mean discharges for the scenario W_H, which is derived from the IPCC RCP8.5 scenario, it is thought to have an average discharge in the summer in the order of 400/500 m^3/s, during the winters the average will be in the order of 4500 m^3/s. Also the most extreme discharge is expected to increase (e.g. from 17,000 to 19,000 m^3/s). However, the probability that these extreme discharge reach the Netherlands is relatively small because with discharges larger than 16,500 m^3/s dikes in Germany, between Wesel (Germany) and Lobith, will overflow (de Vriend et al., 2016). For the G_l scenario, which is less extreme than the RCP2.6 scenario, the average discharges will be in the order of 1400 and 3600 m^3/s for respectively the hydrological summer and winter.

The boundary conditions for an actual design are important and must be more accurate than the above mentioned possible conditions for multiple scenarios. The boundary conditions mentioned above are used as guidelines for the functional strategies given in Chapter 5.2.

5.1.2. Functions

The functions for the Haringvliet area are thought to remain the same as can be found in Section 2.2 and Figure 2.2. The same three functions, flood protection, fresh water availability and ecology are mostly focussed on. The functions: navigation, accessibility and recreation have become important for the region and are kept in mind during the verification of the functional strategies.

5.1.3. Requirements

Most requirements as used for the assessment of the current Sluice complex remain the same. With the relatively new Kierbesluit introduced and the current growth of interest in ecology it is assumed that the requirements concerning ecology can change and become more important. Paalvast (2016), Noordhuis (2017), Noordhuis (2018) and Wijsman et al. (2018) all conclude that the ecology can increase and benefit more from the Haringvliet if there would be a larger tidal effect. However, safety is thought to be the most important requirement.

The most important requirements for the new strategies remain the same as for the assessment of the current structure. Some requirements, mentioned in Chapter 3, are added to the requirements used for the assessment of the current structure. The requirements are summarized here:

- The stability, strength, maintainability, adaptability and constructibility of the structure(s) must be guaranteed. However these are not calculated, it must be thought of, meaning that the designs must be structurally feasible.
- Water at the intake points may not contain more than 300 mg chloride per litre.
- The hydraulic loads the dikes and structures of the hinterland must be within the boundaries as described in Ministerie van Binnenlandse Zaken (2018).
- Fish species must be able to migrate from the North-Sea to the Haringvliet and Nieuwe Waterweg migrating more upstream. Therefore, all fish species must have 50% of the time as indicated in the migration calender, see Appendix I, to migrate upstream.

All the requirements are coming from the same stakeholders as already mentioned. The opportunities for the ecology are important for all the stakeholders. Other stakeholders which have large power and/or interest, like Rijkswaterstaat, Waterboards, Provinces and Municipalities, are interested in improving the ecology, but their main priorities are the availability of fresh water and safety against floods (Rijkswaterstaat, 2016).

5.2. Developing Functional Strategies

In this section the functional strategies are proposed. In the first subsection the proposed functional strategies are described. In the subsections following each functional strategies is explained with expectations concerning fulfilment of the requirement. In Section 5.3.4 the functional strategies are verified based on logical reasoning and little data. The verified strategies are evaluated with the use of a multi criteria evaluation in Section 5.4.

5.2.1. Functional Strategies

In this section functional strategies are developed. The functional strategies always incorporate the fact that the current Haringvliet sluices structurally fail. The functional strategies proposed in this thesis contain only a small selection of potential solutions. Societal changes, changes in requirements and other factors have large influence on the final strategy. When the lifetime of the Haringvliet sluices is reached, the requirements, criterion can be changed significantly such that other strategies which are not proposed in this thesis can lead to a better fulfilment of these different requirements. The functional strategies proposed in this thesis are traditional hydraulic structures. The verification of these structures is mostly based on logical reasoning substantiated with little data and computations.

The requirements and functions of the Haringvliet can change over time. However, as mentioned in Section 5, it is expected that the functions and requirements for the Haringvliet area remain the same. The boundary conditions change, as mentioned in the previous section. The functional strategies proposed to meet the requirements for the Haringvliet are listed here:

1. Remove the Haringvliet Sluices, such that the Haringvliet becomes an estuary again.
2. Remove the current Haringvliet dam and built a similar sluice complex which is able to deal with higher water levels.
3. Close off the Haringvliet from the North-Sea. This can be a dike, a sea wall, creating dunes or with another permanent structure.

When only implementing one of the strategies above, not all the requirements are fulfilled. With new larger sluices for instance, there will not change much compared to the situation at the end of the lifetime of the current Haringvliet Sluices. Therefore, other structures and improvements need to be implemented together with one of the main strategies as proposed above. These could be locks, fish passages, pumps or other solutions.

In total three functional strategies are proposed:

1. The Haringvliet sluices are removed. The dikes at the hinterland will be reinforced. The fresh water inlet points will be moved further upstream. A new bridge is designed at the location of the sluices.
2. The Haringvliet sluices are replaced by a larger structure. In this larger structure discharging sluices, locks and fish stairs are present.
3. Permanent closure of the Haringvliet by a sea dike. At the sea dike pumps are installed which can be used during large discharges. The road on top of the structure will be preserved. Another measure proposed, is that the river discharge distribution at the junction at Werkendam needs to be changed such, that more river water is discharged via the Nieuwe Waterweg. Also fish locks are included in the Haringvliet sea dike.

It is reasoned if these concepts can meet the requirements mentioned in the previous section. This reasoning is mostly based on interpretations and qualitative analysis. In some cases Hydra-BS calculations are used to substantiate the qualitative analysis. What must be noted is that dike reinforcements due to sea level rise is not incorporated in the functional strategies. These reinforcements are thought to be necessary for all concepts. In case the functional strategy chosen is thought to increase the hydraulic loads on the hinterland, the reinforcements of dike sections will be mentioned.

During the verification of the sluices the influence on morphology is not taken into account. The influence on morphology can not be concluded from a qualitative analysis. However, morphology is an important aspect. Large flow velocities can decrease the stability of bottoms and retaining structures. This must be looked into when working out a full design.

5.3. Verification of the Strategies

In this section the strategies will be described and verified. This section will end with a conclusion on the verification of the strategies.

5.3.1. Removal of the sluices

The firstly suggested functional strategy is is to remove the Haringvliet sluices and the Haringvliet becomes an estuary. When removing the current sluices some functions will be lost and additional structures are needed to fulfil the requirements. Some functions may prosper without the Haringvliet sluices. The effects of the removal of the sluices and the new measures proposed, are summarized below:

- The water levels at the Haringvliet will largely follow the water level at sea. There will be a larger tidal effect due to the removal of the Haringvliet sluices.
- Sea water will mix with the fresh river water. The mixing zone and thus the plume line will change over time, depending on the discharges and water level at sea. The limit of 300 mg/l chloride will during winters, with relatively large discharges, be found between Hellevoetsluis and Willemstad. During summers this salt limit can reach the Biesbosch (Wijsman et al., 2018) due to low river Rhine discharges. This means that the current fresh water intake points need to be relocated.
- There are more opportunities for the ecology due to the brackish water and the increase in tidal effect.
- The removal of the Haringvliet Sluices leads to the removal of the road on top of the sluices, the N57. Therefore a bridge needs to be constructed between Hellevoetsluis and Stellendam. Therefore, nothing changes for the accessibility between the islands.
- The water levels at the Haringvliet are not manageable any more. This can lead to navigability problems.

Without sluices, the hydraulic loads at the Haringvliet will increase. This is indicatively shown in Figures 5.1 until 5.3. In Hydra-BS the failure probability for the failure mechanism of not closing is set to 1.0. However the piers and dams are not included in the calculation, the opening width is underestimated in the calculations. Therefore, the water levels are thought to be larger than shown in Figures 5.1 until 5.3.

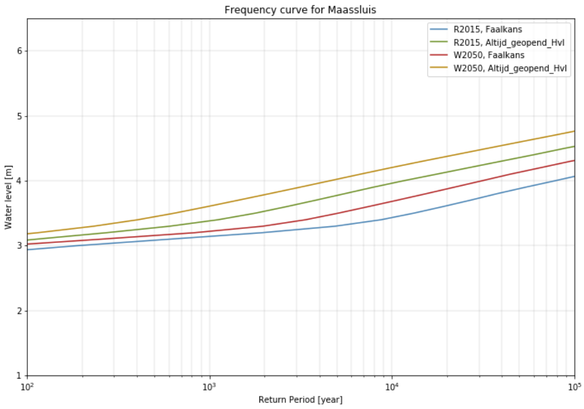


Figure 5.1: Return period and water levels Maassluis

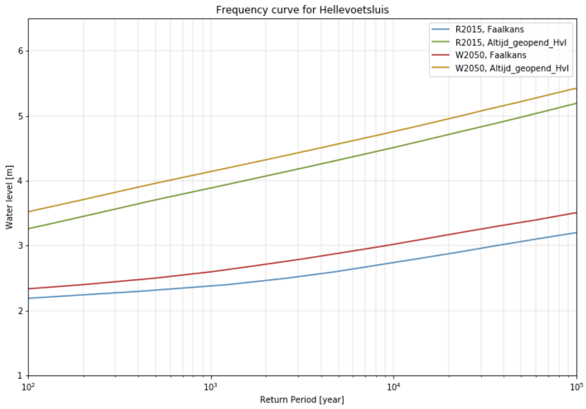


Figure 5.2: Return period and water levels Hellevoetsluis

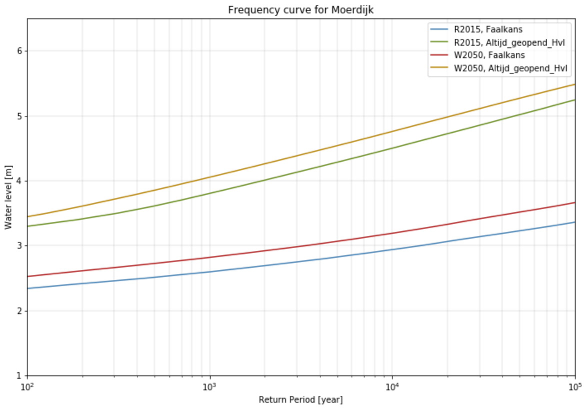


Figure 5.3: Return period and water levels Moerdijk

The frequency curves show what the effect of removing the sluices has at three locations. The water level increases when the Haringvliet sluices are removed.

Compared to the calculations above, the frequency lines will be higher. With an expected sea level rise between 1 and 3 meter in 2230, it is expected that the frequency lines will probably be shifted by 1 to 3 meters too. With these increased water levels, it is expected that most dike sections need to be reinforced. The dikes need to be strengthened due to the removal of the sluices. Disadvantage concerning safety against flooding is that due to an open connection, waves from the sea can reach and run-up dikes at the western side of the Haringvliet. Expected is that the larger water levels and the wave attack increases, which on its turn increases the hydraulic loads on the hinterland even more.

As already mentioned, the fresh water intake points for drinking water must be relocated further upstream. Therefore, new pipelines and larger pumps are necessary. The fresh water intake points for agricultural purposes become more problematic. Agricultural companies are currently fed with water directly distracted from the Haringvliet. These extraction points are currently located at the entrance of the Spui, the east part of the Haringvliet, Hollandsch Diep, but also at the Dordtsche Kil and the Oude Maas. The number of extraction points found is ± 50. Without the Haringvliet sluices the water quality for agricultural purposes will most of the time not be sufficient. The fresh water intake locations need to be fed with fresh water from upstream. Therefore, multiple adjustments must be made. The costs due to the relocation of the fresh water intake points to make the Kierbesluit possible is 75 million Euros (Schreuder, 2018)). In case these points are relocated more upstream it is thought that due to a larger distance, more pump capacity and multiple pipelines are necessary. Therefore it is thought that relocating the fresh water locations more eastward will transcend 75 million Euro.

Two different ways for which fresh water can potentially be extracted are creating a basin and relocating the intake point more eastward. First option thought of is to create a fresh water basin in the Hollands Diep. This basin is separated from the flow in the river and can be fed with Rhine and/or Meuse water flowing downstream. The basin is filled by pumps. If the water quality at the Hollands Diep is not of the required standard, the pumps are shut off. The salt intrusion lengths will however reach eastward of the Biesbosch, as can be seen in Figure 5.4. These salt intrusion lengths are estimated based on isocline lines shown in Wijsman et al. (2018). Due to the influence of climate change, the salt intrusion lengths are thought to reach east of the Biesbosch.

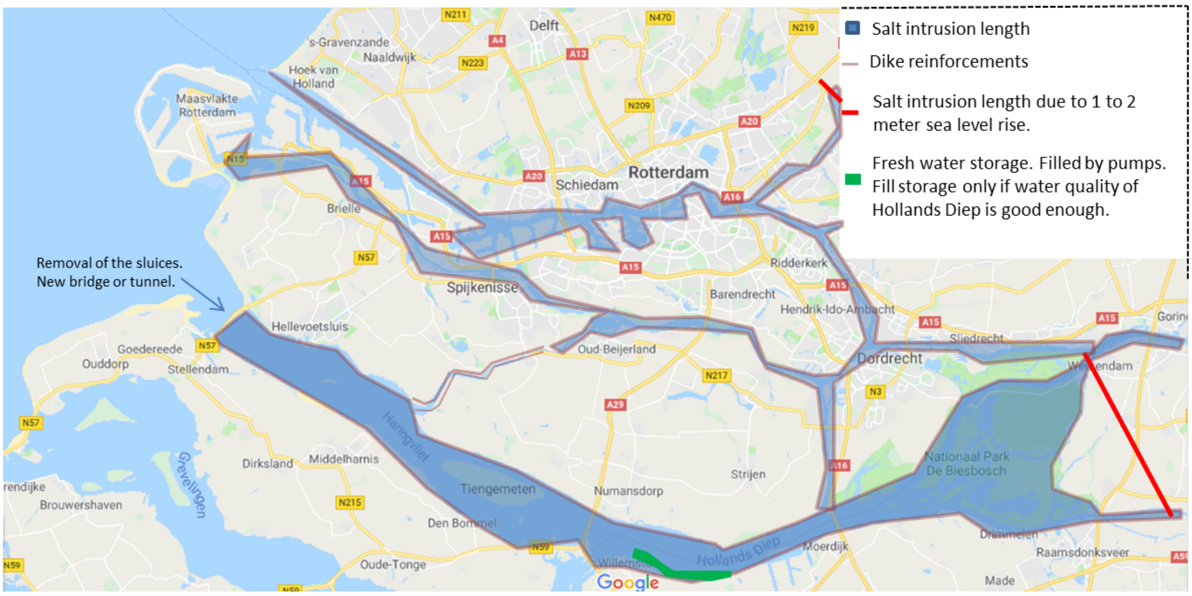


Figure 5.4: The lay out of a new design for the south-western delta, without a structure at the Haringvliet mouth. All fresh water intake points westward of the red line will be removed. The fresh water storage facility (green) located in the Hollands Diep will be connected with that area.

Therefore, the fresh water availability can not be guaranteed in case of a fresh water storage in the Hollands Diep.

Another point for the extraction of fresh water can be the Volkerak-Zoommeer. However, the water quality at the Volkerak-Zoommeer is in summers below average due to the large amount of blue-green algae (Rijkswaterstaat et al., 2009). Also, currently the yearly costs to keep the Volkerak-Zoommeer fresh are relatively large, around 5 million Euro (Rijkswaterstaat et al., 2009). It is thought that with a sea level rise of 1 to 3 meter, these costs increase significantly. Also, there are multiple plans to make the Volkerak-Zoommeer brackish again (Rijkswaterstaat et al., 2009). Therefore, this solution does not meet the requirements.

To connect Voorne-Putten and Goeree-Overflakkee at the west side of the islands, a bridge is built. It may be possible to re-use the piers used for the sluices to built a bridge between the two islands. All measures and effects of the removal of the sluices are shown in Figure 5.4.

5.3.2. Similar Sluice Complex

Another option is to replace the Haringvliet sluices for a similar sluice complex. Due to the expected backward salt intrusion via the Nieuwe Waterweg a closure needs to be built at the Nieuwe Waterweg. The effects of closing the Haringvliet and the Nieuwe waterweg is summarized here:

- The hydraulic loads at the Haringvliet increases due to sea level rise. Due to the closure of the Nieuwe Waterweg and the Haringvliet, the water levels at the Haringvliet can under normal conditions be controlled, which could reduce the influence of the sea level rise.
- The lifetime concerning fresh water availability is reached, meaning that the sluices can only discharge water during low tide, keeping the Haringvliet fresh.
- Fish stairs are installed to improve the fish migration. Increasing the ecological value of the area will with closures of the Nieuwe Waterweg and Haringvliet not be feasible.
- The accessibility is guaranteed with a road next to the new sluice complex.
- The water levels on the Haringvliet are manageable again. This is a positive result for navigation on the Haringvliet. However, the closure and installation of locks at the Nieuwe Waterweg is a disadvantage for navigation. This will lead to larger sailing times, which is expensive.

From the above it can be concluded that closing the Nieuwe Waterweg and Haringvliet could avoid strengthening and heightening of the dikes. With enough capacity to discharge the river water, the water levels in the delta are manageable. The Nieuwe Waterweg closure should include large locks for navigational ships that want to reach the harbour of Rotterdam, and discharging sluices to discharge the river water coming from the Rhine. Closing of the Nieuwe Waterweg is a sensitive topic from a social point of view. Closing the Nieuwe Waterweg increases the shipping time from and to the harbour of Rotterdam. This means that the costs for the harbour activities increase. Because the exact costs for the shipping industry in case the Nieuwe Waterweg is closed off is not fully investigated, the verification can solely be based on the solutions and structures implemented at the Haringvliet.

Closing of this delta means that both the Haringvliet and Nieuwe Waterweg will become fresh. The locks at the Nieuwe-Waterweg will bring in some salt water. Assumed is that the amount of salt water is too small to intrude to the Haringvliet via the Spui. The fresh water availability will therefore not be a problem any more.

The ecological benefits do not reach further than the possibility for fish to migrate. Fish species could migrate all year via fish passages. Other ecological goals will be hard to meet with the disappearance of the tidal effect in the south-western delta. There will be a negative impact on ecological species which benefit from the tidal effects. The delta will contain only species which could prosper in fresh water.

The connection between Voorne-Putten and Goeree-Overflakkee needs to be maintained. Therefore a separated bridge is built close to the Haringvliet sluices. It is chosen to built a separate bridge to increase the adaptability of the system.

With a closed delta the water levels remain dependent on the water level at sea. This is due to the fact that the sluices discharge water by gravity. The influence of the sea level in the delta is relatively large. The mean water level increases due to the sea level rise. This ensures that the navigational depths are satisfied. This is assumed not taking into account the flow velocities and morphological changes. The flow velocities and the influence of morphology are hard to indicate but these are of large influence on the navigability. It is thought that within a closed delta the sediment exchange between the North-Sea and the Nieuwe Waterweg can not take place. Expected is that with closed sluices the flow velocities become small in both the Nieuwe Waterweg and Haringvliet. Sediments are able to settle down, causing sedimentation. Expected is that when the sluices open during low-tide, part of the settled sediments erode and are transported to the sea. Dredging the waterways remains needed. The exact influence of a closure on the flow velocities, morphology and dredging volumes are not quantified.

All the measures discussed above are shown in Figure 5.5.

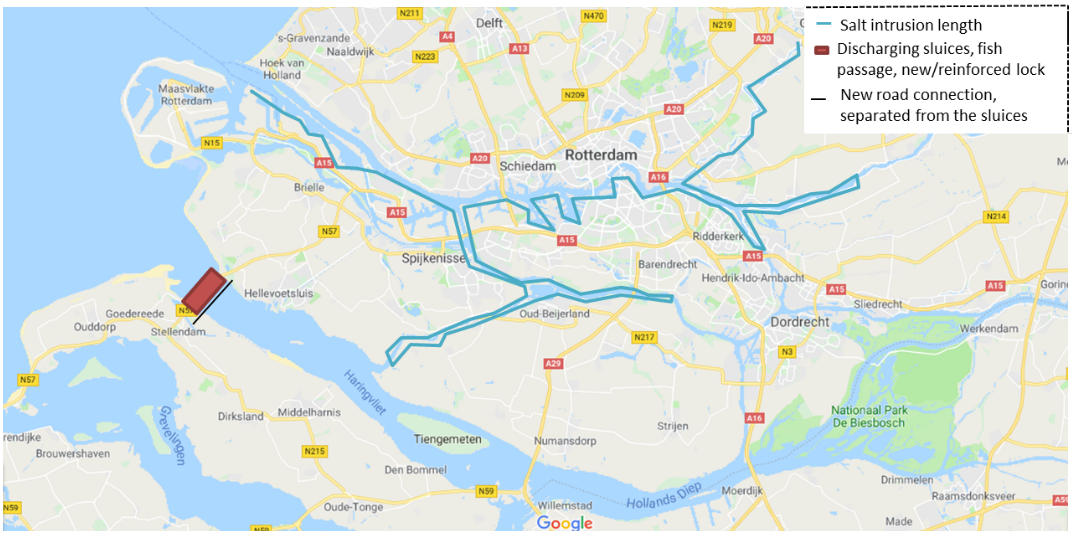


Figure 5.5: The lay out of a new design for the south-western delta, with a replacement of the current sluices.

5.3.3. Closed Haringvliet, Open Nieuwe Waterweg

The effect of closing off the Haringvliet permanently in combination with an open Nieuwe Waterweg, has the following effects:

- The water levels at the Haringvliet can not be controlled and will, with an open Nieuwe Waterweg, be dependent on the river Rhine and Meuse discharges and water levels at sea.
- Sea water can not reach the Haringvliet due to the closure. Backward salt intrusion is the only possibility. At the junction at Werkendam the discharge of the river Rhine must be regulated such, that most water reaches the Nieuwe Waterweg. In that case the probabilities of backward salt intrusion decreases. However, with low discharges and the amount of sea level rise, it is thought that backward salt intrusion can occur. Sea water will intrude via the Spui into the Haringvliet. When this happens, it is thought that the salt concentrations will remain in the Haringvliet for quite some time, because the Haringvliet can not be flushed fresh. This means that the function of fresh water intake is lost for a certain amount of time.
- The effects of the corridor function for migrating fish is fulfilled with fish passages.
- A road is designed on the closure work.
- The water levels on the Haringvliet are not directly manageable. This has a negative effect on the navigation on the Haringvliet. The Nieuwe Waterweg remains open which has a positive effect on the navigability.

The water levels at the Haringvliet become larger when the Haringvliet is always closed. As already mentioned in Section 5.3.1, the water levels will be larger due to sea level rise and will be in the order of 1 to 3 meters.

The effect on the water levels in case of a permanent closure is calculated with the existing databases with Hydra-BS. The frequency lines are calculated by choosing a failure probability of 1.0 for the failure mechanism of 'not opening'. The results are shown in Figures 5.6 until 5.8.
In Figures 5.6 until 5.8 frequency lines for the current failure probabilities of not closing and not opening (Faalkans) and frequency lines when the sluices are always closed (Altijd_gesloten_Hvl) are shown. They are shown for both climate scenarios, R2015 and W2050. The influence of always closed sluices can be seen clearly.
The calculations with Hydra-BS, with relatively small sea level rise rates do not show an increase of the water levels at Maassluis, located at the Nieuwe Waterweg. By closing the Haringvliet, the water of the rivers

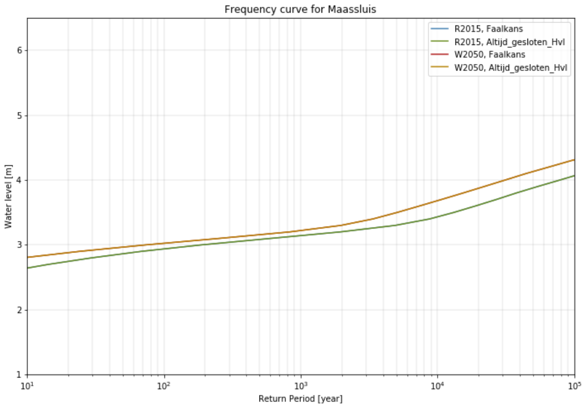


Figure 5.6: Return period and water levels Rotterdam

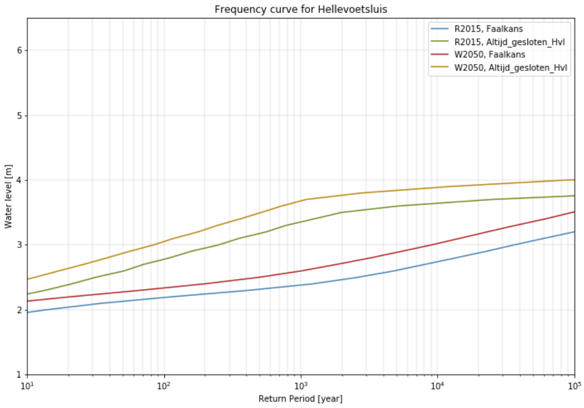


Figure 5.7: Return period and water levels Hellevoetsluis

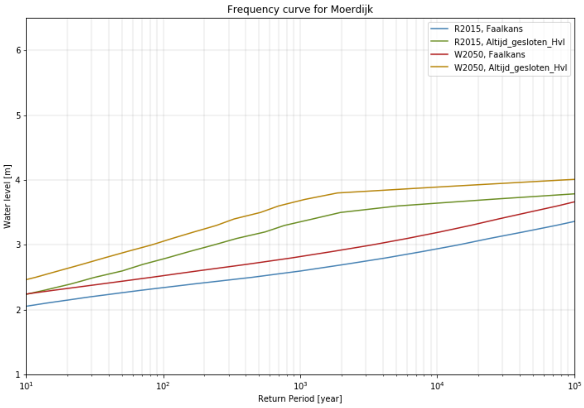


Figure 5.8: Return period and water levels Moerdijk

Rhine and Meuse will be discharged into the North-Sea via the Nieuwe Waterweg. The water levels and their return periods at the Nieuwe Waterweg will not change due to a closure of the Haringvliet. This can be explained by the fact that the water level at the Nieuwe Waterweg is mainly influenced by the water level at sea and the effect of (the large failure probability of) the Maeslantkering. Another explanation is that during large discharges, the distribution of this water in the direction of the Haringvliet and Nieuwe Waterweg is not changed. When totally closing of the Haringvliet, the water levels at the Haringvliet increase.

Another problem which may arise is the physical limit. The flow area of the Haringvliet is 2 to 3 times larger than the flow area of the Nieuwe Waterweg. It is therefore expected that the water levels at the Nieuwe Waterweg will increase with the measure of closing the Haringvliet.

To avoid strengthening and heightening of most dikes around the Haringvliet, it can be chosen to install pumps at the closure. These could pump the water over or through the dike. Complementary, the discharge distribution must be changed in such a way that less water reaches the Haringvliet. This can be achieved by changing the distribution at the Boven Merwede at the junction of Werkendam. This can be achieved by building sluices or a weir at this junction.

For the fresh water intake, the closure of the Haringvliet in combination with larger discharges through the Nieuwe Waterweg is advantageous. Direct salt intrusion becomes impossible, backward intrusion via het Spui will, due to more discharge via the Nieuwe Waterweg, be reduced too. However, with 1 to 3 meter sea level rise, salt will intrude further into the Nieuwe Waterweg compared to the situation at the end of the lifetime. With low discharges during dry summers, backward intrusion could still lead to problems.

Ecological benefits, accessibility of the islands and navigation are thought to be the same as in 2.

In Figure 5.9 the expected backward salt intrusion is shown. Indicated are also the dike segments around the Haringvliet, Hollands Diep and Spui which need extra reinforcements due to the closure of the Haringvliet sluices. With a structure changing the river discharge distribution, pumps at the closure, the increase on the hydraulic loads is thought to be reduced.

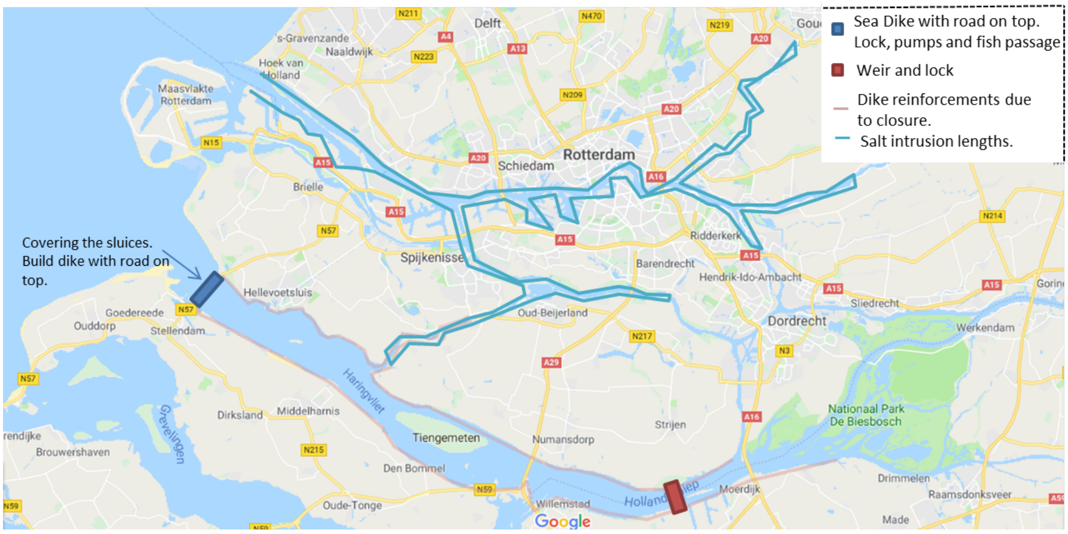


Figure 5.9: The lay out of a new design for the south-western delta with a closed Haringvliet and an open Nieuwe Waterweg and the measures needed due to the closure.

Concluded is that the fresh water problem is shifted towards the fresh water intake points around Rotterdam and at Gouda.

5.3.4. Conclusion of the Verification

The functional design verification is based on knowledge gained during the literature review of this thesis, historic data, reports and papers (mostly Paalvast (2016); Noordhuis (2017, 2018); de Goederen et al. (2006); Wijsman et al. (2018); Huismans (2016)). Some functions, like flood protection, navigation, fresh water availability and to a certain extent ecology, can be analysed more quantitatively with models. However, due to the relatively large remaining life time of the current Haringvliet sluices, the uncertainty of certain parameters and other factors make it hard to quantify if the requirements are met for these functions.

To verify the functional concepts described above, the designs are assessed by functional reasoning. In some cases water level calculations are executed with Hydra-BS. The boundary conditions for the year 2230 are kept in mind during the verification. This means that a sea level rise between 1 and 3 meter could occur. Also the river discharge distribution over the year will be more extreme and is kept in mind.

The decision making of the closure of the Nieuwe Waterweg is not investigated in full detail. When looking at the requirements for the Haringvliet a closure of the Nieuwe Waterweg will be beneficial. However, there is a lack of qualitative and quantitative information and data with respect to closing of the Nieuwe Waterweg with locks. Costs, the extra travel time for the navigation, availability of the sluices, restrictions of lengths of ships, availability of locks and other factors missing, are not included in this thesis. Therefore, the closure of the Nieuwe Waterweg is not used in the verification process.

Removal of the Sluices

The first solution, removing the sluices is not a functionally feasible solution. With the large sea level rise scenarios, the hydraulic loads on the hinterland will increase significantly. It is assumed that all dike segments need to be reinforced on top of the reinforcing due to sea level rise. This is thought to be societally unacceptable. The reinforcements take lots of space in both, height and width. With an open Haringvliet it is thought that dikes need to be reinforced by meters. During a storm these dikes are the primary flood defence. The influence of waves become important, which increases the loads even more. Flood risk wise this is not seen as a feasible option.

It is also thought that with a sea level rise of 1-3 meters the salt will reach until the Biesbosch or even further. This means that the fresh water must be transported from another location. This location can only be eastward of the Biesbosch, otherwise the quality is not sufficient. This is thought to be a complex and expensive solution. The navigability and ecology will thrive with an open Haringvliet. The accessibility between Voorne-Putten and Goeree Overflakkee is maintained by building a bridge.

Similar Sluice Complex
This solution includes a similar, larger and stronger, sluice complex with a fish passage separated from the sluices. The lock at Stellendam needs to be replaced to a larger lock to guarantee navigability for the ships to and from the Haringvliet. Because the ecological and fresh water availability were the most conflicting functions, these functions are decoupled by constructing a structure for each function. Under normal circumstances, during low tide, the sluices can be opened to discharge the water into the sea. Fish are able to migrate from sea to the Haringvliet and vice versa via the fish passages. During storm conditions the sluices are closed and fish can temporarily not migrate from the sea to the Haringvliet. The availability of fresh water can be guaranteed because the sluices are only opened during low tide, as in the LPH86 program.

The accessibility can be guaranteed by building a bridge between Goeree-Overflakkee and Voorne Putten.

Permanently Closed Haringvliet
This concept is quite similar compared to the previous concept. The closure at the Haringvliet causes that the Haringvliet is filled with fresh water and leads to a fulfilment of the availability of fresh water requirement. The permanent closure is a seadike which is built over the current sluices. With a permanent closure the river water can not be discharged any more. Therefore, pumps are installed at the closure. Advantage of pumps compared to sluices is that in case of large river discharges during storms the water can still be pumped from the Haringvliet to the sea. Disadvantage are the costs.

The functions for ecology and navigation are met due to the fish passages and locks. A road is built over the dam to ensure the connectivity between the islands is guaranteed.

With the requirements as stated in this thesis, the Haringvliet needs to be closed of from the North-Sea. As already mentioned before, the coherence between the Haringvliet and the Nieuwe Waterweg can not be unseen. However, in this thesis focussed is on the Haringvliet and the Haringvliet sluices. To fulfil for the ecology requirements fish passages are built. Locks for navigation are needed to fulfil the requirements concerning navigation.

The variants in which the Haringvliet Sluices are covered by sand to create a dam and a closed Haringvliet with a new sluice complex fulfil all the requirements. These are evaluated in Section 5.4.

5.4. Evaluation of the Strategies

In this section the verified strategies are evaluated with a multi criteria evaluation. Also costs are estimated which together with the multi criteria evaluation leads to a conclusion on the design objective.

5.4.1. Criteria and Weight Factors

A Multi Criteria Evaluation (MCE) is a valuable tool which is used to arrive to a reliable choice of the verified designs. The criteria are based on the fact that the lifetime of the functional designs under changing circumstances must be reached. Also, the set of criteria must be in balance to come to a reliable outcome. In the multi criteria evaluation, all strategies are assessed for the criteria coming from the functions which are based on preferences of multiple stakeholders, as described in Section 5.1.3. The criteria used for the multi criteria evaluation are described briefly below:

Criterion 1: Adaptability of the design.
The uncertainty in climate change can lead to relatively fast changing boundary conditions. A design which is able to adapt to multiple scenarios is desirable.

Criterion 2: Capacity to discharge river water.
It is an advantage if the more extreme river discharges expected in the far future can be discharged into the North-Sea.

Criterion 3: The reliability of (moving) structures.
The reliability of sluices, pumps, locks or other structures should be easy to maintain over the years and is therefore stated as a criterion.

The weight factor for each criterion is based on a subjective relative ranking of importance. The weight factors for the criterion are numbered between 0 and 1. The larger the criterion score, the more important that criterion. The scores for the multi criteria evaluation are between 1 and 5. The higher the score, the better this variant scores for that criterion. In the end, the sum of all weight factor times the score for that criterion, is the total score. The higher, the better the strategy scores. The weight factors used to assess the new strategies are shown in Table 5.1.

Table 5.1: The weight factors for the Multi Criteria Evaluation (MCE)

Evaluation Criteria	**Adaptability**	**Capacity**	**Reliability**
Weight factors	0.9	0.9	0.8

The scores 1 and 2 mean that the new strategy scores insufficient on the criterion. The score 3 means that the criterion is just met, while the scores 4 and 5 means that the criterion is fulfilled.

5.4.2. Evaluation: New Sluices

The multi criteria evaluation results are shown in Table 5.2. This is for the measures in which new sluices at the Haringvliet are built, as shown in Figure 5.5.

Table 5.2: The multi criteria evaluation focusses on the requirements for the Haringvliet and Hollandsch Diep. However, the Haringvliet and Hollandsch Diep are part of a larger system. The focus in this MCE is on the Haringvliet and further upstream. In this MCE the current sluices are replaced by larger sluices.

Criteria / **Functional Design**	**Adaptability**	**Capacity**	**Reliability**	**Total score:**	**Weighted**
New Sluices	4	5	3	10.5	4.04

The design variant of the new sluices scores relatively high on the criteria of adaptability and capacity. The criterion reliability scores average. Comparing a new sluice complex with the current Haringvliet Sluices, the sluices are able to cope with large discharges due to the adaptability of the sluice doors. Therefore, the water level at the Haringvliet remains manageable during large river discharges. Further, a new sluice can be designed such that relatively simple adjustments, like replacing doors which are not sufficient concerning height, can be replaced by larger doors.

The reliability of the sluices is hard to qualify without an actual design. Again, referring to the current Haringvliet sluices, the reliability of discharge sluices which are operated independently is large. With a system as incorporated in the current sluices, the reliability of the sluices is assumed to be large. The reliability and functioning of fish passages need to be investigated further. However, when using the Afsluitdijk fish passage as an example, the reliability is large. This fish passage works well for fish migrating in both directions (Didde, 2016).

5.4.3. Evaluation: Closed Haringvliet

The multi criteria evaluation for the concept in which the Haringvliet is closed permanently for which pumps are installed and in which fish passages are constructed, is shown in Table 5.3.
The design variant with a dike and sluices scores average on the adaptability and reliability of the design. The capacity criterion scores the maximum score. With a closure of the Haringvliet the adaptability of the system is average. The dike which is thought to be built over the sluices is not very adaptable. The capacity of the

Table 5.3: Result of the MCE of a functional design which incorporates a closure of the Haringvliet. The Haringvliet is closed of by dike at which pumps are installed, a fish passage and a movable weir at Steurgat (south of Werkendam) at the Nieuwe Merwede is built to reduce the incoming river volume at the Haringvliet during normal conditions.

Criteria / Functional Design	Adaptability	Capacity	Reliability	Total score:	Weighted
Sea Dike with pumps and a weir	3	5	3	9.6	3.69

pumps and the movable weir are adaptable, making this functional design score an average adaptability.

The capacity of the pumps is important concerning flood risk. In case more water arrives at the Haringvliet as calculated, the pumps must be able to pump this water into the North-Sea. The capacity of the weir must be investigated but must be adjustable such that the discharge distribution is most efficient.

The reliability of the combination of the large sea dike, pumps and weirs is thought to be average.

5.4.4. Costs

Costs are included in the evaluation to come to a better insight in which concept has most potential. The costs are estimated based on the structures. The costs for the structures is based on costs for similar structures and is coming from research and the literature study.

New Sluices

The costs for the functional design of new sluices in the Haringvliet are based on the costs of the structures. The structures which are evaluated are:

- Removal of the Haringvliet Delta Work
- Discharging sluices at the Haringvliet
- Fish locks at the Haringvliet
- New road connection between the islands

The costs are estimated on key figures or by comparing the costs of other projects and are shown in Table 5.4 (Hillen et al., 2010), (Opdrachtgeverschap, 2003).

Table 5.4: Cost estimation in case of closing the Haringvliet with a sluice (Hillen et al., 2010), (Opdrachtgeverschap, 2003)

	Costs (€ M)	Number	Total (€ M)
Removal structures	50	1	50
Discharging sluices	500	1	500
Fish passage	80	1	80
Lock (Stellendam)	300	1	300
Road Connection (bridge)	100	1	100
Uncertainty		0.15*total	155
Total			**1.18 billion**

Seadike, Pumps and Weir

The costs for the concept of a sea dike including pumps at the Haringvliet and a weir and locks at Steurgat (south of Werkendam) are based on the costs of the structures. The structures evaluated are:

- Covering of the Haringvliet Delta Work, building a sea dike
- Installation of pumps at the Haringvliet sea dike
- Costs of the structure of a movable weir
- Fish locks at the Haringvliet

The costs are estimated based on key figures or by comparing the costs of other projects and are shown in Table 5.5 (Rijkswaterstaat, 2018), (Hillen et al., 2010), (Opdrachtgeverschap, 2003).

Table 5.5: Cost estimation for the concept of closing the Haringvliet with a sea dike (Hillen et al., 2010), (Opdrachtgeverschap, 2003).

	Costs (€ M)	**Units**	**Quantity**	**Total (€ M)**
Pumps	35	€M/m3/s	8000 (m3/s)	280 billion
Weir	100	per/piece	1	100
Fish passage	80	per/piece	1	80
Locks	300	per/piece	2	600
Sea dike	0.04	euro/meter	1500 (m)	60
Road	10	euro	1	10
Uncertainty			0.15*total	42 billion
Total				**323 Billion**

The costs for the installation of the pumps, which should be able to pump 8000 m3/s of water, are the largest expense (Rijkswaterstaat, 2016).

5.5. Conclusion and Discussion of Functional Designs

Four functional designs were proposed in this thesis in which two were verified. These two functional designs are evaluated within a Multi Criteria Evaluation. The scores for the MCE are given per functional design and are summarized in Table 5.6.

Table 5.6: The results of the multi criteria evaluation of the two verified functional designs.

Criteria **Functional Design**	**Adaptability**	**Capacity**	**Reliability**	**Total score:**	**Weighted**
New Sluices	4	5	3	10.5	4.04
Sea Dike with pumps and a weir	3	5	3	9.6	3.69

From the Multi Criteria Evaluation, the new enlarged sluice complex turns out to be most favourable. However, the differences between the MCE results are relatively small. Subtle changes in the weight factors or scores will give different outcomes. The overall score of a strategy will never be excellent. Due to a lack of time, data, and a lack of the availability of good models, the results of the verification as well as the MCE shown in Table 5.6, are uncertain. More research is needed to verify and quantify the functional designs as proposed in this thesis.

As mentioned, the long time span and the uncertainties which come with a long time span, make the multi criteria evaluation fairly unreliable. The qualitatively assessed strategies can be seen as an indication.

Costs and MCE

Considering the multi criteria evaluation and the cost assessment, the most suitable strategy is proposed. The costs of the most expensive solution scores 1.0 and the other strategies scores a fraction of the costs of the most expensive solution. The final score is based on the MCE score divided by the cost parameter. The results are shown in Table 5.7.

Table 5.7: The new strategy with the most potential following the multi criteria evaluation and cost turn out to be a closure of the Haringvliet sluices and a closure of the Nieuwe Waterweg with multiple sluices.

	MCE score:	**Cost factor**	**Total score**
New Sluices	10.5	=(1.18 billion /323 billion) = 3.67E-03	2860
Sea Dike **With pumps** **Weir at Hollands Diep**	9.6	1	9.6

5.5.1. Conclusion Functional Designs

With the multi criteria analysis and cost estimation the design objective stated in Section 1.4.2 is answered. The objective is:

Which functional design option(s) can lead to a fulfilment of the requirements and to what degree do(es) they/it fulfil the criteria?

Within this thesis the functional design with new sluices turn out to fulfil the requirements and criteria the most. However, the reliability of the verification and multi criteria evaluation are thought to be relatively low, as will be discussed in the following subsection.

5.5.2. Discussion of the Uncertainties in the Evaluation

The results of the functional designs are highly unreliable due to the large time span. This leads to large uncertainties with respect to the requirements and criteria used. Also, the influence of new technical and economical aspects can not be taken into account in this analysis. It can not be stated that one functional design proposed in this thesis has most potential. The future decisions are based on societal and political influences. These are local and also international political influences, leading to the decision making (van Meerkerk et al., 2013).

As prior mentioned, the MCE and cost estimations are based on assumptions and key figures. Therefore, the executed MCE and cost evaluation can be seen as a rough estimation and gives small insight in what new strategies will approximately cost. However, these are only the initial costs. In an actual design phase, the costs during the lifetime and costs due to for example extra shipping time need to be included in the calculations.

As prior mentioned, multiple other strategies and functional designs can be thought of. These can be conventional hydraulic structures or more unconventional solutions. These unconventional solutions are not proposed in this thesis. The assessment, evaluation and cost estimation of unconventional solutions cannot be substantiated to come to a reliable judgement. However, in further research some conventional and unconventional ideas can be a solution.

6

Conclusion, Discussion and Recommendations

In this chapter conclusions, discussions and recommendations following from this report will be presented. Section 6.1 presents the conclusion of this thesis. All the research and functional designs questions will be answered. In the second section, Section 6.2 the results will be discussed. The validity of the results of this research and evaluation of functional designs will be discussed. The last section, Section 6.3, will contain recommendations which are thought to be most important.

6.1. Conclusion

All the research objectives stated in are answered in this thesis. In this section the conclusion of each of the research questions will be given. By answering the objectives, the main research question can be answered.

6.1.1. Research Question 1

Which mechanism or function can lead to the end of the lifetime of the Haringvliet sluices prior to the design lifetime?

This question is answered by using three sub-questions.

Which functions are influenced by the Haringvliet sluices?
The functions the Haringvliet fulfils are multi disciplinary. An analysis of the region around the Haringvliet lead to all functions the Haringvliet sluices fulfill. From all the functions five main functions are extracted which are:

- Flood protection
- Fresh water availability for industries, companies, agricultural purposes, etc.
- Ecology
- Navigability and accessibility
- Recreation

For which functions will the Haringvliet sluices be assessed?
From literature research and the stakeholders the most important functions the Haringvliet sluices fulfil concern:
- Flood Risk
- Fresh water availability
- Ecology, especially fish migration.

These functions were used for the assessment of the Haringvliet sluices. The navigability, accessibility and recreation are important functions for the Haringvliet. However, the navigability at the Haringvliet is largely determined by morphological processes which is not included in this thesis. The accessibility between the islands is thought to be fulfilled under all circumstances because of the height of the sluices. Recreation in and around the Haringvliet can be dependent on the water levels and influences from climate change. However, multiple other aspects are important as well, which are not included in the scope of this thesis.

Which indicators show that the functions are not fulfilled any more?
The indicators used for the assessment of the Haringvliet sluices differ per function. Concerning Flood Risk, the indicators are the water levels leading to larger hydraulic loads at the Haringvliet and further upstream. Concerning fresh water availability the indicator is the salt intrusion length which is expressed in chloride per litre. For the assessment of ecology the indicator is the time fish are able to migrate in both North Sea and Haringvliet direction.

6.1.2. Research Question 2

Which requirements must be met and which methods are used to asses this?
This research question is answered in two phases.

Which requirements must be met?
For each function at least one requirement is given. These requirements are composed from literature and a stakeholder analysis. The requirements which must be met are listed below:

- The stability and strength of the sluices must be guaranteed. This is the structural failure requirement. This requirement is assessed based on a semi-structured interview. The lifetime concerning stability and strength of the sluices is based on an amount of sea level rise for which the strength of the sluices is thought to become insufficient.
- Concerning Flood Risk the requirements are based on the failure mechanism overtopping and overflow for the dikes at the hinterland. The effect of the failure mechanisms of the Haringvliet sluices are therefore considered. Because failure of the sluices does not immediately have to lead to a flooding, overtopping and overflow of the dikes around the Haringvliet are used for the assessment. The requirements for flood protection are enforced by law. Therefore, the effect of multiple failure mechanisms of the Haringvliet sluices are calculated. The failure mechanisms of the Haringvliet sluices to calculate the hydraulic loads on the hinterland are: Not opening, not closing, overtopping and overflow. Also, the effect of sea level rise is included which leads to larger hydraulic loads at the hinterland. When the Haringvliet sluices fail, there is no direct flood. Therefore, failure of the Haringvliet Sluices is reached if two dike segments effected by the failure mechanisms of the Haringvliet sluices fail for overtopping and overflow. With Hydra-BS the hydraulic loads are calculated. If two dike segments have a hydraulic load of 0.2 metres larger than the retaining height, the Haringvliet sluices are set to fail concerning flood risk. If the hydraulic loads just exceed the retaining height (less than 0.2 meters), it is thought to be more efficient to come up with local measures of these dike sections.
- Concerning fresh water intake, the water at the imaginary line Spui-Middelharnis may not contain more than 300 milligram chloride per litre. The 300 mg/L chloride limit is the limit for when fresh water becomes brackish and is mentioned in multiple papers (Paalvast, 2016; Noordhuis, 2017, 2018; Wijsman et al., 2018).
- Concerning fish migration, the fish migration periods are used to assess the sluices. Each migratory specie has a different migration period. If the period reduces for one single specie by 50 % of the time compared to the current situation, the requirements are not met for the Haringvliet sluices. In this requirement, the current Kierbesluit is used as guideline. Another criteria concerning the ecology is that the sluices may not be closed for 50 consecutive days. The values chosen for which the ecological requirements are assessed, are based on information from reports and expert judgement (Noordhuis, 2018; Kemper, 1997; Wijsman et al., 2018).

What methods are used to, qualitatively and quantitatively, assess these indicators?
For the assessment of safety against flooding, the potential failure modes of the Haringvliet sluices are mapped. The failure modes: not opening and not closing of the sluice doors, overtopping and overflow over the sluices and piping are considered as potential failure mechanisms. The probability of piping is thought to be negligible due to the relatively large length of the bottom protection and the concrete piles which avoid buoyancy. Other measures to reduce the probability of piping, as described in Chapter 2, are taken during the construction. Therefore, the failure probability of piping is assumed to be negligible.

The influence of the failure mechanisms of not opening and not closing is calculated with the models SOBEK-RE and Hydra-BS. In the hydrodynamic 1D model SOBEK-RE multiple structures are included. The failure modes of not opening and not closing are included in this model. The results of the SOBEK-RE calculations are transferred to a database which is used for probabilistic calculations with the program Hydra-BS. The indicators are the hydraulic loads at the dikes of the hinterland. If the hydraulic loads at these dikes increase significantly due to the probabilities of these failure mechanisms, these should be incorporated in the assessment of the overtopping and overflow volumes of the dikes.

For the failure mechanisms of overtopping and overflow the study from Van der Meer (2008) is used. The overtopping formula found in Van der Meer (2008) is used, for which the increase of the water levels due to the overtopping and overflow volumes at the Haringvliet are calculated.

For the final assessment for safety against flooding, sea level rise, the influence of not opening and not closing sluices, model uncertainty of Hydra-BS and the influence of the overtopping and overflow volumes are incorporated.

The assessment on fresh water is based on research and measurements. The measurements are coming from a test for which the sluices were opened for five consecutive days during both low and high-tide. With the results from the measurements in Jacobs et al. (2003) and the research and models used in Noordhuis (2017), Paalvast (2016) and historical data and maps inWijsman et al. (2018), the 300 mg/l chloride concentration line is estimated for the summers with the most extreme climate scenarios from KNMI'14.

The ecological value is based on the migration of multiple fish species thought to migrate upstream. The fish calender as shown in Appendix I is used as reference scenario in combination with the river discharges for which the sluices can be opened. The months for which species migrate from sea to river is used as indicator and this time may not halve. The expected change in river discharges for the most extreme KNMI'14 scenarios and the research of Noordhuis (2017), which shows the percentages the sluices can be opened, are used to assess the sluices on the lifetime concerning ecology.

6.1.3. Research Question 3

What is the final lifetime of the Haringvliet sluices?

This question is split up in three sub-questions. First of all when the lifetime is reached without lifetime extending measures. Secondly, which lifetime extending measures can be implemented. And thirdly, what will the lifetime be after implementing life time extending measures?

Which and when is a (failure) mechanisms or requirements from the stakeholders firstly not met?

Concluded is that before applying lifetime extending measures, some fish species have too little time to migrate upstream. Both requirements concerning ecology are not met. This means that the time some fish species want to migrate, halves compared to the current situation. Also, the sluices are thought to be closed for 50 consecutive days or more. Concluded is that certain fish species have too limited time to migrate around the year 2050 in case of the most extreme KNMI'14 scenario. For the average and G_L scenarios, the first requirement(s) which can not be met is also concerning ecology. In those cases the requirements concerning ecology are not met around the years 2100 and 2160 respectively, as can be seen in Table 6.1.

Table 6.1: Lifetime per function and Climate Scenario

Function **Climate Scenario**	**No Advantage Ecology**	**Fresh Water Availability**	**Flood Protection**	**Structural Failure**
$\mathbf{W_h}$	2050	2115	2105	2100
Average	2105	2165	2145	2135
$\mathbf{G_l}$	2160	2210	2185	2170

Which measures can be implemented to extend the lifetime of the sluices?

Extending the lifetime in case of the most extreme scenario means that the lifetime concerning ecology must be increased. The migration time for some fish species reduced too much compared to the current situation. Also, the time the sluices will be consecutively closed is thought to become too large with the Kierbesluit used as described in Paalvast (2016). The Kierbesluit as described in Paalvast (2016) is thought to be relatively conservative. With an optimised Kierbesluit it is thought that the sluices can be opened during high-tide for lower discharges, e.g. 1100 or 1200 m^3/s. When applying a Kierbesluit for which the sluices are opened for lower discharges, it is thought that the lifetime is extended significantly. However, the lifetime of the fresh water availability decreases due to this measure. The probability of the salt intruding into the Haringvliet reaching till the line Middelharnis-Spui increases.

Which and when is a (failure) mechanism or requirement not met any more after applying lifetime extending measures?
With the lifetime extending measures, all functions fail in a short time span of 20 years around the year 2130 (for the average scenario, see Table 6.2. The first failure mechanism reached is the lifetime concerning fresh water availability. Second, 5 years after fresh water availability, structural failure is thought to occur. This means that the sluice needs to be replaced, removed or maintained. In case of the least extreme climate scenario, structural failure is reached first and thus thought is that the sluices need to be replaced, removed or maintained.

In case of the most extreme climate scenario used in this thesis, the lifetime concerning ecology and fresh water availability are reached first, see Table 6.2. The larger water levels at the North-Sea and the more extreme river distributions over the year, cause that the sluices must be closed more frequently in the summer. Meaning that the requirements concerning fish migration can not be met. Also, the larger the sea levels the further the salt water intrudes. With a Kierbesluit opening at discharges of 1100 or 1200 m^3/s, the intrusion lengths are thought to become too large. This is based on the results of the results found in Jacobs et al. (2003). However, this can not be made quantitative.

Table 6.2: Lifetime per function and Climate Scenario

Function **Climate Scenario**	**No Advantage Ecology**	**Fresh Water Availability**	**Flood Protection**	**Structural Failure**
W_h	2080	2080	2105	2100
Average	2135	2130	2145	2135
G_l	2190	2175	2185	2170

6.1.4. Main Objective: Can the Haringvliet sluices fulfil the functions as it currently does till it reaches the design lifetime?

Climate change and especially the effect of sea level rise and the change in discharge distribution have a significant effect on the lifetime of the Haringvliet sluices. Especially in case of a relative extreme climate scenario, some functions can not be fulfilled any more in this century.

Assessing the Haringvliet sluices concerning ecology and fresh water availability showed that these functions thrive with opposite conditions. It is advantageous to open the sluices during high and low tide and create a more brackish Haringvliet for the ecology. With a larger sea level rise and a lower discharge for which the sluices are opened, the fresh water at the intake locations can turn brackish. The effect of the Kierbesluit is measured by Rijkswaterstaat and it is still investigated what the optimum is for the Kierbesluit. From measurements carried out in Jacobs et al. (2003), for which the opening was 2 to 3 times larger compared to the current Kierbesluit, it is thought that the sluices can be opened for slightly lower discharges to extend the lifetime of the sluices.

The effect of the failure mechanisms assessed in this research is thought to be relatively small. However, with a rising sea level the effect of overtopping and overflow can become significant. Due to the large area of the Haringvliet, this volume can be stored under normal river discharges. The probability that these overflow and overtopping occur while a large discharge of the river Rhine arrives at the Haringvliet is relatively small.

The structural functionality is solely based on reasoning what the effect of sea level rise is on the sluices and, especially the NABLA-beam. The design included a sea level rise which corresponds with the current sea level rise rate of 0.2 m/century. However, even with the least extreme climate scenario from the KNMI2014 the sea level is thought to rise faster than the current rate. The design lifetime will not be reached. It is expected that lifetime extending measures for structural purposes are relatively hard in case the NABLA-beam fails. This part is deeply embedded in the design.

Concluded is that the sluices can not, even when lifetime extending measures are included, fulfil all the functions and requirements within the original design lifetime. The lifetime reached is dependent on climate change. New strategies are thought of in case the average climate scenario occurs.

6.1.5. New Strategies

For the new strategies the following design objective is answered:

Which functional design options can lead to a fulfilment of the requirements and to what degree do they fulfil the criteria?

As stated, the final lifetime of the Haringvliet sluices will probably be reached around 2130 due to failure of all the functions assessed. Because structural failure of the NABLA-beam is expected, lifetime extending measures can not be taken. It is assumed that the requirements for all functions remain similar.

The designing lifetime of a new structure is thought to be 100 years, meaning that the boundary conditions of 2230 should be used for the design. Because of the large remaining lifetime of the Haringvliet sluices and the large uncertainty in boundary conditions, the functional strategies proposed are qualitatively assessed. All strategies are qualitatively assessed. Two functional designs are verified, meaning that the requirements can be met. For the verified functional designs a Multi Criteria Evaluation is carried out. Also a cost indications is made. The criterion used in the multi criteria evaluation are: adaptability, capacity and reliability.

The three main strategies for the Haringvliet chosen are:

- Create an open estuary.
- Build a similar sluice complex.
- Permanent closure of the Haringvliet from the North-Sea in which pumps and a weir are placed.

The three different proposed strategies are worked out, for which the concept of a new sluice complex and a permanently closed Haringvliet are verified. These verified concepts are evaluated in a multi criteria evaluation.
The costs are based solely on the demolishing or building of the new structures. These are the costs for the sluices, locks, fish passages and new roads. Costs are considered separately and are at the end evaluated in combination with the multi criteria evaluation.

With all the outcomes, from the multi criteria evaluation it is concluded that a closure with similar sluices is most favourable.

The results of the MCE and cost indications will be discussed in section 6.2.

6.2. Discussion

In this section the validity of the research is discussed. The methodology, climate scenarios chosen, models used, assumptions done, uncertainties and other discussion points are mentioned here.

6.2.1. Assumptions

Assumptions are made during a research. For the assessment of the final lifetime, multiple assumptions are made. Examples of assumptions are that the bed levels remain the same, the functions and requirements barely change over time, the criteria do not change, that the lifetime of the Haringvliet is based on only four functions and the most influential assumption is that the lifetime is in between the 50% percentiles of the most extreme climate scenarios.

6.2.2. Climate Scenarios

In this thesis the most extreme KNMI 2014 climate scenarios, W_h and G_l, are used. Concerning sea level rise, multiple researches show new mechanisms which could increase the (global) sea level rise. These mechanisms are not fully understood yet. In the most recent IPCC emission scenarios, which the KNMI transforms for the situation in the Netherlands, the effect of these mechanisms are partly included in the sea level rise scenarios. These IPCC 2018 scenarios are not transformed for the Dutch coast yet. Therefore, the scenarios used in this thesis are a point of discussion. In the IPCC 2018 report, the most extreme sea level rise scenario for the year 2100, is almost twice the amount of sea level rise compared to the most extreme scenario used in this thesis. Yet, other recent research, Baart (2018), shows that the mean sea level rise for the Netherlands has not accelerated in the last century. Therefore, it is considered that with the 50% percentiles of the most extreme scenarios, the lifetime estimated is in a realistic range. With a more extreme scenario, the lifetime of the Haringvliet sluices will reduce significantly.

Concerning the climate scenario and the effect on the river discharge of the river Rhine, the same scenarios, W_h and G_l are used as well. The effect on the discharges is that more extremes are found during summer and winter for the scenario Warm. The trend of dryer summers and more precipitation in the winters can be found in researches and historical data analysis. The scenario G_l does not include the dryer summers, as shown in Figure 4.30. It is thought that the scenario of G_l underestimates the extremes concerning river discharges.

6.2.3. Models and Calculations

Assumptions and the influences of the calculation methods will be discussed here.

In this thesis SOBEK, Hydra-BS and Hydra-NL are used. With the calculations of SOBEK a database is created which is used for the Hydra-BS calculations. For Hydra-NL the WBI-2017 database is used. The WBI-2017 database is used to compare the database made with the SOBEK calculations. The SOBEK database is only suitable for Hydra-BS. When no uncertainties are used in the Hydra-NL calculations, the outcomes of both databases correspond with each other, meaning that the self-made database is similar to the WBI-2017 database.

The Haringvliet sluices are incorporated in SOBEK as 17 openings which could be closed by one door. In reality, two doors close one opening, which decreases the probability of failure. The doors incorporated in SOBEK are considered to be of infinite height, which means that overtopping and overflow are not possible. Also leakage through the sluices is not considered. For the SOBEK calculations, the failure time is constant and chosen to be 24 hours. With other failure durations, the calculation will give other results. An expert judged that it is thought to be realistic to have failure durations of 24 hours. However, this will not always be the case.

Other discussion point are the individual calculated effects on the hydraulic loads. With SOBEK two different failure modes are calculated: all doors and 8 doors fail to open or close. However, all possible failure configurations should be calculated to come to a conclusion on the effect on the hydraulic loads. With 8 failing doors the effect is not visible, concluded from Hydra-BS calculations. With 17 doors, the effect is visible for the hydraulic loads. It is therefore thought that with the failure probabilities used, the effects of 12 failing doors and more have a relative small influence on the hydraulic load. Because the effect is limited, it is realistic to only take into account the effect of all doors failing.

The probabilities used in Hydra-BS for the failure of not opening and not closing, are the required probabilities. This is the probability for a single opening, meaning that both doors per opening should fail at the same time. As mentioned, the 17 openings are modelled to be closed by a single door. In reality there are two doors which are independently triggered. The effects calculated are therefore thought to be really conservative.

The influence of the probabilities is relatively large concerning the Hydraulic loads. This is shown with the Hydra-BS calculations for which the required probabilities are multiplied with 10. However, when taking into account the model uncertainty, which is calculated with the WBI 2017 database in Hydra-NL, the effect of failure due to not opening and not closing is very small. Therefore it can be concluded that the model uncertainties but also the uncertainties in the statistics of the boundary conditions, which are included in Hydra-NL and not in Hydra-BS, lead to a large increase of the hydraulic loads. The increase of the hydraulic loads on the hinterland are taking into account in the form of, the model and statistical uncertainty, the effect due to failure and the effect due to overtopping and overflow of the sluices.

The calculations executed with Hydra-BS underestimate the actual hydraulic loads. Dike segments of the hinterland are assessed for the failure mode overtopping and overflow. Other failure modes are not considered due to the fact that the influence of the Haringvliet sluices is mainly on the water levels. Other failure mechanisms will fail with larger water levels, but other conditions are needed to fail. Because a lack of time and available data to find these conditions, decided is to only assess overtopping and overflow.

The assessment was carried out with Hydra-BS. The dike sections used are from VNK, which deviate slightly from the actual dike profiles. The effect of these deviations is thought to be negligible. With Hydra-BS the loads were calculated for the return period for allowable overtopping rates of 1 and 10 l/s/m. Because Hydra-BS does not include model and statistical uncertainty, the effects were added to the hydraulic loads. The uncertainties were calculated by comparing calculations between Hydra-BS and Hydra-NL, without failure mode. These differences were added linearly to the hydraulic loads which are calculated with Hydra-BS. By adding these uncertainties linearly, this could give over and underestimations of the final lifetime.

Because the set of SOBEK calculations is only executed with two sea level rise scenarios, the results from the Hydra-BS calculations are extrapolated. This extrapolation is thought to be quite inaccurate because only two points are used. Comparing the results of the calculations with the failure probabilities per mechanism as described in Rijkswaterstaat Projectbureau VNK (2014), the outcomes are considered reasonable.

Concluded is that the calculations with SOBEK, Hydra-BS, Hydra-NL and the extrapolated expected sea level rise, are reasonable, but there is room for improvement.

For the calculations concerning the influence of the river discharges, mostly other researches are used to come to a conclusion. In some of the assessments some assumptions are made, which in combination with the research, are thought to be valid.

For the ecological and fresh water functions, multiple assumptions are validated with expert judgement. For the assessment of the Haringvliet sluices for the availability of fresh water, only salt intrusion via the sluices is taken into account while backward salt intrusion will firstly become a problem in the Haringvliet. However, the Haringvliet sluices can not avoid this and are therefore not assessed for this mechanism. Concerning ecology, the assumptions are, that with a reduction of 50% of the time in which fish could migrate from the sea to the Haringvliet and that with a closure of 50 consecutive days, the Kierbesluit will not work any more. These assumptions are based on reports and papers about the migrating species in the Haringvliet. Some of these reports contain simulations and data analysis which are used as reference.

6.2.4. Functional Strategies

For the functional strategies, the assumption that the Haringvliet sluices need to be removed is valid in case of an average scenario. In case of a relatively large sea level rise and more extreme river discharges, the lifetime is determined by the fresh water availability and ecology. In that case, other measures can be taken to increase the lifetime.

For the functional strategies, the multi criteria evaluation is based on multiple assumptions and an estimation of what will happen. These estimations are substantiated by papers and reports. From this multi criteria evaluation it becomes clear that the differences between the variants is relatively large. Due to the many assumptions, the large uncertainties and large time span (circa 100 years) it can be stated that the functional strategies proposed and the outcomes of the evaluation is very unreliable.

It is suggested to assess the structure at least once every 10 years. The functions and requirements the sluices must fulfil can be analysed and betimes a new strategy can be come up with. With a assessment every 10 years, the influence of multiple technological advances can be included. This can change the program of requirements and criteria for a sluices drastically, meaning that the lifetime of the current structure can change as well.

6.3. Recommendations

In this section recommendations are given. Future research topics which are not treated in this thesis are stated here.

- In this thesis the required failure probabilities for not opening and not closing are used. These are assumed to be constant. The actual failure probabilities are unknown. Research to the actual failure probabilities would give more insight in the effect on the hydraulic loads and if it is necessary to incorporate these failure mechanisms. Also the dependency between all the doors is a good point for new research. Including the effect of sea level rise on the failure probabilities will lead to a better and more substantiated answer to the question if the failure mechanisms are of importance for the future.
- In this research all functions the Haringvliet due to the Haringvliet sluices fulfils are assessed. For the Haringvliet sluices, only the failure mechanisms of not opening and not closing are assessed. Other failure mechanisms as piping, structural stability and the influence of vibrations due to traffic are qualitatively assessed or assumed to be negligible. Research to all the other failure mechanisms of the Haringvliet sluices could give better insight in the remaining lifetime of the sluices.
- Multiple climate scenarios should be simulated with SOBEK. Extrapolating the effects of sea level rise based on two scenarios is insufficient to come to a thorough conclusion.
- The quantities of leakage and overtopping and overflow of the Haringvliet sluices should be researched in combination with future sea level rise. The differences over the sluices will increase and the water level will rise. The probability that the effect of overflow and overtopping is significant, increases. The effect of sea level rise on the overtopping and overflow quantities for the Haringvliet sluices will gain better insight in the hydraulic loads on the hinterland. Including these insights in the SOBEK model will lead to more accurate calculations.
- The large uncertainties and the number of available scenarios for climate change, make it hard to conclude on the lifetime of a structure. The range the sea level will rise in 2100 is in the order of meters. Concluding on the remaining lifetime of a structure will therefore lead to a range in the order of hundreds of years. It is therefore suggested that research on climate change must be focussed on the probabilities that an available scenarios will occur. The outcomes will help to assess multiple structures more accurately, which increases the safety or could save money.
- Currently, the salt concentrations around the Haringvliet are measured. With longer datasets, these measurements could be used as validation of a 2 or 3D salt distribution model for the Haringvliet.
- Another solution which is presented in the research of Reeze et al. (2018). In this research it is pleaded to change the water distribution of the rivers Rhine and Meuse upstream of the Haringvliet and Nieuwe-Waterweg. Multiple fresh water intake points are not necessary any more and the Nieuwe Waterweg could remain open. The Haringvliet sluices remain as they are.
- Another possible new strategy is suggested at www.delta21.nl. Here it is suggested to built a tidal like in the North Sea at the mouth of the Haringvliet. This plan is not fully worked out yet. It is thought that the tide creates energy, reduces the probability of flooding and increases the ecological value of the Haringvliet. It is thought that the sluices can be opened all the time.

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Appendices

A

Current Delta Work

In this chapter the design and construction of the Current Delta Work is given. Research to the lifetime of the Haringvliet Delta Work depends on the structure and design criteria used for the current Delta Work. The last section of this chapter states the current probability of failure allowed for the Haringvliet Delta Work.

A.1. Design of the Haringvliet Dam and Sluices

The outline of the Haringvliet work design was ready in 1955. This is 2 years after the establishment of the Delta Commission (Ferguson, 1971). Main goals of this outline were to determine the:

1. Functions, demands and wishes
2. Location of the Haringvliet work
3. Possible designs
4. Costs

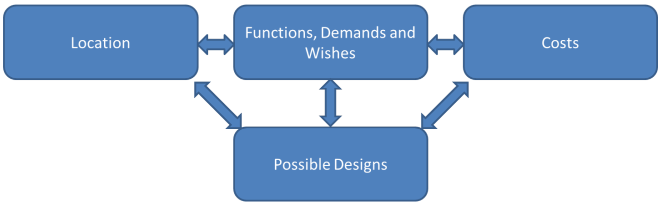


Figure A.1: Scheme of the main goals and their relations, from Ferguson (1971).

At a later stadium, a fifth goal, the construction, was added. In Figure A.1 the four main goals and their interaction are showed in a scheme. Almost all goals mutually influence each other.

A.2. Functions, Demands and Wishes to be fulfilled by the Haringvliet Sluices and Dam

The functions the Haringvliet Delta Work have to fulfil were mostly considered from a hydrological and practical view. The functions, demands and wishes (the middle block in Figure A.1), which the Haringvliet Delta Work should fulfil are described in Ferguson (1971):

- The sluice complex is part of the flood defence and should therefore have a probability of failure of 10^{-4} per year.
- Discharging of high river discharges to the North-Sea, without water levels exceeding norms in the delta
- Regulate the discharges in such a way, that salt intrusion for the Nieuwe Waterweg will be avoided
- Regulate the water level for the fresh-water intake at the Haringvliet
- Regulation and discharging of ice sheets from the river
- Let icebreakers sail through the sluice openings
- When building the Northern part of the dam, the gates must be open to reduce the flow velocities at the northern part
- Remove salt leakage water
- Let fish pas through openings, which are available in some piers
- Discharging on sea to reduce sedimentation outside of the sluice during dry periods

A.3. Location of the Work

The second goal to achieve (left block in Figure A.1) during the design of the Haringvliet Delta Work was to decide for a location. To decide for a location, three locations are compared. Most important by choosing these three locations was the possibility to build a construction pit at a shoal. This was done to reduce the flow area least. Depths at shoals are relatively small and would therefore influence the flow area least. Large reduction of the flow area would cause larger flow velocities, which are undesirable during construction (Deltadienst, 1970; Ferguson, 1971). Looking at the possibilities to construct at a shoal, three locations were chosen: De Slijkplaat near Hellevoetsluis (purple in Figure A.2), De Plaat van Scheelhoek between Stellendam and Goedereede (green in Figure A.2) and at the sea-side at Goedereede (blue in Figure A.2).

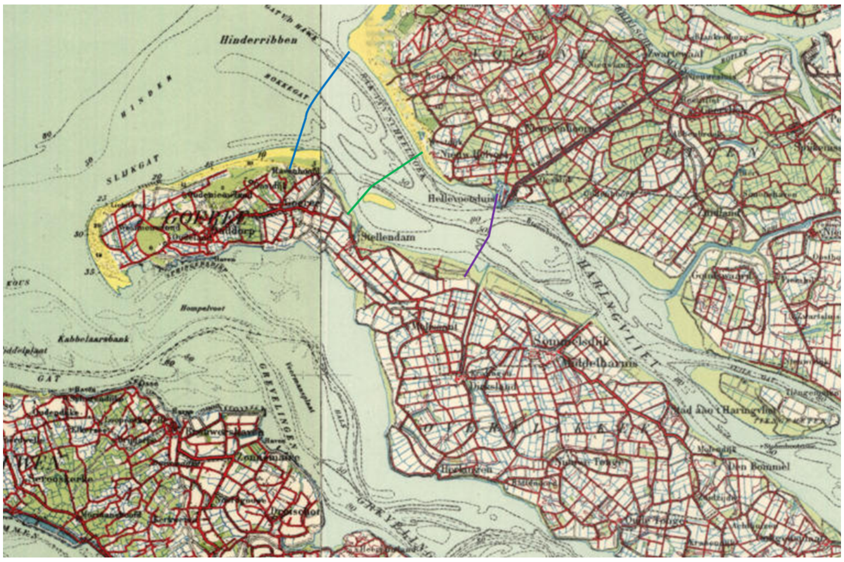


Figure A.2: Three possible locations for the closure of the Haringvliet, from Ferguson (1971).

For the final location some criteria to be thought of were listed as follows (Ferguson, 1971):

- Sediment transport along the coast
- Development of channels and shoals seaward of the sluices
- The capacity of the soil
- The expected siltation in front of the sluices
- Keep the fishing industry going
- Hydrodynamic forces on the sluice (gates)
- Road over the sluice and dam
- Length of the coastline
- Area of fresh water in the Haringvliet basin
- Recreational areas
- Working hours due to tides during construction of the construction site.
- Risk during construction
- Maintenance of the channels
- Removal of ice

The weight of each mentioned criterion above is not equal. Some criteria had a larger influence on the definite location than others. Most important are the factors of sediment transport and sedimentation in channels, hydraulic loads on the sluices, siltation in front of the sluices and periods which can not be worked during construction. When the closure was finished, the current was reduced significantly. This could cause a sedimentation problem in the channels in front of the sluices. Also embankments would form in front of the sluices. Between the embankments and the Haringvliet closure work a short-tidal basin would form.

Looking at the more important criteria, the option at Goedereede would cause sedimentation problems. The tidal basin would become so small, that too much sediment will settle in the existing gullies. For this location, wave attack from the North-Sea would also be largest at Goedereede. This location was not considered suitable. ’De Slijkplaat’ and ’De plaat van Scheelhoek’ both had pros and cons. Eventually, the location of ’De Plaat van Scheelhoek’ was chosen based on the following aspects:

- More suitable location for traffic
- More suitable location for fishermen
- Shorter coastline
- Less danger during construction

- Easier to keep the Voornse Kanaal fresh
- Easier to provide fresh water for agricultural purposes at de Kop van Goeree
- Larger fresh water lake

A.4. Possible Designs and the Construction of the Haringvliet Dam and Sluices

The third goal to achieve (bottom block in Figure A.1) during the design of the Haringvliet Delta Work was to have a detailed plan for the construction phase. In history, never a dam and sluice complex like this was built. This complex roughly consists of three different parts: the lock at the south side of the closure near Stellendam, the sluice complex and the dams connecting the lock, sluices and land with each other. In the following sections these structures will be described.

Important was the order of construction, which was chosen in such a way, that the flow velocities would not become too large in the estuary, meaning that the remaining flow area should be large enough during construction. The sluices and lock were built first. The sluices were built at the shallow Plaat van Scheelhoek, leading to a relative small reduction of the flow area. When the sluices and lock were ready, the doors were kept open, causing that the flow velocities during construction of the dams were not too large. The dams were built last, leading to a closure of the Haringvliet from the North-Sea and a connection between Voorne-Putten and Goerree-Overflakkee.

A.4.1. Construction of the Lock

The Goereese lock has been built in the dry. A construction pit was built by creating a polder in the Haringvliet estuary. The sand dikes were made by nourishing sand from offshore. Sand dikes turned out to be not sufficient and it was decided to cover them with asphalt. The polder was pumped dry. In this dry construction pit, the Goereese lock was built. The lock is 144.50 meters long, 16.38 meters wide and the bottom is constructed at NAP - 5.0 meters. After completion, the dikes were removed and the doors were kept open.

A.4.2. Design and Construction of the Sluices

Designs and Criteria

For the design of the sluices, multiple demands were set. The first demand was that the sluices could open and close. The second demand was that the width of the sluice gates should be sufficient for ice sheets coming from the rivers. Further the structural design depends on the guiding hydrological conditions. Numerical models were not available at that time and therefore model tests were executed in laboratories. Significant wave height, significant wave period and the zero order energy spectrum were determined from tests in the labs. Outcomes are shown in Figure A.3.

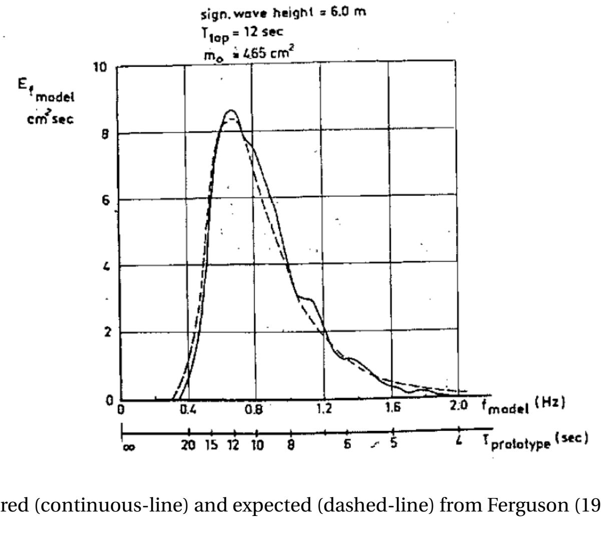
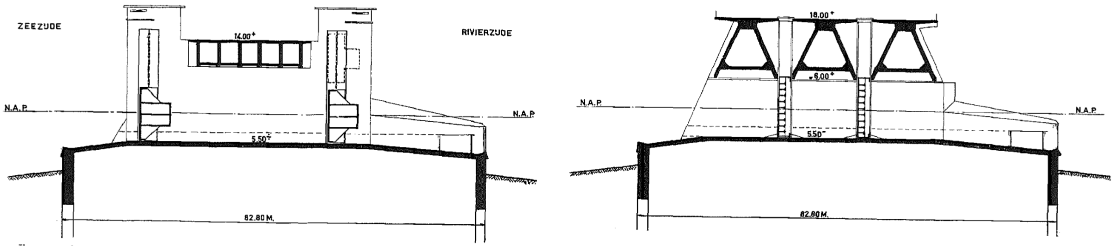


Figure A.3: Wave spectrum measured (continuous-line) and expected (dashed-line) from Ferguson (1971)

For the Haringvliet sluices, three different designs were considered. To close off one kilometre with one sluice was considered impossible, (Ferguson, 1971). Therefore, the first design criterion was to have multiple doors. Looking at other works, an opening of 100 meters was suggested. This was deemed necessary for the discharge of river ice. Looking at all the designs, 100 meter per sluice segment appeared to be constructional and economical not efficient. The first design, which consisted of straight sluice doors was considered efficient for a width of 20 meters. Otherwise, calculations showed, the sluice segment would become heavy and expensive. Therefore the first design, shown in Figure A.4a, was not considered any more (Ferguson, 1971).

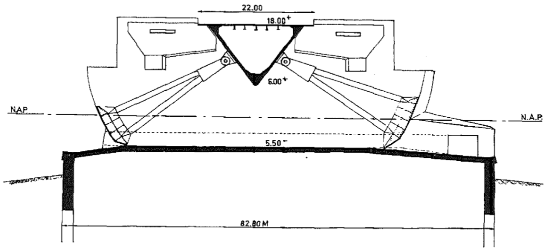
The second design consisted of large vertical doors. The doors should be supported at the bottom and top op the bridge. For this design two problems arose. First problem would be the height of the total structure. These vertical doors have a length of 11.5 meter. When opening these doors the height of the sluices should be NAP + 18.0 meter, see Figure A.4b. Second problem was the support when opening the doors. The doors would lose the support of the bottom and due to large forces from waves, it would be hard to (Ferguson, 1971).

To cope with the height-problem, the third design was based on moving arms. To support these arms, a large concrete beam was needed. This beam can be seen as the spine of the sluices. Extra advantage was the possibility to use the top of this beam as foundation for the road, see Figure A.4c. After some structural and economical calculations, the third option was worked out in more detail (Ferguson, 1971).



(a) Design 1

(b) Design 2

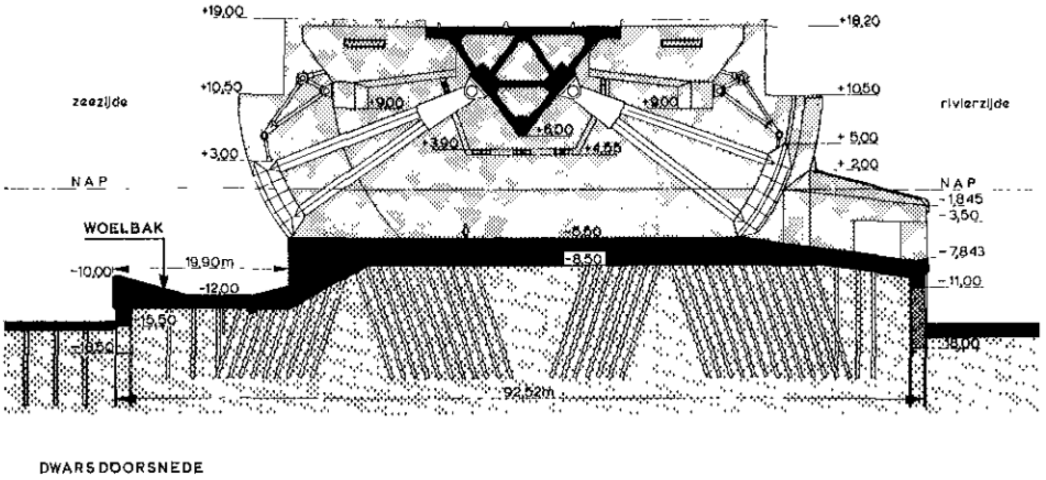


(c) Design 3

Figure A.4: The three designs for the closure of the Haringvliet, from Ferguson (1971)

The forces of the waves on the sluice gates should eventually be transferred to the piers. These forces are transferred from the segments to the arms, which on their turn transfer the forces to the Nabla beam. This beam eventually transfers the forces to the Nabla beam. To construct fully retaining sluice segments, the arms and retaining door would have dimensions which were constructionally not feasible (Van der Meer, 2008; Ferguson, 1971). The constructional calculations showed that the sluice door at the sea side could maximum be NAP + 3.0 m high to avoid excessive forces on the Nabla beam. The forces at the sea side door are large due to the waves and due to the configuration and shape of the doors. The doors at the river side, their configuration is more favourable concerning absorbing wave forces and were constructed NAP + 5.0 m high (Ferguson, 1971). The sea and river door heights in total are respectively 8.5 and 10.5 meters. In Figure C.1b a detailed drawing is shown of the final design, including dimensions.

Construction
For the sluices which are one kilometre long, a dry construction pit was built on the Plaat van Scheelhoek. It took two years to construct the construction pit at the Plaat van Scheelhoek. The construction pit was 1.4 by 0.6 kilometres. The dike rings around the construction pit, were nourished with sand. The nourished sand was kept in place by asphalting these nourished dikes. Transport of goods was done by a bridge which was built between Goeree-Overflakkee and the construction pit.



!ht

Figure A.5: The cross section of the sluice complex including heights, with the seaside at the left and the riverside at the right, from Deltadienst (1970)

Research showed that due to relatively large flow velocities when discharging, erosion pits could occur. This could undermine the stability of the sluices. Also, the soil at the Plaat van Scheelhoek was too weak to build on directly (Ferguson, 1971; Deltadienst, 1970). Therefore, a protection layer was made out of concrete. This protection layer was constructed over concrete piles which were driven into the ground which can be seen in Figure C.1b. In Figure C.1a the dimensions of the soil protection structure can be seen. The soil protection around the sluices consists of reinforced concrete slaps (Dutch = Gew.beton) and further from the sluice complex, rubble is used (Dutch = stortsteen).

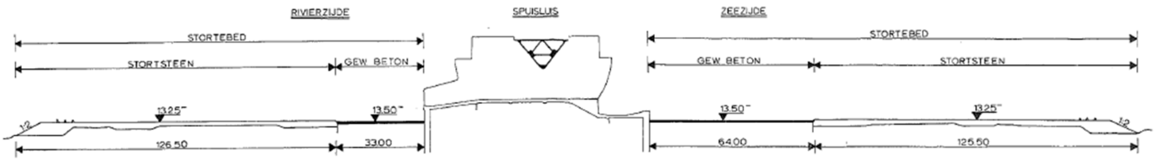


Figure A.6: The cross section of the Haringvliet surroundings. As can be seen are the concrete slab and the filter bed in front of the concrete slab. With on the left side the riverside (Dutch = Rivierzijde) and on the right side the Seaside (Dutch = Zeezijde). From Ferguson (1971)

After finishing the protection layer, the piers were built. The piers have multiple functions. Primary function is to absorb the forces from the Nabla girders. Further, the piers are provided with ice cutters at the river side and fish passages are built through some piers.

After the piers were finished, the Nabla girders were transported to the construction pit. These were placed between the piers. 22 girders were placed in between two piers. The open spaces between the girders were closed with concrete. After closing the gaps between the girders, one massive Nabla beam was finished. This was done for all gaps between the piers which meant that the concrete skeleton of the Haringvliet Delta Works was finished (Ferguson, 1971).

The last part of the sluice construction were the arms and sluice gates (Ferguson, 1971; Deltadienst, 1970). In total 34 sluice gates were needed, 17 at the sea side and 17 at the river side. Per sluice segment, four arms were needed, which were attached to the Nabla beam. These arms are attached with hinges to make the arms rotatable. After installing the arms, the segment sluice doors were transported into place. This finished the construction of the Haringvliet sluices in the construction pit.
In Figure A.7 a detailed drawing of the sluice is shown.
After the construction of the sluices, the construction pit was removed and the sluices were opened for the

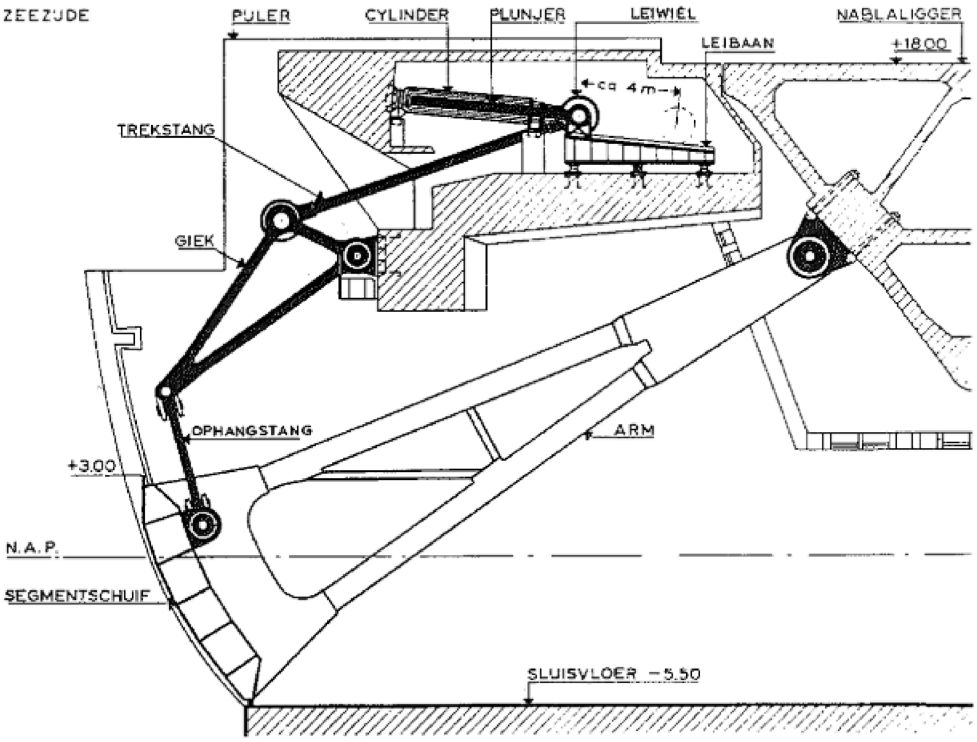


Figure A.7: Detailed drawing of the connection of the sluice doors via the arm to the Nabla beam. Image from Ferguson (1971).

first time. Opening of the sluices was necessary to reduce the flow velocities during the construction of the dams, to finalise the closure of the Haringvliet from the North-Sea.

A.4.3. Construction of the Dams

After finishing the sluices and removing the ring dikes around the sluices, the flow area increased again to 21.000 m^2 (Ferguson, 1971). Three openings had to be closed. Between Voorne-Putten and the sluices, this opening was filled with concrete blocks, between the sluices and the lock, that opening is filled with sand and rock and the opening between the lock and Goeree is filled with sand and rock.

The closure between the lock and Goeree was started with. This was done with sand and rocks. The closure later was used as transportation place to the construction pit for the sluices and lock. After finishing the sluices and lock, started was with the closure of the Noord-Pampus, the gap between the sluices and lock. This was a relatively small gap. Due to the opening of the sluices the flow area increased to such an extend, that it was possible to close this gap with sand and rock.

The closure between Voorne-Putten and the sluices was constructed by using cable cars. These cable cars dropped approximately 93,000 concrete elements into the opening, to create a dam. After this closure, approximately $11 \cdot 10^6$ m^3 sand was nourished over the concrete blocks. With this, the dam was formed. The height of these dams is built to NAP +5.0 m and the width of the crest is approximately 50 meters (Ferguson, 1971). On the crest of this dam a road was built which connects with the road over the sluices. This road connects Goeree-Overflakkee with Voorne-Putten.

A.5. Costs

The costs of all the Delta Works together, before construction, were estimated to be 1.5 to 2.0 billion gulden (old Dutch currency). After completion of all the Delta Works, the total costs were estimated to be 9.3 billion gulden. The costs for all Delta Works were larger due to the implementation of advanced techniques and research done in laboratories (Deltadienst, 1970). From this 9.3 billion gulden, 720 million gulden was needed for the construction of the Haringvliet dam and sluices (Ferguson, 1971).

Figure A.8: Costs of all Delta Works and the costs of the Haringvliet Sluices, from Algemeen Dagblad (1986)

B

Stakeholders

A stakeholder analysis is carried out to see what power and interest a stakeholder has. Stakeholders can be defined as: 'every individual or group who influences or is influenced by a project for which an organisation want to reach their goal', (Freeman et al., 2010). When executing a stakeholder analysis for the Haringvliet, the following questions can be asked:

- Who are the stakeholders?
- What are their goals?
- What are their stakes?
- What influence and potential has the stakeholder?
- Is there an external network which the stakeholder could mobilize?

Answering these questions gives an idea of how important and how much interest each stakeholder has. Still, some answers could be quite subjective. This has to do with the human influence, which want the questions to be answered in their or their companies favour. Still, a stakeholder analysis gives good insight in the stakeholders which will work with you on a project or want to be kept informed.

During a stakeholder analysis, the stakeholders can be placed in a participation matrix, to see at what stage of the project, which stakeholders do or need what. An example of a participation matrix can be seen in Table B.1.

Table B.1: An example of a stakeholder participation Matrix, based on (Administration Overseas Development, 1995)

Step in cycle	**Inform**	**Consult**	**Partnership**	**Control**
Problem Formulation & Search for Solutions				
Plan Development				
Implementation				
Monitoring and Evaluation				

For the following stakeholders, the stakeholder participation matrix is filled in:

- Rijkswaterstaat
- Provinces
- Municipalities
- Water Board Hollandse Delta
- Consultancy companies
- Agricultural companies
- Drink water companies
- Industrial companies
- NGO's
- Inhabitants near the Haringvliet.

Table B.2: Participation Matrix of the Haringvliet, based on Administration Overseas Development (1995).

Step in cycle	**Inform**	**Consult**	**Partnership**	**Control**
Problem Formulation & Search for Solutions		Rijkswaterstaat Consultancy companies	Rijkswaterstaat Waterboard Consultancy companies	
Plan Development	Municipalities. NGO's. Agricultural, drink water and industrial companies. Municipalities	Rijkswaterstaat Consultancy companies Waterboard Industrial companies (engineering)	Rijkswaterstaat Waterboard Consultancy companies	Municipalities. NGO's. Agricultural, drink water and industrial companies. Inhabitants near the Haringvliet.
Implementation	Agricultural, drink water and industrial companies. Provinces Municipalities	Rijkswaterstaat Consultancy companies Waterboard	Rijkswaterstaat Waterboard Consultancy companies Industrial companies (engineering)	Consultancy companies Rijkswaterstaat
Monitoring & Evaluation	Agricultural, drink water and industrial companies. Provinces Municipalities. Inhabitants near the Haringvliet.	Rijkswaterstaat Consultancy companies Waterboard NGO's	Rijkswaterstaat Waterboard Consultancy companies Industrial companies (engineering)	Consultancy companies. NGO's. Rijkswaterstaat.

To fill in the participation matrix for each stakeholder, the questions at the beginning of this section are kept in mind, and answered per stakeholder. The participation matrix for the Haringvliet will become as Table B.2. From this participation matrix an power-interest figure is created. This is done by looking at the various stakeholders and how often these are mentioned in each column of the participation matrix. When a stakeholder is mentioned often in the columns: inform or control, these stakeholders have quite some interest, but not to much power. For the other columns, partnership and consult, the power of these stakeholders is large, leading to a power-interest grid as show in Figure B.1.

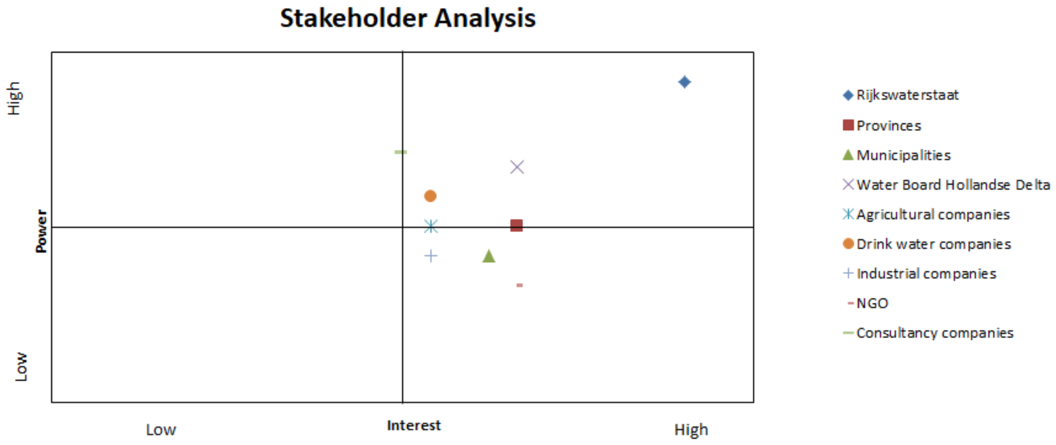
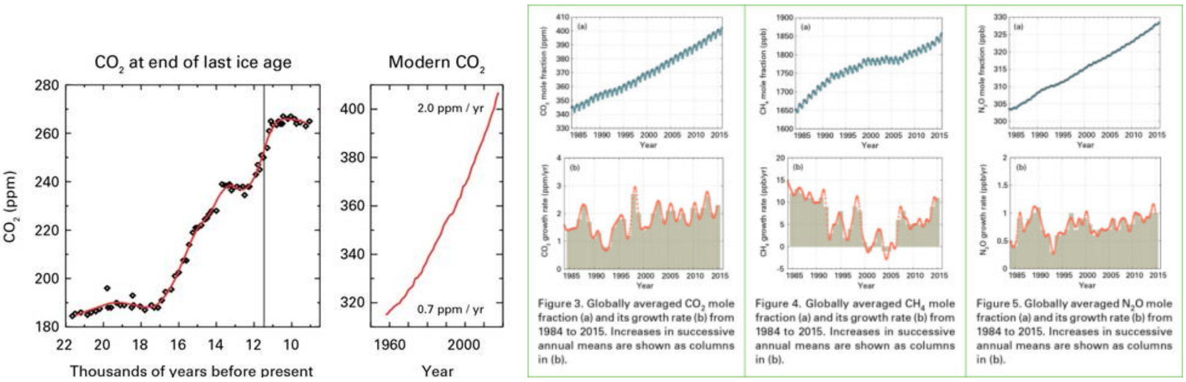


Figure B.1: Stakeholder Analysis for the Haringvliet area.

C

Climate Change

The climate is changing which is leading to Global Sea Level Rise. The level of Greenhouse gasses increased which lead to a mean global temperature rise. Reason of increasing greenhouse concentrations, especially CO_2, are the increased fuel consumption by humanity and due to nature phenomena like El Niño and volcanic eruptions (Keenan et al., 2017). In the last decades, green house gas levels have reached quantities which have not been reached since the start of the measurements. Since 1950 the atmospheric CO_2 concentration increased from 290 parts per million (p.p.m) to 400 p.p.m in 2015.



(a) (b)

Figure C.1: a) CO_2 emissions since ice age and modern $CO\ _2$ levels, from (WMO, 2015) b) Emissions of CO_2, CH_4 and N_2O, which are all greenhouse gasses, from (WMO, 2015)

Expected is that the CO_2 concentration will increase in the near future (IPCC, 2014a). However, in Keenan et al. (2017) the growth of the CO_2 will decrease. This has to do with terrestrial ecosystems, which act as sinks for CO_2 since the beginning of this century (Keenan et al., 2017).

Previously expected was that the global mean temperature (GMT) would increase with 0.2 °C per decade (IPCC, 2007). Meaning that in 2100 the GMT would increase by 2.0 °C compared to 2000. New research suggest that In the last century the Global Mean Temperature increased with 0.7 °C, as can be seen in Figure C.2. Multiple countries agreed that a global mean temperature increase causes negative effects which should be avoided. Therefore, in the UNFCCC (2015) engagement, which is signed by 195 countries (United Nations, 2018), is stated that the mean global temperature may not rise more than 2.0 °C compared to the pre-industrial levels. This must be achieved by reducing the emissions of greenhouse gasses to 40 gigatonnes per year (UNFCCC, 2015). What makes it complicated is that the pre-industrial levels are not defined in UNFCCC (2015). In this thesis, chosen is to see the pre-industrial levels as the period from 1720-1800. In that period, the number of volcanic eruptions and the levels of solar radiation were similar to those nowadays. When comparing current temperatures with the period 1720-1800, concluded can be that the differences are likely caused by human activities (Hawkins, 2017).

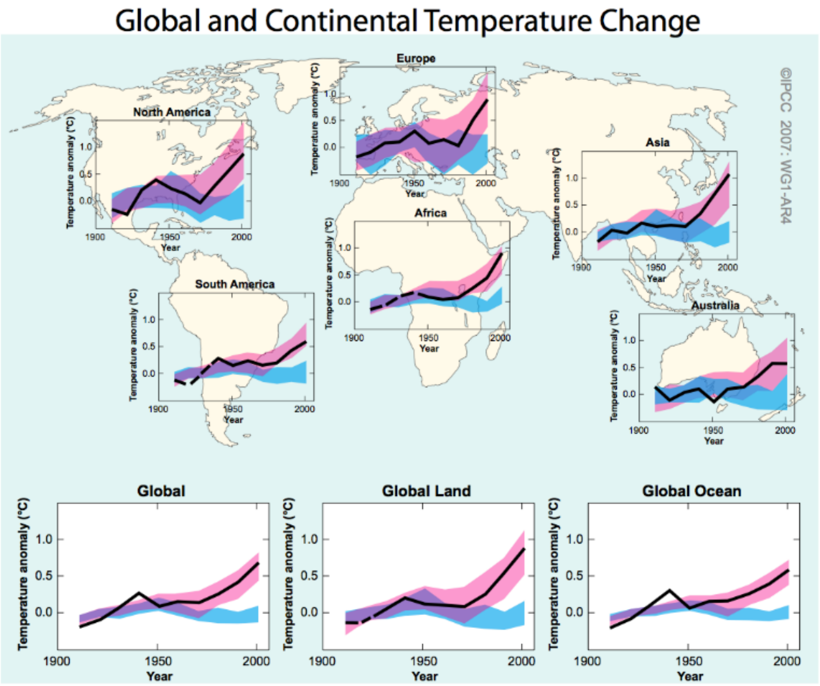
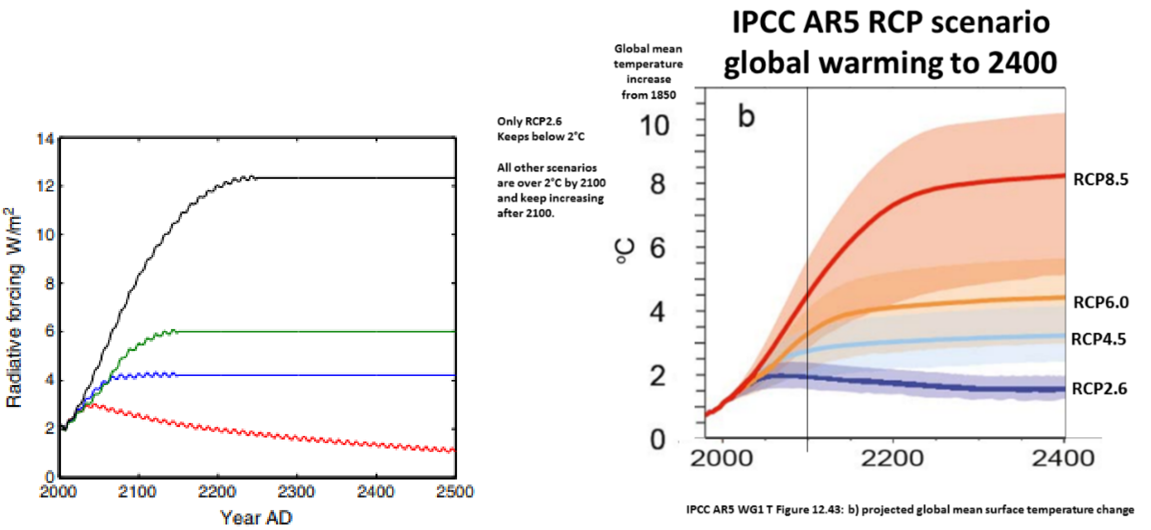


Figure C.2: Global variation of temperature over time, in which the local differences in time are given. At the bottom the mean temperatures from all continents. The black line are the measured temperatures, the blue bands are intervals of 5-95% if only natural forcings would have been taken into account and the pink band is including the anthropogenic forcings. From (IPCC, 2014b)

In IPCC (2007) four Representative Concentration Pathways (RCP) scenarios have been developed. These scenarios are named after the expected radiative forcing (W/m^2) in 2100. In these scenarios the expected greenhouse gas concentrations and natural forcings are taken into account. The RCP2.6 scenario has the lowest expected radiative forcing in 2100. This is due to reduced greenhouse gasses and is shown in red in Figure C.3. RCP4.5 and RCP6.0 are two different stabilisation scenarios and are shown respectively as the blue and green lines in Figure C.3. These radiative forcings stabilize around 2100 and stay constant afterwards. The extreme radiative scenario RCP8.5, is the black line in Figure C.3a. The 8.5 W/m^2 is reached in 2100. In 2200, this scenario reaches 12 W/m^2. After 2200 the forcing stabilizes at 12 W/m^2.

These larger forcings cause an increase in global mean temperature. The expected temperature increase is shown with the solid lines in Figure C.3. Due to the large uncertainties a bandwidth is shown along with the expected temperature. The bandwidth becomes larger over time because the uncertainties increase.



(a) The four RCP radiative forcings scenarios by the IPCC

(b) RCP temperature changes due to the expected radiation forcings. The temperature changes are surface temperatures and relative to 1986-2005.

Figure C.3: The radiative forcings (left) and global warming scenarios (right)

C.1. Global Sea Level Rise

As stated, predicting sea level rise is hard because of all the different processes which play a role. Some of these processes influence each other, which cause negative or positive feedback. These processes influencing each other can be seen in Figure C.4.

In Bindoff et al. (2007) explains the mechanisms causing Sea Level Rise. These mechanisms are melting glaciers, melting ice sheets (West Antarctic Ice Sheet and Greenland) and Global mean thermal expansion (Katsman et al., 2011). As already stated, climate change causes that the mean temperature expected climate change and the following larger global mean temperature, all these processes will cause SLR.

Thermal Expansion

Sea level rise and fall can be locally seen, depending on the temperature. If the water of an an ocean warms, the level rises and if it cools it drops (Bindoff et al., 2007). The volume of water is not only dependent on temperature but also on pressure. Therefore, the global sea level is dependent on a three-dimensional distribution of ocean temperatures and pressures (Bindoff et al., 2007). Figure C.2 shows that the temperatures are rising. Due to the rising air temperatures, the temperatures of all water bodies increased too. Multiple researches have been done to see what influence increasing water temperature has. One outcome of these researches is that with higher temperatures, water expands more. Thermal expansion due to climate change and the effect on global mean SLR can be seen in Figure C.5. The effect of thermal expansion contributes to half of the total Global Sea Level Rise (Bindoff et al., 2007). Locally the effect of thermal expansion can be significantly larger or smaller than the Global effect. Another effect on local Sea Levels is the Salinity (halosteric steering).

Melting Glaciers and Ice Caps

Melting glaciers and ice caps are the most visible indications of climate change. The mass of ice caps and glaciers, at the surface, is determined by the local climate. Glaciers and ice caps have different masses year round (Katsman et al., 2011). Large parts of the world have summers and winters. At these parts, in winter the ice and snow mass increases (accumulation) and in summer a percentage of mass melts (ablation). If these differences of accumulation and ablation do not differ over the year, the total mass loss equals zero. Temperatures and precipitation patterns are changing due to climate change. Expected is that worldwide the ablation rate will increase and the accumulation rate will decrease, causing mass loss (IPCC, 2007; Katsman et al., 2011). The effect of other precipitation patterns is yet not fully understood. What is known, is when precipitation comes down in the form of snow, it gives negative feedback on glacier melt, meaning that the glacier will not melt further. If the precipitation is rain, mass loss will further increase (positive feedback)

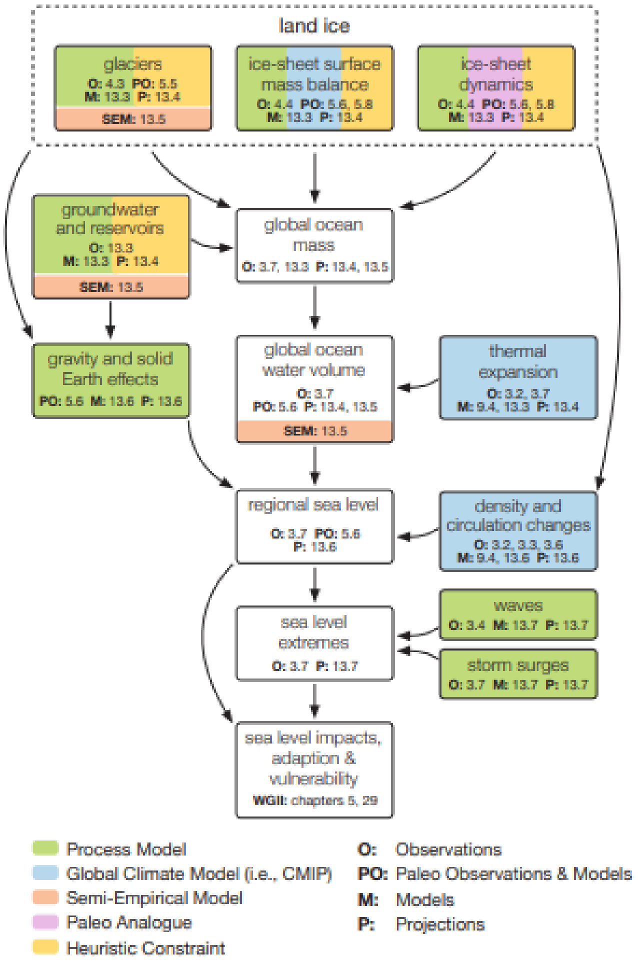


Figure C.4: All processes which cause SLR and which processes influence each other, from (Church et al., 2013)

(Kopec et al., 2016). Due to Climate Change it is expected that it will rain more often and snow less than nowadays. Meaning that glaciers will melt more. Melting glaciers contribute to a large extend to Sea Level Rise (Katsman et al., 2011).

Melting Antarctic Ice Sheet and Greenland Ice Sheet

The melting of the Antarctic ice sheet (AIS) and Greenland ice sheet (GIS) are the most uncertain factors in the prediction of SLR (Katsman et al., 2011). The understanding of dynamic ice sheet behaviour is limited due to two factors, the complexity and the lack of long-term data. At present, observations and measurements state that the WAIS is losing mass. The East Antarctic ice sheet (EAIS), however does not seem to change in volume. In total the AIS is losing mass (Katsman et al., 2011).

New studies suggest that due to increasing emission of greenhouse gasses, leading to global mean warming, cause the Antarctic ice sheet to melt (Tollefson, 2016; le Bars et al., 2017; Strauss et al., 2015; DeConto and Pollard, 2016). The Intergovernmental Panel on Climate Change (IPCC) investigated in IPCC (2014a) the potential SLR due to melting of the WAIS. The contribution to SLR due to melting of WAIS is presumably less than 34%. But as stated, the understanding of the dynamic ice sheet behaviour is not fully understood yet. However, models become better due to new research and newly discovered processes which are included in these models, as done by DeConto and Pollard (2016). Processes included in new models are hydrofracturing and ice cliff failure. Hydrofracturing is the process in which melt water runs into ice cracks which are present at the surface of the ice sheets. The water infiltrates deeply in this ice. Therefore, parts of ice will break of the ice sheets which is ice cliff failure. Ice cliff failure is due to the weight of ice cliffs. If ice cliffs become relatively large, their weight becomes larger than the shear stress between the ice sheet and the ice cliffs. Both hydrofracturing and ice cliff failure can be seen in FigureC.6. This process, called ice cliff failure, in which

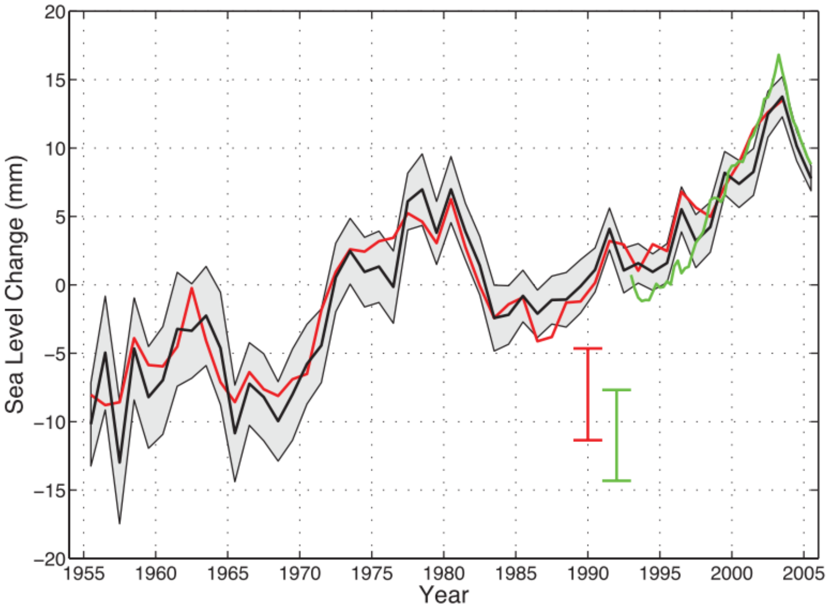


Figure C.5: Relative SLR due to thermal expansion of water basins, from (Bindoff et al., 2007). The red line is from Levitus et al.(2005) and the black one from Ishii et al. (2006). The green line is from Willis et al.(2004). The shaded band is the 90% confidence interval for the red and black line.

large ice cliffs break, cause WAIS mass loss (DeConto and Pollard, 2016; KNMI, 2016). Due to these new insights and new models, predictions show larger SLR rise than previously thought.

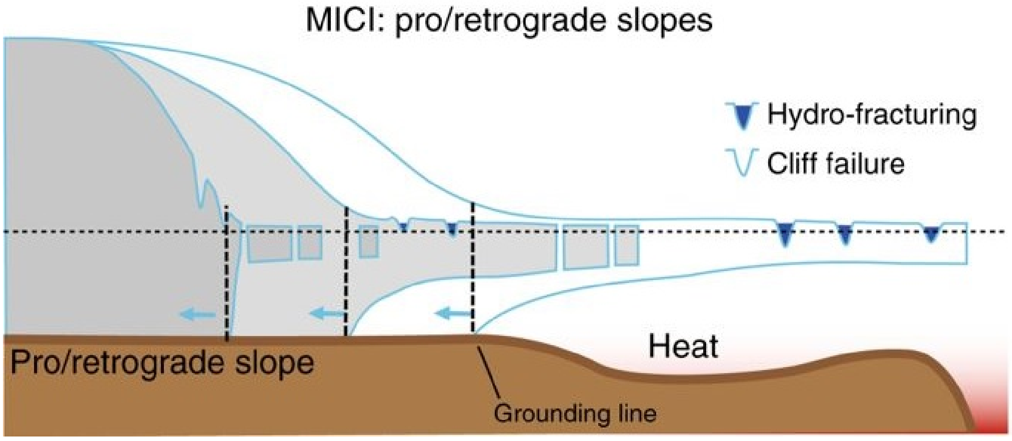


Figure C.6: The phenomena hydrofracturig and ice cliff failure which cause ice mass loss of the WAIS, from Pattyn (2018)

The Greenland Ice Sheet (GIS) is losing mass since the beginning of the nineties (Hu et al., 2011). Estimated is that at the beginning of the 21st century the GIS will lose around 200 gigatons of ice (Hu et al., 2011). The mass loss seems to be accelerating since the nineties. If the concentration of green house gasses keeps growing at the current rate, a significant SLR is expected due to the melting GIS. In Figure C.7, multiple scenarios can be seen. All scenarios are coming from the IPCC A1B scenario, (Nakicenovic and Swart, 2000). This is the midrange emission scenario which includes an increase of greenhouse gasses from 1999 of 368.5 ppm till 2099 of 688.5 ppm. This level of 688.5 ppm is kept constant till 2199.

Researches showed an increase of global warming due to an increase in greenhouse gasses, which led to the UNFCCC (2015). In UNFCCC (2015), aimed is at a maximum mean global warming increase compared to industrial times of 1.5 °C in 2100. This is estimated to be equivalent to 425 ppm CO_2. The maximum increase for the year 2100 is set to be 2.0 °C. This is estimated to be equivalent to 475 ppm CO_2. The scenario in Figure

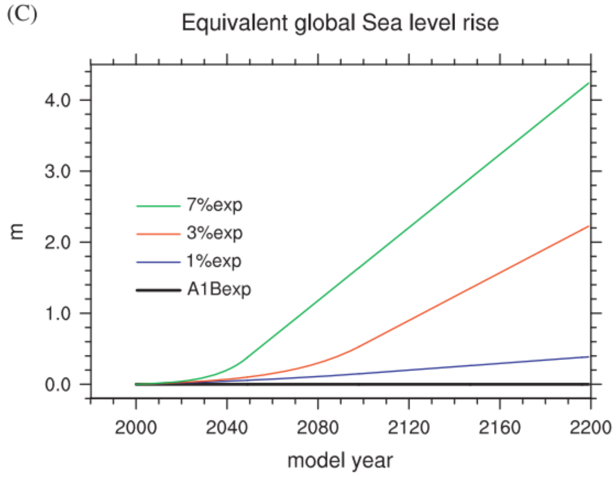


Figure C.7: Global SLR scenarios for melting GIS (Hu et al., 2011). The black line indicates the SLR if the GIS melting is excluded. The blue and red line show the Sea Level Rise with an exponential mass loss of respectively 1 and 3% till 2100 after which the loss increases linear. The green line shows a SLR which increases exponential with 7% due to mass loss of the GIS till 2050 and afterwards increases linear.

C.7 is, with 668.5 ppm, an overestimation if the UNFCCC (2015) will succeed.

C.2. Sea Level Rise Netherlands

The Global Mean Sea Level (GMSL) is rising. Locally the effect can deviate largely from the mean. Therefore, the effect of SLR for The Netherlands will be investigated. In Katsman et al. (2011) a study is done to the local SLR for the Netherlands. For this local investigation in water levels, two effects have been investigated. Local steric-changes and elasto-gravity effects (Katsman et al., 2011).

Local Steric Changes

Steric effect is a local effect which could lead to a deviation in local sea level rise compared to GMSL. Steric-effects are driven by density differences caused by temperature and salinity variations (Katsman et al., 2011). The density is of large influence on local sea levels. The influence of higher atmospheric temperatures on local steric-changes are modelled for the North East Atlantic Ocean (Katsman et al., 2011). From these models, two different outcomes were found. First outcome showed that the local sea level rises at the same rate as the global sea level. The second outcome showed a higher local sea level than the GMSL, which increased when a higher atmospheric temperature was found. From these models the contribution due to local steric changes is assessed to be -0.05 to 0.20 meter for the Netherlands in 2100. (Katsman et al., 2011)

Elasto-gravity effects

Melt water from melting ice masses on land is not distributed uniformly over the oceans. Locally different sea levels can be found due to this phenomena. Ice masses exert a gravitational pull on the surrounding ocean. If the ice mass melts, the gravitational pull force decreases. Therefore, the water level close to the ice mass will decrease. Farther away, the sea level will increase due to the smaller gravitational pulling force. This effect is larger compared to when melting water would be evenly distributed over the ocean. A schematic representation is given in Figure C.8.

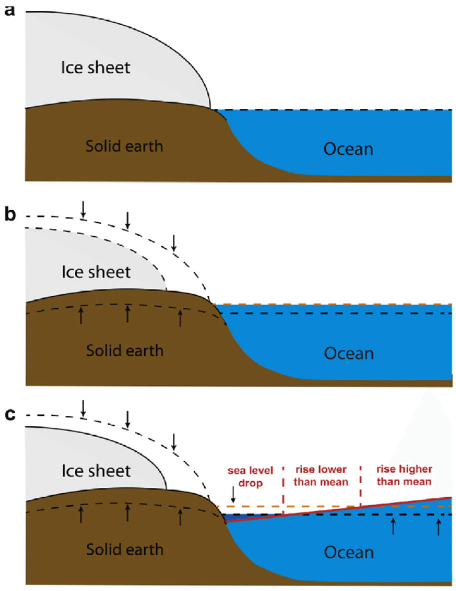


Figure C.8: Elasto-gravitational effect. Schematic representation of the gravitational effects on SLR due to melting ice sheets on land from (de Boer et al., 2017). a) The situation is in equilibrium. b) A layer of ice melted, the sea level rose, and the solid earth rose too. c) The gravitational pull of the ice sheet and solid earth decreased. Therefore, the sea level rise near the coast is smaller, can even decrease, than the mean sea level rise.

For the location of the Netherlands, a ratio of $\frac{\text{Local SLR}}{\text{Global SLR}} = 0.8$ is found for the effect of elasto-gravity effect. This can be explained by the fact that the Netherlands is located relatively close to Iceland and the Svalbard islands, which influence the ratio largely. The contribution of elasto-gravity is included in the local Dutch sea level rise, stated in Katsman et al. (2011).

When looking at the scenarios on sea level rise for 2100, which include a sea level rise of 1.0 meter or even larger, the elasto-gravity effect will be of greater influence than the local steric-effect. Which will lead to a smaller local sea level rise compared to the global sea level rise.

Due to the uncertainties in the above mentioned processes, decided is to use the KNMI scenarios 2014 G_l and W_h. These are described in Tank et al. (2015). The scenarios used are shown in Figure C.9. For which the scenario W_h is extrapolated as a quadratic function while the G_l scenario is extrapolated linearly from 2100.

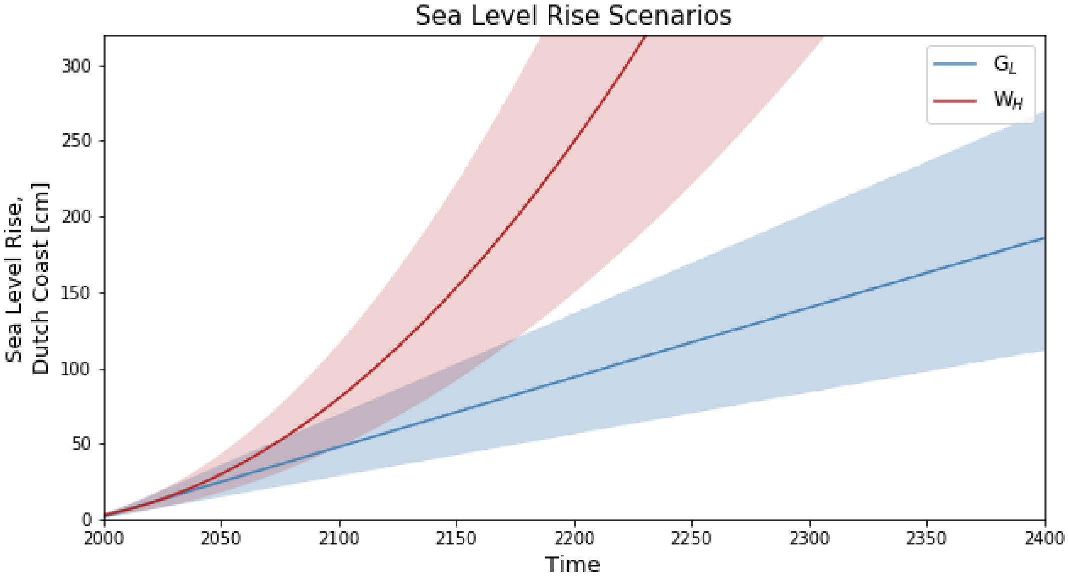


Figure C.9: The sea level rise scenarios used for the assessment of the Haringvliet sluices.

C.3. River Discharge Distribution

For the scenarios Gemiddeld and Warm, the expected discharge distribution of the Rhine is different. With the scenario Gemiddeld, it is expected that the distribution almost remains the same for the river Rhine. For the scenario Warm, the average discharge over the year, slightly increases for the year 2100. However, the distribution over the year differs largely. Due to warmer and drier summers, the discharge during the summers will decrease. With more rainfall and melt water in the winters, the discharge during the winters will increase. This means that the return periods will differ too. This is shown in Figure C.10.

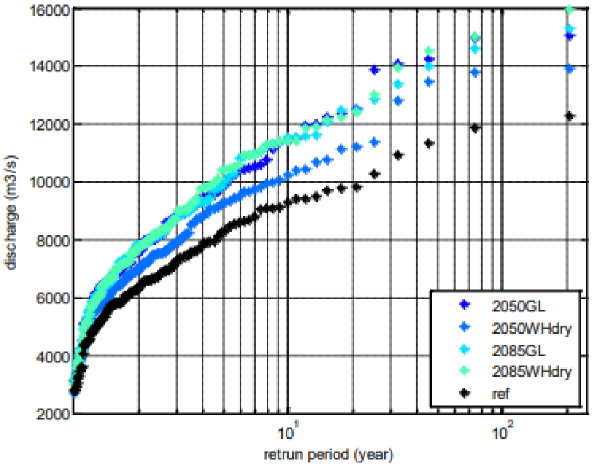


Figure C.10: The potential return periods due to climate change.

These more extreme river discharges are incorporated in the Hydra-BS calculations. Due to the increased possibilities of flooding in Germany, the discharges are capped for a discharge larger than respectively 17,000 and 18,000 m^3/s for the scenarios G_l and W_h.

D

WBI2017

In the statutory assessment tool (in Dutch: Wettelijk Beoordelingsinstrumentarium from 2017, WBI2017) requirements for assessing primary flood defences in the Netherlands are described. These primary flood defences must be assessed at least once every twelve years, (Rijkswaterstaat, 2017d). In the assessment tool, multiple software programs, calculation rules and data is available (Rijkswaterstaat, 2017d). The assessment tool is updated regularly due to new insights, information and research. With the assessment tool, hydraulic loads on flood defences can be calculated, for which the flood defence will guarantee the strength or need to be reinforced (Rijkswaterstaat, 2017d). When assessing flood defences following WBI2017, multiple failure mechanisms should be looked into. For most flood defence segments, probabilities of failure have been derived per failure mechanism. These are stated in Rijkswaterstaat Projectbureau VNK (2014).

The actual performance of an assessment consist roughly out of three phases. Starting with the preparation, than the actual execution and ending with a report of all steps taken, see Figure D.1 from (Rijkswaterstaat, 2017d).

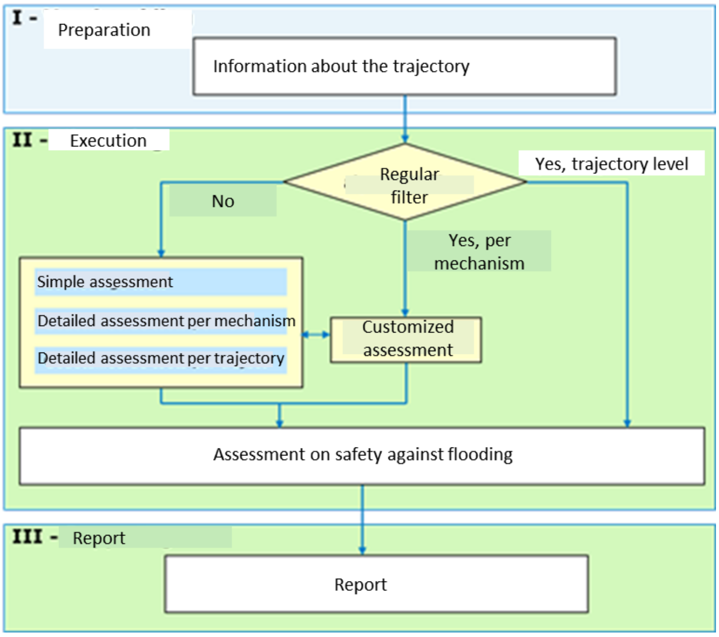


Figure D.1: Assessment scheme following WBI2017, translated from (Rijkswaterstaat, 2017d).

In the preparation phase, all information about the segment or structure to assess needs to be gathered. When there is a lack of information, measurements, calculations and laboratory tests could be performed. With all this information, all failure mechanisms need to be schematized. These schematizations are used in models in combination with other data, which differs per failure mechanism. In these data set, there are uncertainties. Therefore, assessments should include uncertainties and probabilities, which gives slightly conservative outcomes. For each failure mechanism another model is used.

The assessment of a flood defence depends on the failure mechanisms which could lead to failure. First of all, a simple and global assessment can be done for a segment. If it turns out that the probability of failure due to multiple failure mechanisms is negligible, no further action is needed. However, when the uncertainty in the results of the simple assessment is too large, a more thorough and detailed assessment needs to follow (Rijkswaterstaat, 2017d) as shown in part two of Figure D.1.

In the detailed assessment all failure mechanisms their probability should be calculated. In the detailed assessment it is important to take the correlation and combinations between failure mechanisms into account. The same holds for the hydraulic loads. These probabilities, that multiple events lead to larger hydraulic loads is calculated. This is done with WBI software, which uses probabilities and statistics of wind, sea water level, river discharge and failing structures. From the hydraulic loads, the height a flood defence should have and the strength that the flood defence has to guarantee, can be calculated.

The hydraulic loads, overflow and overtopping and the probability of not opening and not closing of structures are calculated probabilistic. Other failure mechanisms are calculated semi-probabilistic due to the larger uncertainties. Dunes as flood defences are calculated semi-probabilistically. Further the failure mechanisms piping, macro stability and revetments should be calculated semi-probabilistically.

The probabilistic calculations are executed with Hydra-BS. However, Hydra-BS does not include model uncertainties. Model uncertainties are the uncertainties in the model and calculations behind the model. Therefore, Hydra-NL calculations will be used to compare Hydra-NL with Hydra-BS. If there are large differences due to calculating with model uncertainties, the Hydra-BS outcomes need to be corrected for these uncertainties. This will only be done for the water levels and not for hydraulic load calculations.

In this thesis, the failure mechanisms not opening and not closing of the Haringvliet sluices, not closing of the Maeslantkering are used. For the flood defences effected by the failure mechanisms of the Haringvliet sluices and Maeslantkering, the hydraulic loads and their required heights are calculated (Rijkswaterstaat, 2017d).

E

SOBEK calculations

The program SOBEK is used to calculate the water levels in the South-Western Delta. An already existing model called DPRD is used. In this model all information about the topography, branches, structures, boundary conditions and conditions during the calculations are included for the South-Western delta. The Haringvliet sluices will be adjusted. With all the Sobek calculations a database is created which eventually is used to make Hydra calculations.

In the DPRD model, the Haringvliet sluices are schematized as gates, in which the gate height is adjustable. The Haringvliet sluices are schematized by 17 gates. These gates are 56.5 meters wide. If the gate height is 0, the gates are closed. The gate height is adjusted by so called controllers which on their turn are influenced by triggers. In the original DPRD model, the gate height is dependent on the incoming discharge on branch Waal2 and the head difference at sluice gate 1. There are a two head difference triggers, a positive and a negative. The head difference is positive when the water level in the Haringvliet is higher than the water level at sea. If the head level is negative, the controller states that the gate height must be zero, independent on the river discharge. If the head difference is positive, the gate height was regulated as stated in Table E.1. All 17 Haringvliet gates follow this regime.

Table E.1: The gate height depending on the discharge on the branch Waal2

Q [m3/s]	Gate height[m]
0	0
535	0
605	0
655	0
695	0
770	0
845	0
920	0.0251889
995	0.0251889
1025	0.0251889
1070	0.0251889
1105	0.0251889
1145	0.0251889
1190	0.0251889
1240	0.0534005
1290	0.088665
1350	0.126952
1415	0.166247
1475	0.207557
1540	0.250882
1605	0.296222
1675	0.343577
1740	0.392947
1805	0.443325
1875	0.495718
1940	0.550126
2010	0.606549
2145	0.725441
2275	0.850378
2405	0.984383
2535	1.12443
2665	1.24937
2795	1.31083
2925	1.37128
3055	1.43375
3185	1.49521
3315	1.55668
3445	1.61914
3570	1.68161
3705	1.74509
3835	1.80957
3970	1.87406
4300	2.05743
4625	2.267
4935	2.50882
5250	2.78086
5540	3.12343
5825	3.66751
6110	6.04534
6405	11
13000	11
20000	11

If the discharge value is in between values of Table E.1, the gate height is linear interpolated. For the SOBEK calculations in this research, Table E.1 has not been changed. This has to do with the fact that the current kierbesluit does not differ to much from the old LPH86 program. For the calculations, the head difference values were changed to -0.1 meter. This has to do with the new kierbesluit. If there is a small negative head difference and the discharge is large enough, the Haringvliet sluices will remain open.

To incorporate the effect of failing Haringvliet sluices, three different sluice scenarios have been modelled. The cases are: not open, do not close and work as they should. In Table E.2 the triggers and controller settings are given per situation.

In Figures E.1, E.2 and E.3, two water levels of the Haringvliet and two water levels of the Nieuwe Waterweg are plotted. Figures E.1, E.2 and E.3 show the influence of not opening and not closing on the water levels in the Haringvliet. However, the probability of failure is not included in the above calculations. For the probability calculations, multiple scenarios calculated with SOBEK are needed. With all these scenarios, a database should be filled in Hydra format. Every calculation one parameter changed. The variable parameters are stated and explained in Table E.3.

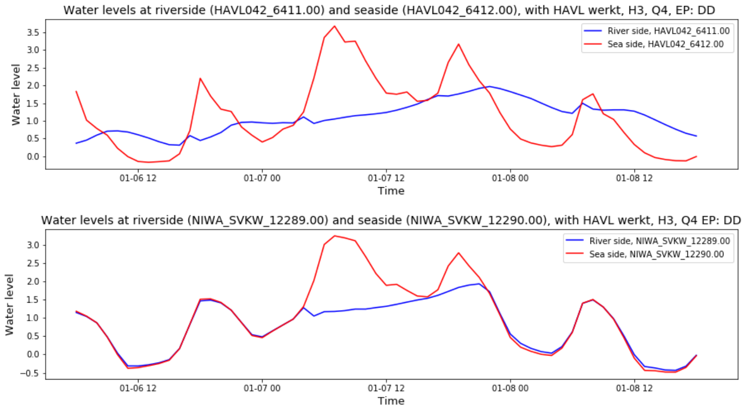


Figure E.1: Water levels at the Haringvliet and Nieuwe Waterweg, while the Haringvliet sluices work as they should

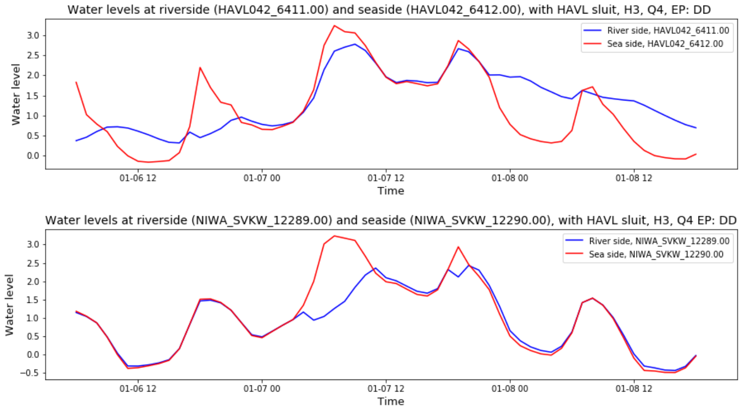


Figure E.2: Water levels at the Haringvliet and Nieuwe Waterweg, while the Haringvliet sluices do not close during the storm

Table E.2: Three scenarios of the Haringvliet sluices, for which the controller(s) and triggers are stated and described

	Controller(s)	**Trigger(s) per controller**	**What does the trigger**	**What does the Controller**
Working	Hvl_Open_Contr	Hvl_OpenVerval_Trigger	Looks at the water level difference at Haringvliet sluis 1, must be larger than -0.1 m	Set the gate height depending on the river discharge and trigger
	Hvl_Sluit_Contr	Hvl_SluitVerval_Trigger	Looks at the water level difference at Haringvliet sluis 1, must be smaller than -0.1 m	Set the gate height depending on the river discharge and trigger
Not Opening	Hvl_Open_Contr	Hvl_OpenVerval_Trigger AND Hvl_w_opent_niet	Hvl_w_opent_niet is a time trigger. At times of properly working, the trigger is 'on'. The OpenVerval trigger remains the same.	Set the gate height depending on the river discharge and triggers, in this case water level difference and time.
	Hvl_Sluit_Contr	Hvl_SluitVerval_Trigger AND Hvl_w_opent_niet	Hvl_w_opent_niet is a time trigger. At times of properly working, the trigger is 'on'. The SluitVerval trigger remains the same.	Set the gate height depending on the river discharge and triggers, in this case water level difference and time.
	Hvl_Opent_Niet	Hvl_opent_niet	Time trigger which says when the sluice can not open.	Set the gate height to 0 m for a duration of 24 hours just after the storm.
Not Closing	Hvl_Open_Contr	Hvl_OpenVerval_Trigger AND Hvl_w_sluit_niet	Hvl_w_sluit_niet is a time trigger. At times of properly working, the trigger is 'on'. The OpenVerval trigger remains the same.	Set the gate height depending on the river discharge and triggers, in this case water level difference and time.
	Hvl_Sluit_Contr	Hvl_SluitVerval_Trigger AND Hvl_w_sluit_niet	Hvl_w_sluit_niet is a time trigger. At times of properly working, the trigger is 'on'. The OpenVerval trigger remains the same.	Set the gate height depending on the river discharge and triggers, in this case water level difference and time.
	Hvl_Sluit_Niet	Hvl_sluit_niet	Time trigger which says when the sluice doors can not close.	Set the gate height to 5 m for a duration of 24 hours during the storm.

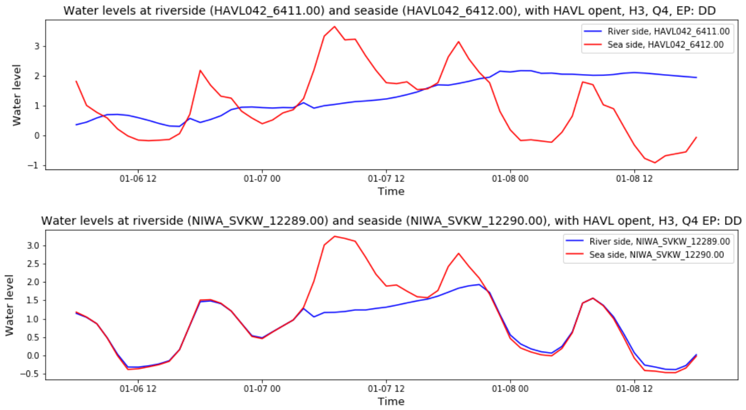


Figure E.3: Water levels at the Haringvliet and Nieuwe Waterweg, while the Haringvliet sluices do not open after the storm.

The water levels plotted in Figure E.4 are the water levels at the entrance of the Haringvliet. The discharges stated in Table E.3 are the discharges at the Pannerdensche Kop. These correspond with the Rhine discharges stated in Table 3.1.

Table E.3: All changing parameters and their options

Parameter	Number of options per parameter	Parameter options
Haringvlietsluizen	3	Works Does not close Does not open
Europoortkering	2	Closes Does not close
Water level [m]	6	6 different water levels (see Figure E.4)
Discharge [m^3/s]	9	Q1 = 550 Q2 = 1,401 Q3 = 2,697 Q4 = 3,997 Q5 = 5,296 Q6 = 6,473 Q7 = 8,285 Q8 = 10,165 Q9 = 11,435
Wind direction [degrees]	7	sw = 225 sww = 247.5 w = 270 nww = 292.5 nw = 315 nnw = 337.5 n = 360
Climate Scenarios	2	Scenario 1 Scenario 2
Number of calculations:	3 x 2 x 6 x 9 x 7 x 2 = 4536	[-]

The water level over time at sea near the Haringvliet sluices are shown in Figure E.4. What can be seen is the tide, which is schematically shown as H1 in Figure E.4. What can also be noted is that a storm starts at the end of January sixth and ends just before the eighth of January.

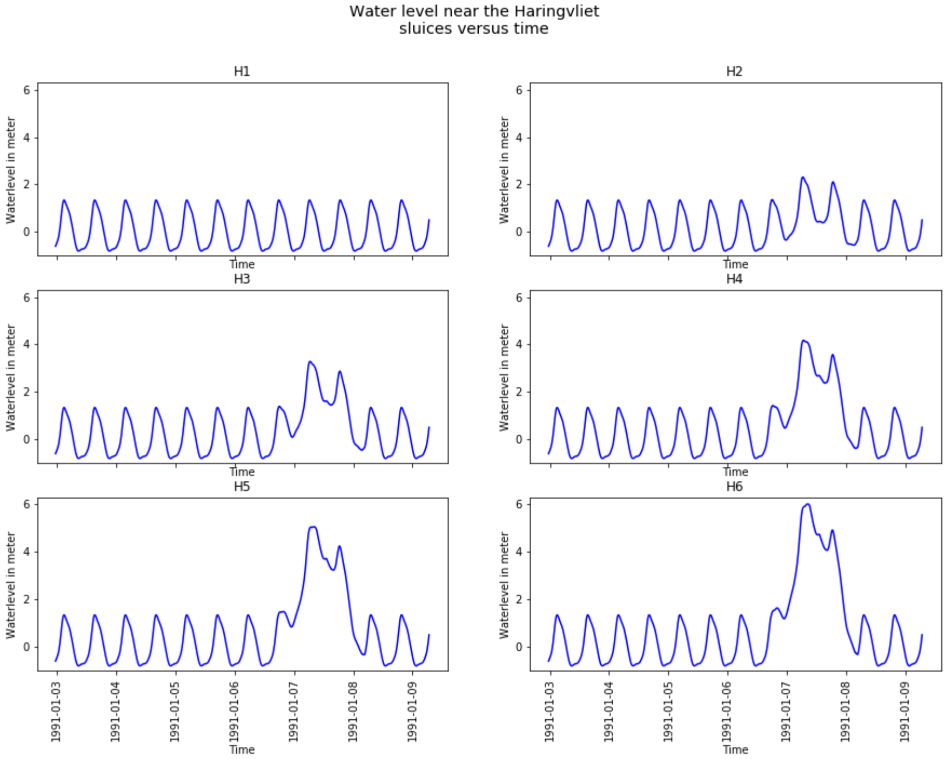


Figure E.4: Water levels used as boundary condition at the sea side of the Haringvliet sluices. These water levels are increased by 0.01 m. for the sea level rise scenario R2015 and 0.28 m. for the scenario W2050.

F

Hydra-NL and Hydra-BS

To calculate the influence of not closing and not opening the Haringvliet with WBI standards, two databases are compared. The following databases are compared:

- Database from SOBEK (2017) following the WBI2017 program, including failing Europoortkering. Excluding failing Haringvliet sluizen. Input for Hydra-NL.
- Database from SOBEK (2019) including failing Europoortkering and Haringvliet sluizen. Input for Hydra-BS.

Calculations with Hydra-BS and Hydra-NL are done to validate that Hydra-BS can still be used. The calculation methods and statistics which are programmed in Hydra-BS and Hydra-NL, differ slightly. This could give different results. These differences are described and explained in the following section.

F.1. Input statistics of Hydra

The probabilities and exceedance frequencies for wind direction and velocity, discharges and water levels are shown in Figures F.1, F.2 and F.3.

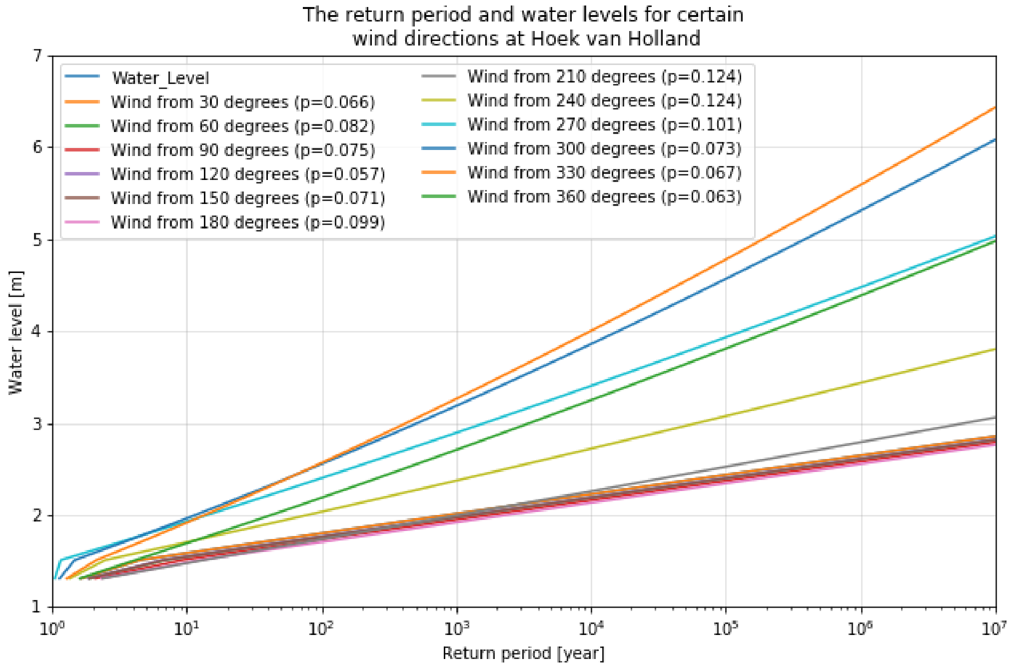


Figure F.1: The exceedance frequencies of the water level for all different directions of the wind. The probability of occurrence of a certain direction is stated as well. These exceedance frequencies are used by Hydra-BS as input files.

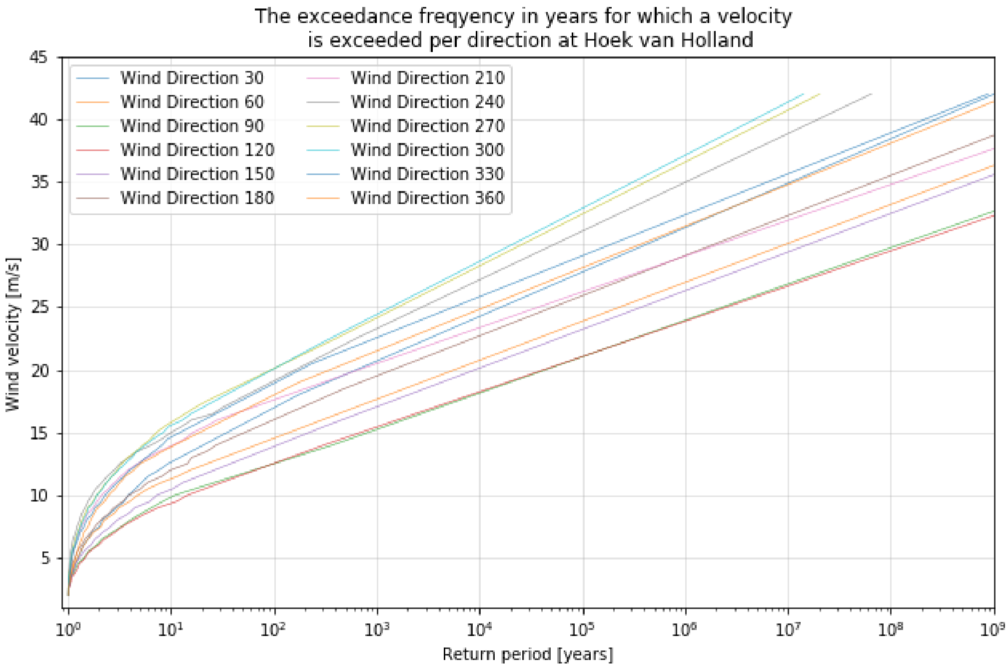


Figure F.2: The exceedance frequencies of the velocity per direction. These exceedance frequencies are used by Hydra-BS as input files.

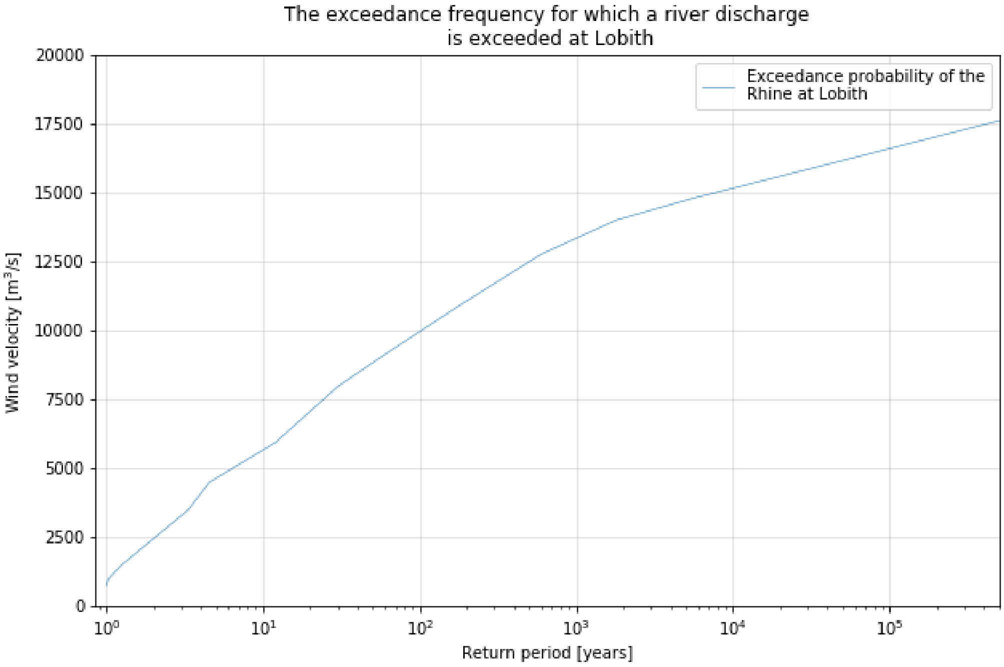


Figure F.3: The exceedance frequencies of the river discharge for the river Rhine at Lobith. These exceedance frequencies are used by Hydra-BS as input files.

F.2. Difference between Hydra-NL and Hydra-BS

When calculating with Hydra-NL, there is an option to calculate with or without model uncertainty. The current standard of WBI2017 is to calculate with this model uncertainty. Therefore, some calculations with Hydra-BS and Hydra-NL have been compared. With the databases mentioned, the return periods versus water levels are calculated with Hydra-BS and Hydra-NL (excluding and including model uncertainty), for four locations: Maassluis, Middelharnis, Goudswaard and Rak Noord. These locations are chosen to see if the effect of the model uncertainty in Hydra-NL is equal over the whole area.

In Figure F.7 the results are obtained using the current climate scenario. All other input variables are the same, meaning that all hydraulic structures act the same and have the same failure probabilities. From Figure F.7, it can be seen that Hydra-BS (blue) and Hydra-NL (excluding model uncertainty, orange) have comparable outcomes in the return periods till around 1000 years. From that point, Hydra-BS gives slightly higher water levels for the same return period compared to Hydra-NL (orange). The difference can be explained by two factors:

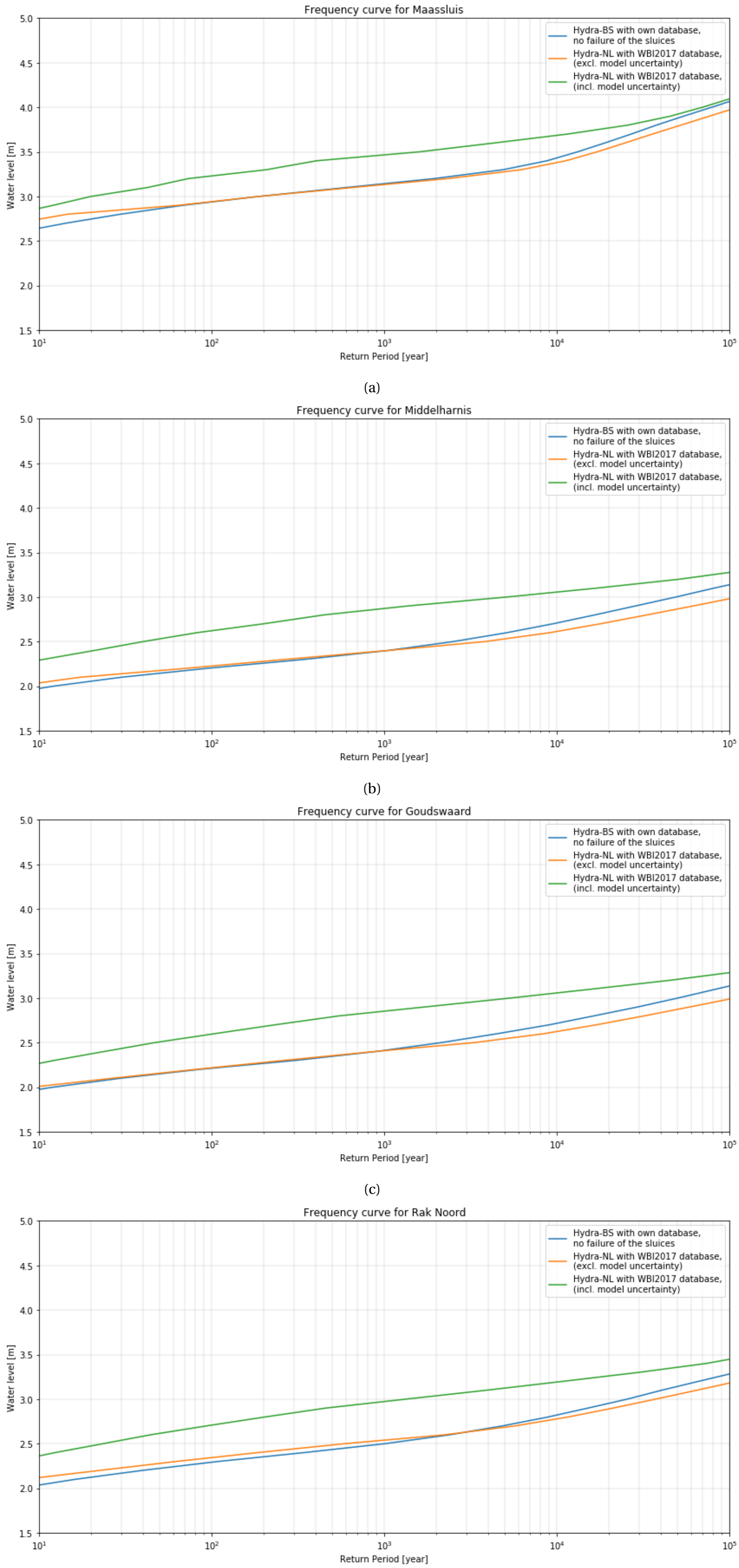
- The input files, with which Hydra-BS and Hydra-NL calculate the return periods and their corresponding water levels, are coming from different Sobek calculations. This has to do with the file type and information the databases should contain. See Figures F.5 and F.6 which tables each database should contain.
- In Hydra-NL statistical uncertainty is included. Statistical uncertainty is the uncertainty of the statistical analysis on the boundary conditions. The water levels and river discharges their probability distributions are differently derived for both programs. In this case, this means that the river discharges corresponding to return periods larger than 1000 years, have smaller values compared to the ones in Hydra-BS. This is due to new insights of rainfall and the corresponding river discharges combined with the probability of occurrence. Concluding that larger discharges have larger return periods, leading to lower water levels. When looking at the statistics concerning water levels at sea, it is unknown how the statistical uncertainty relates between Hydra-BS and Hydra-NL.

When looking at Figure F.7, the water levels for Hydra-NL including model uncertainty (green) has larger values than the calculations without model uncertainty or calculations with Hydra-BS. The differences between the two Hydra-NL calculations are consequences of the uncertainty on the actual water level, wave height and period Duits (2018), which together is the so called model uncertainty.

What can be concluded from Figure F.7 is that Hydra-BS calculates almost the same water levels for return periods till 1000 years as Hydra-NL does without model uncertainty. Probably due to statistical differences in the models and/or differences in the databases, Hydra-BS calculates larger water levels for return periods larger than 1000 years. When looking at the results of Hydra-NL with model uncertainty, in Figure F.7, the water levels are significantly larger compared to those of Hydra-NL without uncertainty and Hydra-BS. Therefore, the Hydra-BS calculations with failure modes incorporated should be corrected for the uncertainty when following WBI2017. Therefore, the water level is corrected for the return time that applies to the flood defense which is present at that location. The differences due to the model uncertainty are taken by subtracting the Hydra-BS results from the Hydra-NL with model uncertainty results. These are given in Table F.1.

Table F.1: Differences of water levels (mean) between Hydra-NL with model uncertainty and Hydra-BS, and differences of water levels between Hydra-NL without model uncertainty with Hydra-BS. For the latter, the difference have been split for return periods 1:1000 year and larger than 1000 years.

	Difference water levels Hydra-NL (with model uncertainty) compared to Hydra-BS (NL-BS)	**Difference water levels Hydra-NL (without model uncertainty) with Hydra-BS (NL-BS)**	
Location	Mean of differences in water levels [m]	Mean of water levels for return periods 1 till 1000 year [m]	Mean of water levels for return periods larger than 1000 year [m]
Middelharnis	0.367	0.011	-0.069
Maassluis	0.269	0.024	-0.039
Goudswaard	0.367	0.011	-0.069
Rak Noord	0.399	0.057	-0.022



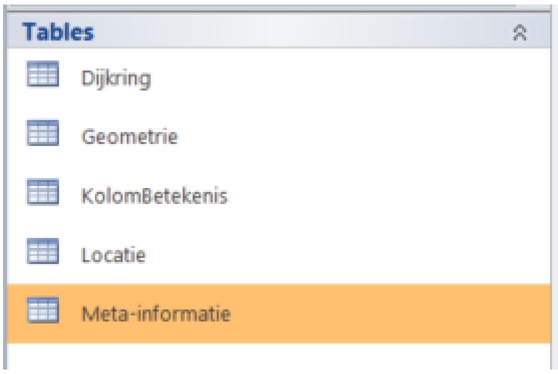
(a)

(b)

(c)

(d)

Figure F.4: Comparison of Hydra-NL with Hydra-BS and the water levels corresponding to their return period for four locations.



Tables

Dijkring

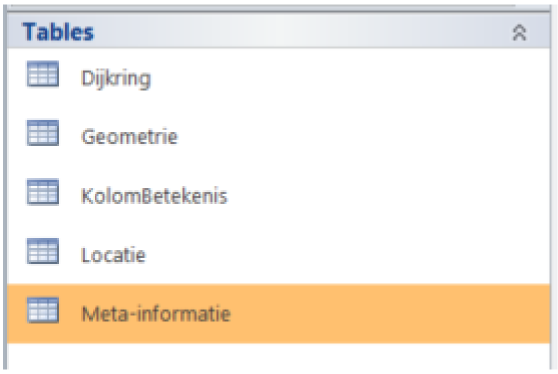
Geometrie

KolomBetekenis

Locatie

Meta-informatie

Figure F.5: A database which is suitable for Hydra-BS



Tables

Dijkring

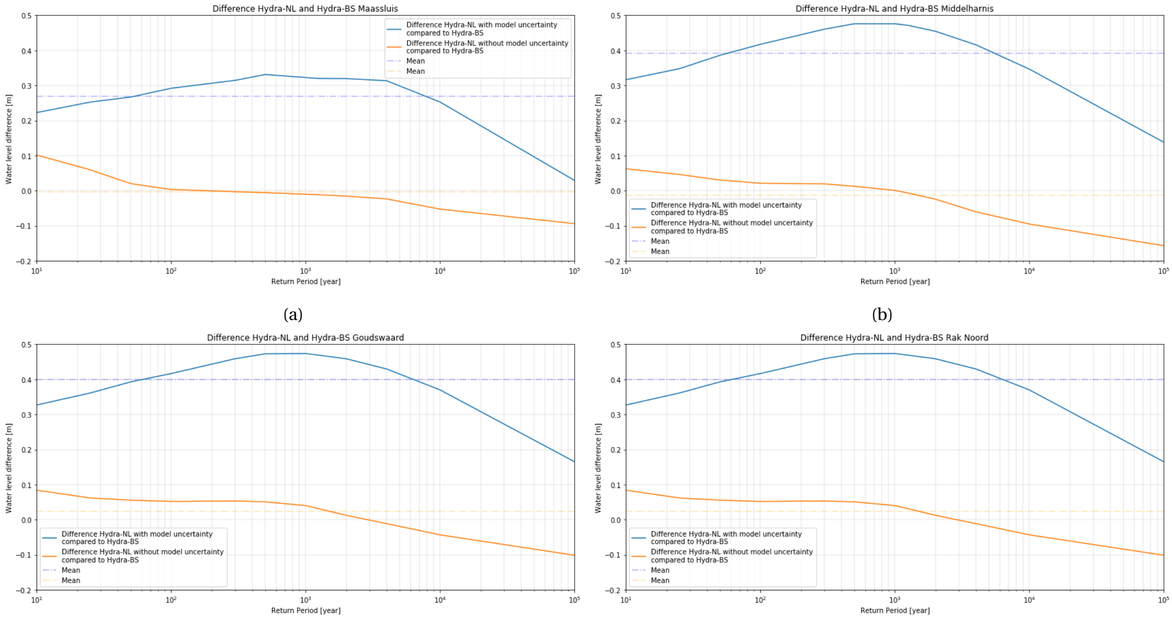
Geometrie

KolomBetekenis

Locatie

Meta-informatie

Figure F.6: A database which is suitable for Hydra-NL



(a)

(b)

(c)

(d)

Figure F.7: Differences Hydra-NL and Hydra-BS

F.3. Hydra-BS water level calculations

With the database from 2019 multiple calculations are carried out. In this section multiple outcomes are shown. For the four locations for which the Hydra-BS calculations are analysed (Goudswaard, Hellevoetsluis, Maassluis and Rak Noord), some more frequency curves are here. The Figures F.8 till F.11 show failure of 8 doors for scenario R2015. Figures F.12 till F.19 show the effect of the climate scenario W2050 for failure of all doors as well as for 8 failing doors.

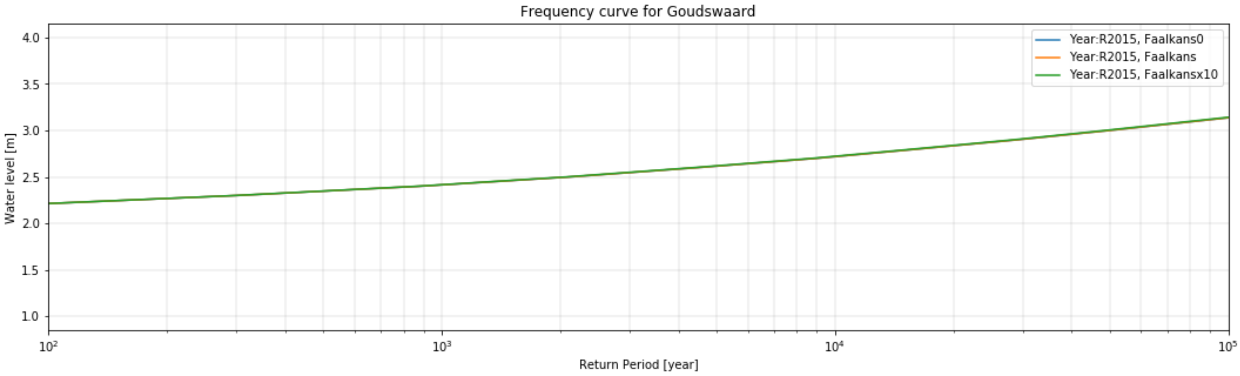


Figure F.8: The frequency curves for the location Goudswaard with 8 sluice doors failing and the climate scenario R2015.

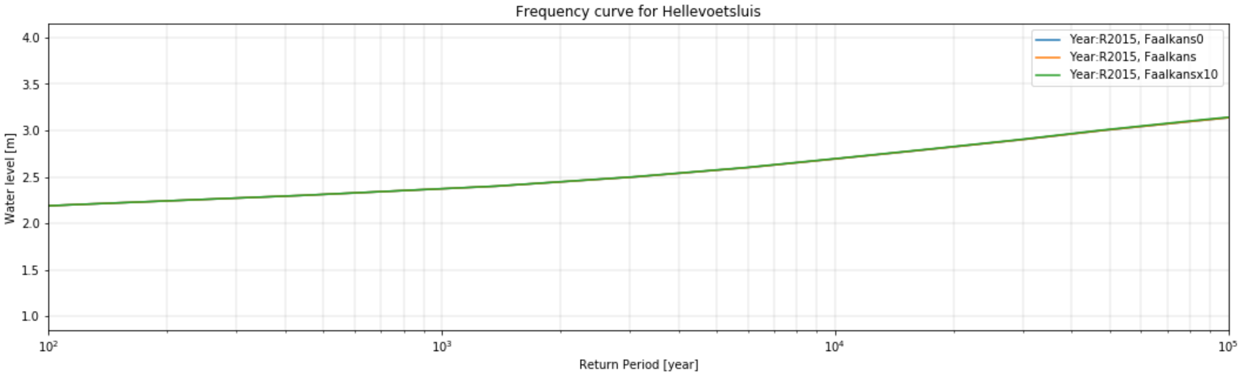


Figure F.9: The frequency curves for the location Hellevoetsluis with 8 sluice doors failing and the climate scenario R2015.

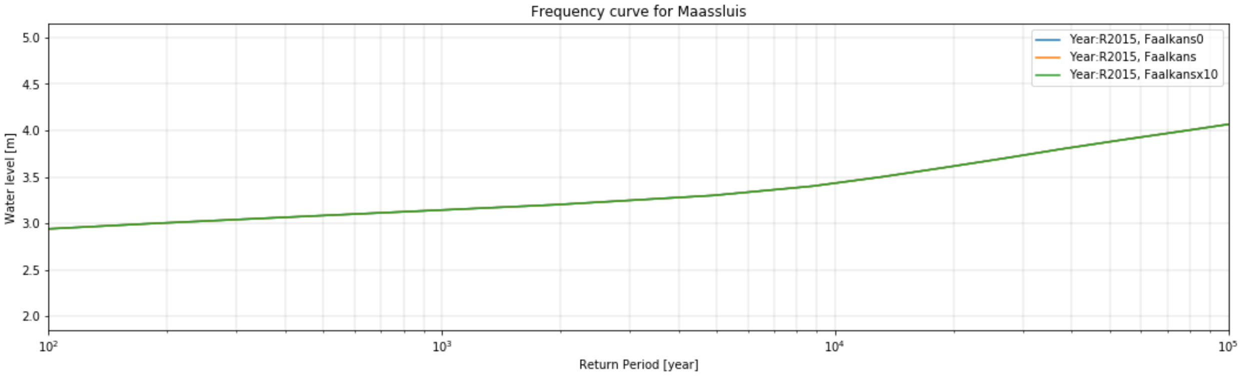


Figure F.10: The frequency curves for the location Maassluis with 8 sluice doors failing and the climate scenario R2015.

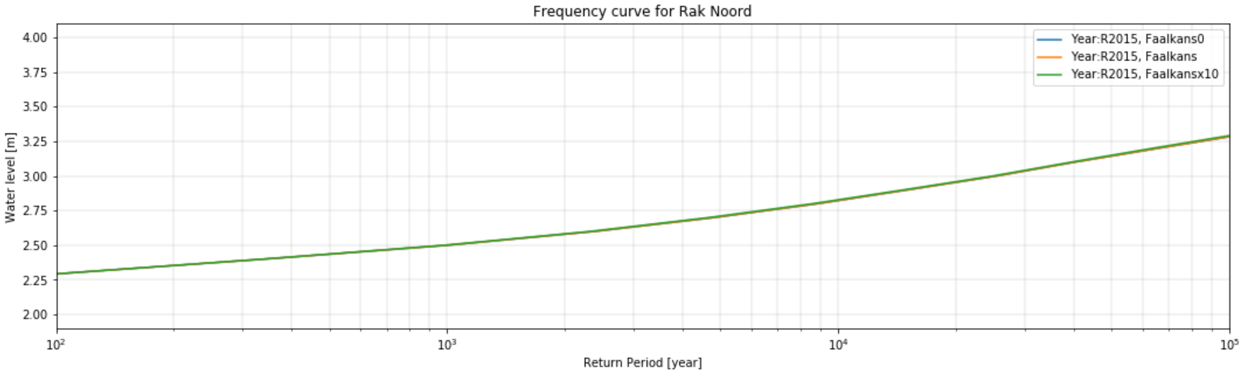


Figure F.11: The frequency curves for the location Rak Noord with 8 sluice doors failing and the climate scenario R2015.

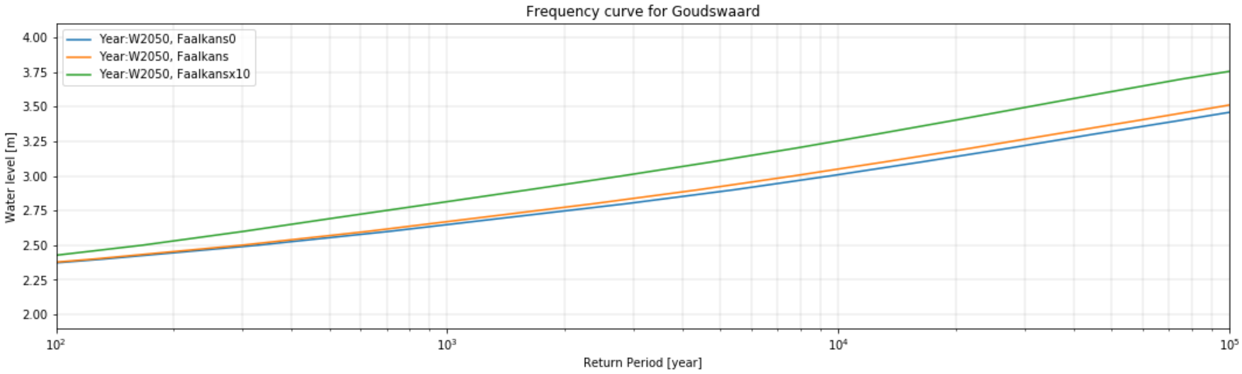


Figure F.12: The frequency curves for the location Goudswaard with all sluice doors failing and the climate scenario W2050.

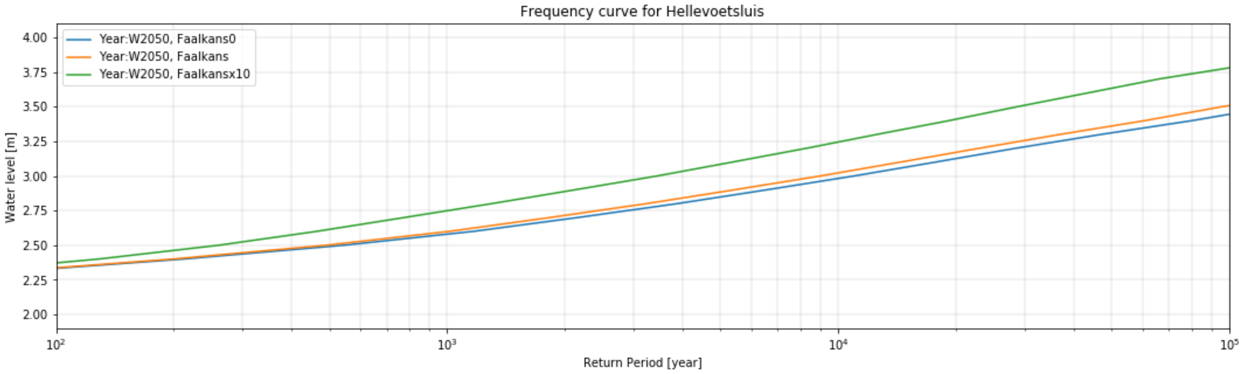


Figure F.13: The frequency curves for the location Hellevoetsluis with all sluice doors failing and the climate scenario W2050.

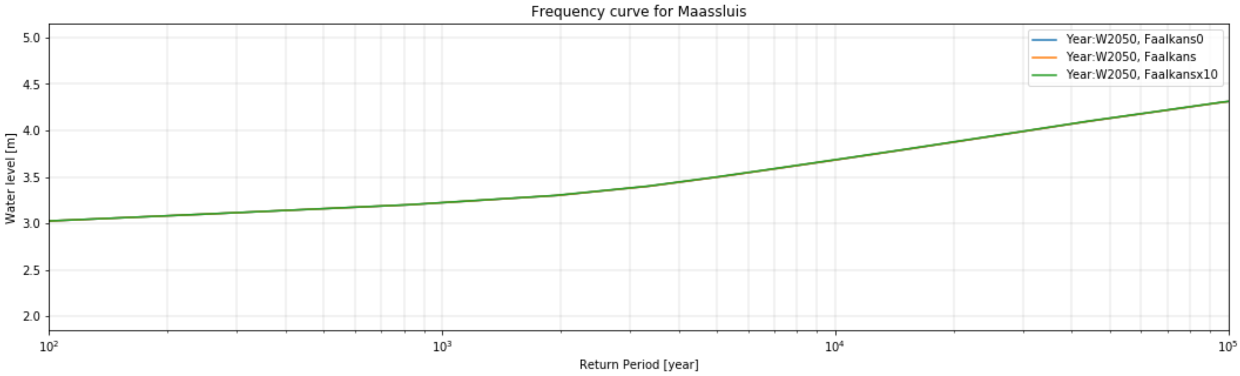


Figure F.14: The frequency curves for the location Maassluis with all sluice doors failing and the climate scenario W2050.

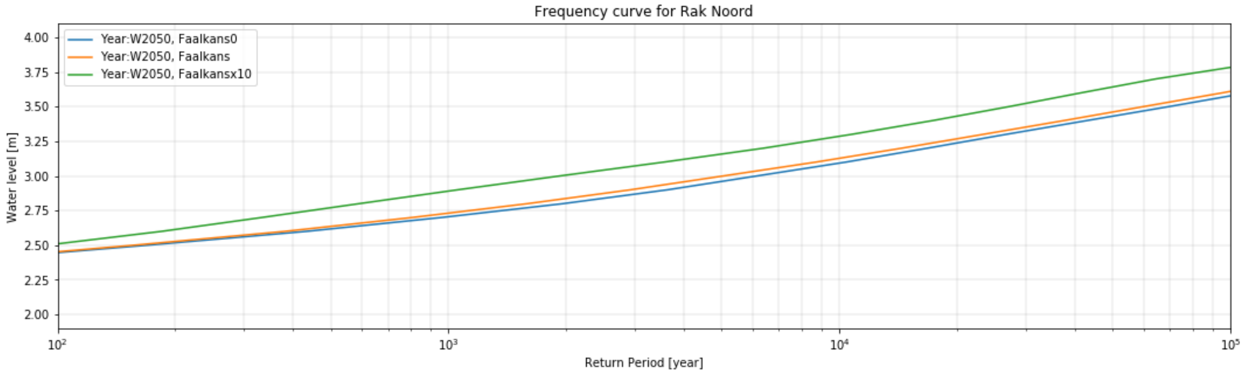


Figure F.15: The frequency curves for the location Rak Noord with all sluice doors failing and the climate scenario W2050.

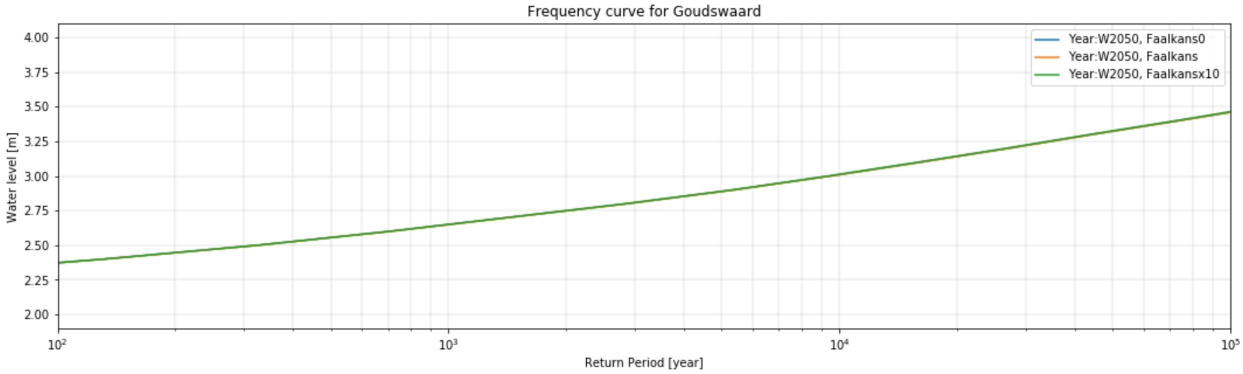


Figure F.16: The frequency curves for the location Goudswaard with 8 sluice doors failing and the climate scenario W2050.

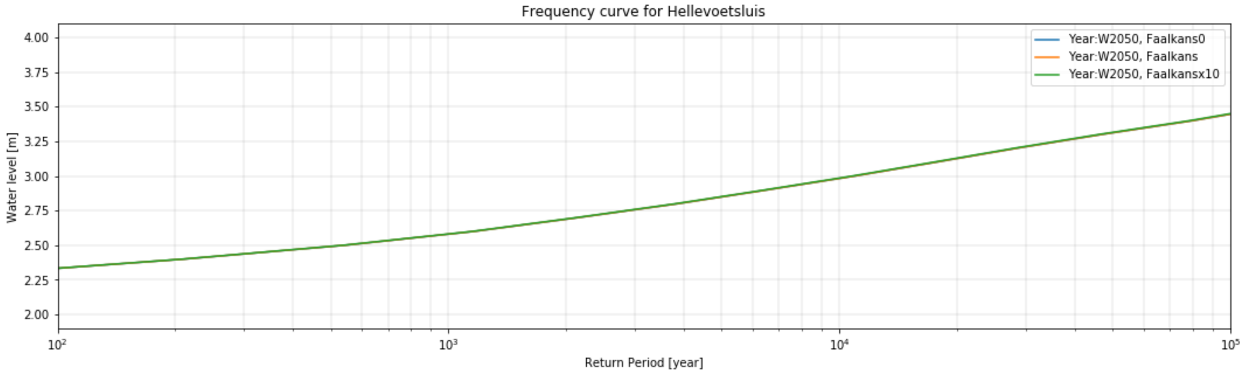


Figure F.17: The frequency curves for the location Hellevoetsluis with 8 sluice doors failing and the climate scenario W2050.

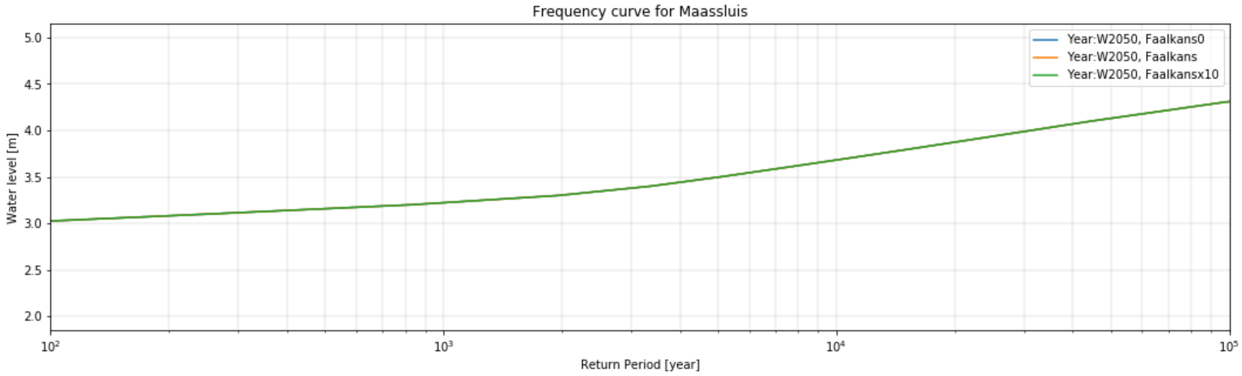


Figure F.18: The frequency curves for the location Maassluis with 8 sluice doors failing and the climate scenario W2050.

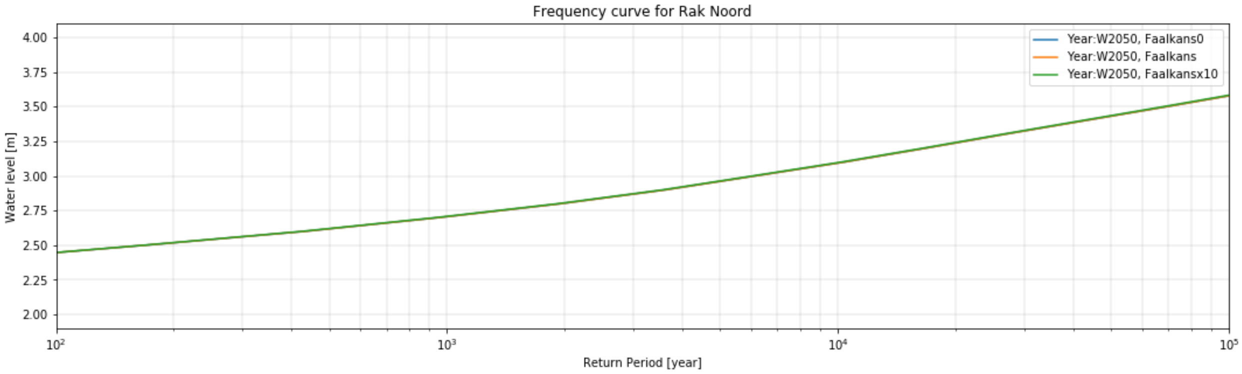


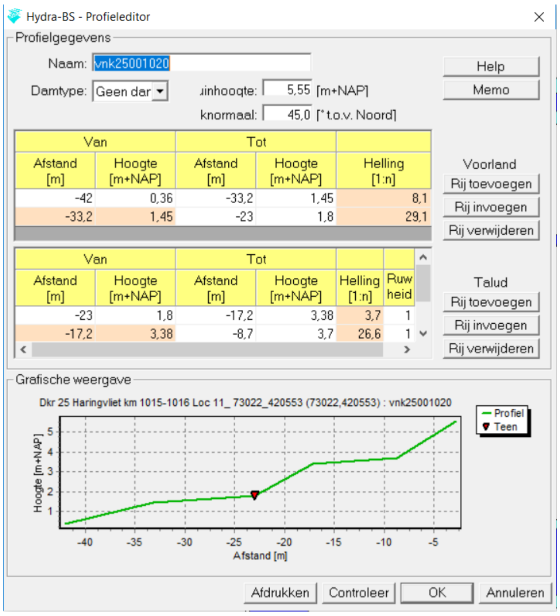
Figure F.19: The frequency curves for the location Rak Noord with 8 sluice doors failing and the climate scenario W2050.

F.4. Hydra-BS Overtopping calculations

With Hydra-BS the height a dike body needs can be calculated for multiple overtopping limits. In this thesis the overtopping limits 1 and 10 l/s/m are used to calculate the needed heights. The needed heights are calculated for the following probabilities of failure:

- Probability of not closing Maeslantkering: 1/100
- Probability of not closing Haringvliet Sluices: 1/5,000
- Probability of not opening Haringvliet Sluices: 1/10,000

Calculations are made for both climate scenarios and for the return period which is applicable to the dike of interest, see a schematized VNK dike in Figure F.20. The calculated crest heights has been corrected by adding the model uncertainty. The model uncertainty used depended on the location and is linearly interpolated if the location was in between two calculated points. Otherwise, the model uncertainty of the closest location is added. All values can be found in Table F.2. For which HBN stands for Hydraulic Load (in Dutch:'Hydraulisch Belastingsniveau') which is the calculated height which is needed to come to the maximum overtopping values 1 and 10 l/s/m. The red values in Table F.2 are the lowest values and will be used to see if overtopping of the Haringvliet sluices could lead to failure. The calculations with Hydra-BS are executed with fetch lengths and depths included in Hydra-BS, as can be seen in Figure F.21.



Naam: vnk25001020

Damtype: Geen dar

ɩinhooqte: 5,55 [m+NAP]

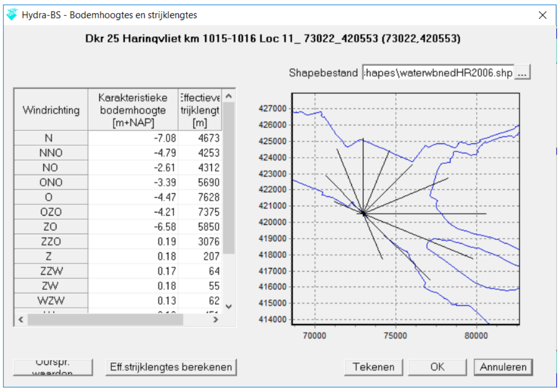
knormaal: 45,0 [° t.o.v. Noord]

Van		Tot		
Afstand [m]	Hoogte [m+NAP]	Afstand [m]	Hoogte [m+NAP]	Helling [1:n]
-42	0,36	-33,2	1,45	8,1
-33,2	1,45	-23	1,8	29,1

Van		Tot			
Afstand [m]	Hoogte [m+NAP]	Afstand [m]	Hoogte [m+NAP]	Helling [1:n]	Ruwheid
-23	1,8	-17,2	3,38	3,7	1
-17,2	3,38	-8,7	3,7	26,6	1

Dkr 25 Haringvliet km 1015-1016 Loc 11_ 73022_420553 (73022,420553) : vnk25001020

Figure F.20: The schematization of a VNK profile.



Dkr 25 Harinqvliet km 1015-1016 Loc 11_ 73022_420553 (73022,420553)

Shapebestand :hapes\waterwbnedHR2006.shp

Windrichting	Karakteristieke bodemhoogte [m+NAP]	Effectieve strijklengte [m]
N	-7.08	4673
NNO	-4.79	4253
NO	-2.61	4312
ONO	-3.39	5690
O	-4.47	7628
OZO	-4.21	7375
ZO	-6.58	5850
ZZO	0.19	3076
Z	0.18	207
ZZW	0.17	64
ZW	0.18	55
WZW	0.13	62

Figure F.21: Fetch length and bottom level used for each direction, left table. The fetch lengths are schematized in the right figure.

Table F.2: Overtopping calculations

		Criteria: 1 l/s/m		Criteria: 10 l/s/m			Criteria: 1 l/s/m		Criteria: 10 l/s/m			Criteria: 1 l/s/m		Criteria: 10 l/s/m	
Location	**Return Period [1/year]**	**HBN R2015_1[m]**	**HBN W2050_1 [m]**	**HBN R2015_10 [m]**	**HBN W2050_10 [m]**	**Actual Dike Height [m]**	**Freeboard: R2015_1 [m]**	**Freeboard: W2050_1 [m]**	**Freeboard: R2015_10 [m]**	**Freeboard: W2050_10 [m]**	**Model uncertainty for their return periods [m]**	**Over height R2015_1 [m]**	**Over height W2050_1 [m]**	**Over height R2015_10 [m]**	**Over height W2050_10 [m]**
Dkr 20 Haringvliet km 1017-1018 Loc 5_74959_424216	1:300	3.173	3.49	2.707	2.965	4.33	1.157	0.84	1.623	1.365	0.431	0.726	0.409	1.192	0.934
Dkr 20 Haringvliet km 1021-1021 Loc 4_71101_425758	1:300	3.84	3.986	3.168	3.279	4.9	1.06	0.914	1.732	1.621	0.431	0.629	0.483	1.301	1.19
Dkr 20 Haringvliet km 1023-1023 Loc 13_68571_426826	1:300	3.373	3.598	2.825	3.039	4.35	0.977	0.752	1.525	1.311	0.431	0.546	0.321	1.094	0.88
Dkr 20 Haringvliet km 1028-1029 Loc 13_64807_429054	1:300	3.417	3.711	2.758	3.045	4.31	0.893	0.599	1.552	1.265	0.431	0.462	0.168	1.121	0.834
Dkr 20 Spui km 1008-1009 Loc 8_77233_424713	1:300	2.381	2.605	2.356	2.558	3.93	1.549	1.325	1.574	1.372	0.431	1.118	0.894	1.143	0.941
Dkr 20 Spui km 999-1000 Loc 6_85508_426651	1:10,000	3.16	3.337	2.929	3.159	4.26	1.1	0.923	1.331	1.101	0.431	0.669	0.492	0.9	0.67
Dkr 21 Haringvliet km 1004-1005 Loc 5_83303_417928	1:100	2.973	3.403	2.605	2.926	4.55	1.577	1.147	1.945	1.624	0.400	1.177	0.747	1.545	1.224
Dkr 21 Hollandsch Diep km 991-992 Loc 3_95531_413289	1:100	2.995	3.267	2.432	2.686	4.65	1.655	1.383	2.218	1.964	0.417	1.238	0.966	1.801	1.547
Dkr 21 Hollandsch Diep km 997-998 Loc 5_90408_414873	1:100	2.591	2.861	2.391	2.602	4.38	1.789	1.519	1.989	1.778	0.417	1.372	1.102	1.572	1.361
Dkr 21 Spui km 1008-1009 Loc 3_78022_423673	1:100	3.37	3.554	2.868	3.044	4.6	1.23	1.046	1.732	1.556	0.292	0.938	0.754	1.44	1.264
Dkr 21 Spui km 999-1000 Loc 4_85838_426483	1:1,000	3.123	3.28	2.854	3.025	4.42	1.297	1.14	1.566	1.395	0.323	0.974	0.817	1.243	1.072
Dkr 25 Haringvliet km 1006-1007 Loc 8_80624_413901	1:1,000	3.648	3.747	3.115	3.221	5.5	1.852	1.753	2.385	2.279	0.457	1.395	1.296	1.928	1.822
Dkr 25 Haringvliet km 1015-1016 Loc 11_73022_420553	1:300	2.67	2.91	2.469	2.684	5.55	2.88	2.64	3.081	2.866	0.461	2.419	2.179	2.62	2.405
Dkr 25 Haringvliet km 1021-1022 Loc 5_69289_422366	1:300	3.042	3.227	2.674	2.852	5.07	2.028	1.843	2.396	2.218	0.461	1.567	1.382	1.935	1.757
Dkr 25 Haringvliet km 1024-1025 Loc 6_66663_424108	1:300	2.689	2.852	2.463	2.63	5.47	2.781	2.618	3.007	2.84	0.461	2.32	2.157	2.546	2.379
Dkr 25 Haringvliet km 1028-1029 Loc 20_61896_426286	1:300	2.357	2.421	2.357	2.421	5.49	3.133	3.069	3.133	3.069	0.461	2.672	2.608	2.672	2.608
Dkr 34 Hollandsch Diep km 991-992 Loc 2_95620_410958	1:300	3.678	3.883	3.179	3.374	4.72	1.042	0.837	1.541	1.346	0.459	0.583	0.378	1.082	0.887
Dkr 34 Hollandsch Diep km 996-997 Loc 13_89525_412391	1:300	3.049	3.157	2.768	2.892	5	1.951	1.843	2.232	2.108	0.459	1.492	1.384	1.773	1.649

Table F.3: In this table the calculations for a sea level rise of 0.87 meter are shown. The hydraulic loads are added by the ratio as found between the calculations for respectively 8 and 35 centimetre sea level rise. However, multiple calculations with multiple sea level rise scenarios would have increased the reliability of these calculations.

Dikering	**New Calculated Hydraulic load (1 l/s/m)**	**Ratio between sea level rise and hydraulic load (1 l/s/m)**	**New Calculated Hydraulic load (10 l/s/m)**	**Ratio between sea level rise and hydraulic load (10 l/s/m)**	**Actual Dike Height**	**Dike height - hydraulic load (1 l/s/m)**	**Dike height - hydraulic load (10 l/s/m)**	**Meeting the requirement for 1 l/s/m**	**Meeting the requirement for 10 l/s/m**
Dkr 20 Haringvliet km 1017-1018 Loc 5_ 74959_424216	4.532	1.174	3.893	0.956	4.33	-0.202	0.437	0	1
Dkr 20 Haringvliet km 1021-1021 Loc 4_ 71101_425758	4.698	0.541	3.924	0.411	4.9	0.202	0.976	1	1
Dkr 20 Haringvliet km 1023-1023 Loc 13_ 68571_426826	4.462	0.833	3.882	0.793	4.35	-0.112	0.468	0	1
Dkr 20 Haringvliet km 1028-1029 Loc 13_ 64807_429054	4.708	1.089	4.029	1.063	4.31	-0.398	0.281	0	1
Dkr 20 Spui km 1008-1009 Loc 8_ 77233_424713	3.467	0.830	3.378	0.748	3.93	0.463	0.552	1	1
Dkr 20 Spui km 999-1000 Loc 6_ 85508_426651	4.109	0.656	4.033	0.852	4.26	0.151	0.227	1	1
Dkr 21 Haringvliet km 1004-1005 Loc 5_83303_417928	4.631	1.593	3.944	1.189	4.55	-0.081	0.606	0	1
Dkr 21 Hollandsch Diep km 991-992 Loc 3_ 95531_413289	4.208	1.007	3.592	0.941	4.65	0.442	1.058	1	1
Dkr 21 Hollandsch Diep km 997-998 Loc 5_ 90408_414873	3.798	1.000	3.425	0.781	4.38	0.582	0.955	1	1
Dkr 21 Spui km 1008-1009 Loc 3_ 78022_423673	4.200	0.681	3.675	0.652	4.6	0.400	0.925	1	1
Dkr 21 Spui km 999-1000 Loc 4_ 85838_426483	3.905	0.581	3.677	0.633	4.42	0.515	0.743	1	1
Dkr 25 Haringvliet km 1006-1007 Loc 8_ 80624_413901	4.395	0.367	3.882	0.393	5.5	1.105	1.618	1	1
Dkr 25 Haringvliet km 1015-1016 Loc 11_ 73022_420553	3.833	0.889	3.559	0.796	5.55	1.717	1.991	1	1
Dkr 25 Haringvliet km 1021-1022 Loc 5_ 69289_422366	4.044	0.685	3.656	0.659	5.07	1.026	1.414	1	1
Dkr 25 Haringvliet km 1024-1025 Loc 6_ 66663_424108	3.627	0.604	3.413	0.619	5.47	1.843	2.057	1	1
Dkr 25 Haringvliet km 1028-1029 Loc 20_61896_426286	3.005	0.237	3.005	0.237	5.49	2.485	2.485	1	1
Dkr 34 Hollandsch Diep km 991-992 Loc 2_ 95620_410958	4.737	0.759	4.209	0.722	4.72	-0.017	0.511	0	1
Dkr 34 Hollandsch Diep km 996-997 Loc 13_ 89525_412391	3.824	0.400	3.590	0.459	5	1.176	1.410	1	1
							Total failure	5	0

G

Failure Mechanisms and their Probabilities

In the Veiligheid Nederland in Kaart (VNK) Klein Tank et al. (2015), results of the actual failure probabilities for each failure mechanism per dike ring are made insightful. For the hinterland of the Haringvliet, the dike rings 20, 21, 25 and 34 are slightly effected by the failure mechanisms of the Haringvliet Sluices. The actual failure mechanisms of dikes are schematically shown in Figure G.1.

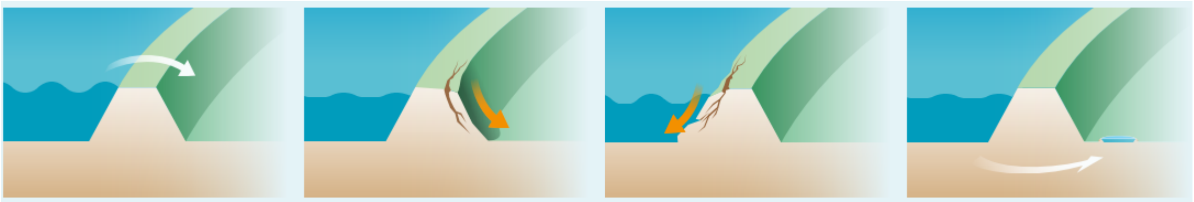


Figure G.1: The fail mechanisms f.l.t.r. overtopping, stability of the inner slope, strength of the revetment and piping, from Rijkswaterstaat Projectbureau VNK (2014).

As already mentioned in the report, the effect on the water levels due to the failure mechanisms of the sluices is thought to have largest influence on the mechanism overtopping. The other mechanisms are influenced as well, but therefore also other conditions are needed to fail.

For the dike rings mentioned, the failure probabilities per mechanism are stated in Table G.1.

Table G.1: The failure probabilities for the dike rings from Rijkswaterstaat Projectbureau VNK (2014)

Ringnumber	**Dikering area**	**Failure probabilities**			
		Overtopping	**Stability inner slope**	**Piping**	**Strength Revetment**
20	**Voorne Putten**	1:9900	1:220	1:460	1:310
21	**Hoekse Waard**	1:11000	1:38000	1:420	1:5700
25	**Goeree Overflakkee**	1:7500	1:260000	1:390	1:5500
34	**West Brabant**	1:3900	1:110	1:140	1:4500

From Table G.1 it can be concluded that other failure mechanisms have larger probabilities, meaning that assessing these dike rings for the failure mechanisms of the Haringvliet on overtopping and overflow, underestimates the failure the actual probability of flooding.

H

Overtopping and Overflow calculations

In (Van der Meer, 2008) the following formulas are used to calculate the transmission of waves.

$$\frac{R_c}{H_{si}} \leq -\alpha - \beta \quad \mathrm{K_t} = 1 \tag{H.1}$$

$$-\alpha - \beta \leq \frac{R_c}{H_{si}} \leq \alpha - \beta \quad K_t = \frac{1}{2}\left(1 - \sin\left(\frac{\pi}{2}\frac{\frac{R_c}{H_{si}} + \beta}{\alpha}\right)\right) \tag{H.2}$$

$$\frac{R_c}{H_{si}} \geq \alpha - \beta \quad \mathrm{K_t} = 0 \tag{H.3}$$

When looking at overtopping, the following formula is used:

$$q/\sqrt{gH_{m0}^3} = a\exp\left(-bR_c/H_{m0}\right) \tag{H.4}$$

In which:

- K_t is the transmission coefficient [-]
- H_{si} is the in coming significant wave height $[m]$
- α coefficient, dependent on the construction = 1.8 [-]
- β coefficient, dependent on the construction = 0.1 [-]
- q is the overtopping volume $[l/s/m]$
- g is gravitational force $[kg/m/s^2]$
- H_{m0} is the significant wave height $[m]$
- Rc is the free board which is the vertical distance between the water level and height of a structure $[m]$.

From the above it can be concluded that the transmission coefficient is dependent on the incoming wave height and free board. When dividing the free board with the incoming wave, the transmission coefficient can be calculated.

The values a and b in Equation H.4 are coefficients depending on the structure. In Van der Meer (2008) the formula is used with values 0.12 and -2.6 for the coefficients a and b respectively. The overtopping formula is only valid for water levels smaller than NAP +5.0 meter. For larger water levels, the overtopping formula would become invalid due to the negative R_c value, and becomes:

$$q/\sqrt{gH_{m0}^3} = 0.12 \tag{H.5}$$

The overtopping calculations are executed with a wave height of H_{m0} = 2.5m and a spectral period $T_{m-1,0}$ = 5.6s. These wave height and period correspond to a water depth of NAP +6.4 meter. In Van der Meer (2008) the water level of NAP +6.4 meter is used as maximum. To use the wave height and period corresponding to these water levels are quit conservative.

I

Salt Intrusion and Ecology with the Kierbesluit

In this Appendix information, formulas and research which is done to the salt intrusion and ecology after the Kierbesluit will be given.

I.1. Salt Intrusion after the Kierbesluit

Salt is hard to model for the Haringvliet due to the 3D components which play an important role. Therefore, the salt and velocity measurements done in 1997 and described in Jacobs et al. (2003) are used as guiding information source.

As already mentioned in the report, the relative water level and density between the sea and Haringvliet, river discharge and the flow area of the sluices are important parameters when it comes to intrusion lengths. Also the sluice configuration is an important parameter as already shown in the report.

The relative water level differs over time due to the tides, river discharge and surges. When taking into account the tides, during flood the flow direction is upstream (in the direction of the Haringvliet). During ebb this is vice versa. This phenomena is called tidal pumping, as illustrated in Figure I.1. During tidal pumping, saline water and fresh water will not mix evenly due to density differences. The salt water will flow under the fresh water. Eventually the Haringvliet will become more saline over time, especially at larger depths. This is shown in Figure I.2, in which an equilibrium chloride concentration is reached for the deeper layers of the Haringvliet. The top layers are dependent on the flow direction. As can also be seen in Figure I.2, layers originate due to density differences.

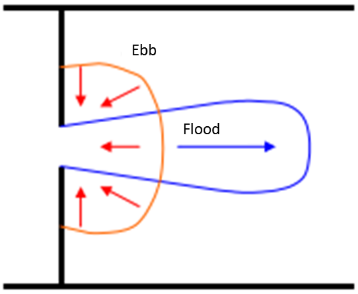


Figure I.1: The effect of tidal pumping schematically shown, from (Jacobs et al., 2003).

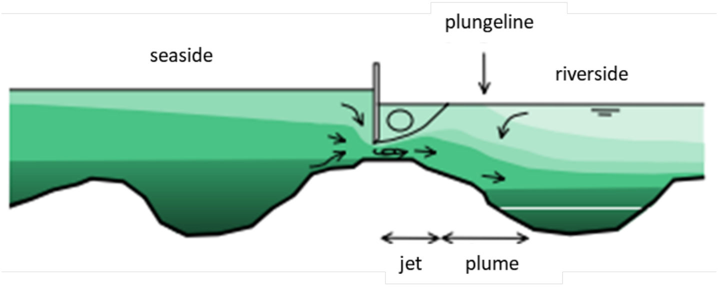


Figure I.2: Equilibrium of the chloride concentrations for deeper layers, from (Jacobs et al., 2003).

The plungline is the line where the fresh from the salt water is
separated, as pointed out in Figure I.2. With the current Kierbesluit this plungeline is clearly visible, Figure I.3. The plungeline does not indicate the intrusion length, because the salt water will travel further at larger depths.

Figure I.3: Plungeline during current Kierbesluit clearly visible from an aerial photo, photo from Rijkswaterstaat.

Before implementing the actual Kierbesluit, velocity and chloride measurements have been carried out at the Haringvliet. At multiple locations, as shown in Figure I.4, the concentrations and flow velocities have been measured. The measurements are carried out in 1997 from March 10 till 14. After the testing period, the sluices were only opened during ebb again. Two days after the tests, the top of the water column (till NAP + 8.0m)turned fresh again (Jacobs et al., 2003). For the deeper layers, this took longer.

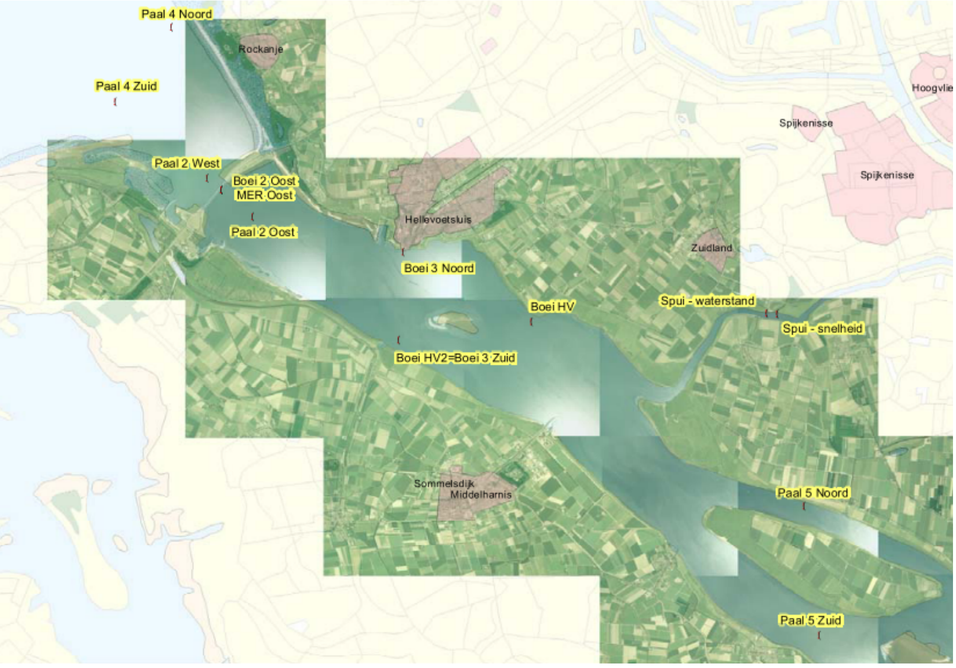


Figure I.4: The locations of the measurements done in (Jacobs et al., 2003). (Paal = pole, boei = bouy)

When it comes to salt intrusion, the buoys HV, HV2 (bouy 3 south) and bouy 3 north and poles 5 North and South are most interesting when it comes to the limit of 300 mg/L chloride at the entry Spui-Middelharnis. For bouys 3 north and south, the chloride limit is exceeded multiple times and the concentration increases over depth, Figures I.5 and I.6. From the 13th of March, the concentration increases significantly. This is possibly due to the configuration of the sluices where a small number of doors were opened but their flow area was relatively large. Also the water level difference was slightly larger compared to other flood periods.

For bouy HV the limit is not exceeded during the measurements, Figure I.7. The measurements from poles 5 are not shown in the report.

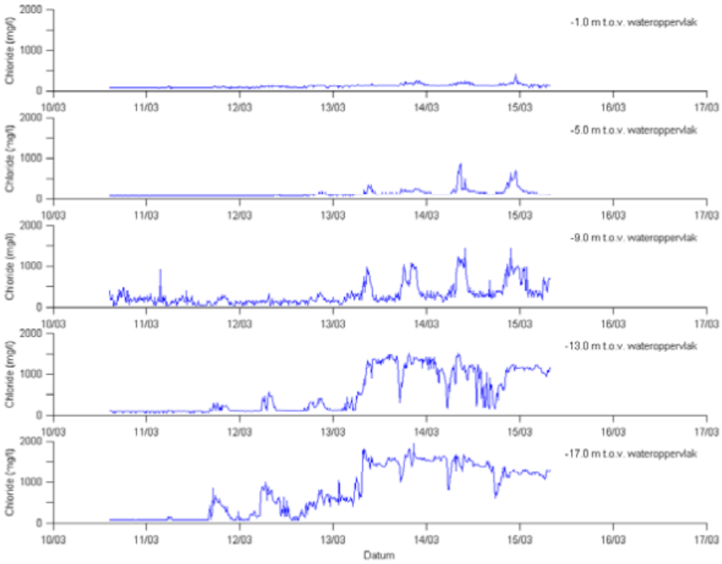


Figure I.5: Chloride concentration over time at different depths at buoy 3 North

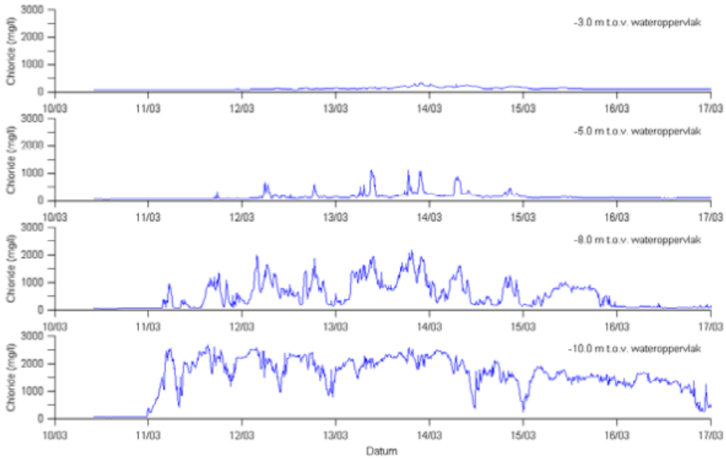


Figure I.6: Chloride concentration over time at different depths at buoy 3 South.

Concluded from the measurements is that the heavier salt water intrudes further at larger depths in the water column. This is especially the case if the openings are large and clustered.

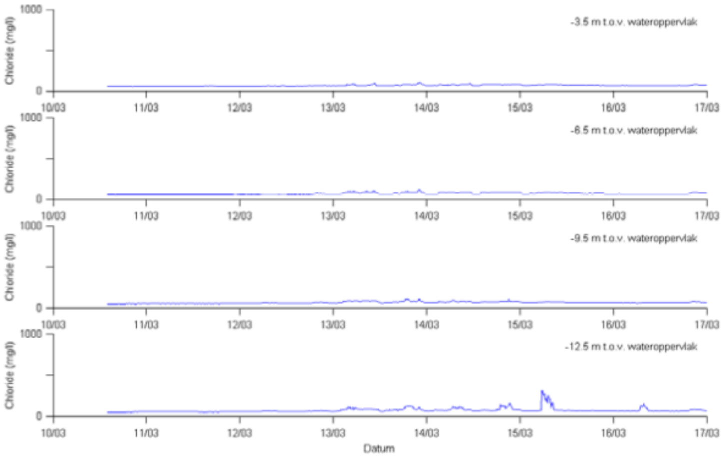


Figure I.7: Chloride concentration over time at different depths at buoy HV.