Assessing the remaining lifetime of the Haringvliet sluices

"A method for a full system analysis of existing hydraulic structures to quantitatively and qualitatively determine plausible adaptive courses for their remaining lifetime"

C.J.J. (Lotte) Bodelier

TU Delft
Master Civil Engineering
Hydraulic Engineering

Delft University of Technology
Faculty of Civil Engineering and Geosciences

Civil Engineering – Hydraulic Engineering (HE-HS)

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Master Thesis by:

C.J.J. (Lotte) Bodelier

to obtain the degree of **Master of Science** in Civil Engineering
at the Delft University of Technology to be defended publicly on 26th of May 2023

18th of May, 2023

Cover photo: The Haringvliet sluices (Rijkswaterstaat, n.d.-b)

Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

Colophon

Title
Assessment of the remaining life time of the Haringvliet sluices

Subtitle
A method for a full system analysis of existing hydraulic structures to quantitatively and qualitatively determine plausible adaptive courses for their remaining life time

Author
C.J.J. (Lotte) Bodelier[1]

Student number
4478401

Date
18-05-2023

Version
Final thesis report

Graduation committee

Chair:	prof. dr. ir. S.N. Jonkman[1]
University supervisor:	dr. ir. A.M.R. Bakker[1,2]
Company supervisor:	ir. E.J. Hamerslag[2]
Committee member:	dr. ir. M. van den Boomen[1]
Committee member:	ir. E.S. van Baaren[3]

[1] Delft University of Technology
Faculty of Civil Engineering and Geosciences

[2] Rijkswaterstaat

[3] Deltares

Preface

The master thesis in front of you concludes the requirements for the degree of Master of Science in Hydraulic Engineering and thereby marks, after nearly eight years, the end of my student days at the Technical University of Delft. I am proud to present to you my thesis “Assessing the remaining life time of the Haringvliet sluices” on which I have worked for the past year. This thesis was carried out in collaboration with Rijkswaterstaat. I hope that despite the technical topics, this thesis and its overarching important themes are accessible to a wide variety of readers.

During my bachelor Civil Engineering I always said that I would never see myself specialize in the field of hydraulic engineering, but at the end of my bachelor it just clicked and it felt as the most natural decision ever. Besides choosing hydraulic engineering as my master, I surprised myself even more by choosing to pursue the specialization of hydraulic structures, which included a lot of difficult dynamics courses. Looking back to this, I can say that I just cannot resist a good challenge. Whether this has been good for me or not in the past few years is debatable, but at least I can say I learned a lot from it. Perhaps stepping out of my comfort zone and looking for a challenge also let me to the decision on this thesis topic, which I definitely have experienced as such. During writing my thesis I learned that the topic of adaptivity did not only apply to the actual thesis content, but more so applied to the entire thesis writing process. The topic of assessing the life time of critical hydraulic infrastructure is a broad topic which can be approached from multiple angles and from multiple disciplines. This broadness makes it a challenging and interesting thesis topic, but also makes it difficult to define and stay within the scope sometimes. Being adaptive during the thesis and to always stay open for new findings or new discussions while still grasping the bigger picture is something I learned while working on this thesis. Now that I am finalizing my thesis, I can say that in choosing the field of hydraulic engineering, I truly found my passion and be warned: without me realizing I will explain to you in great detail and enthusiasm the characteristics of a *woelbak*, or I will point out every hydraulic structure (and their main design considerations or fun facts) as we pass them driving, cycling or walking. I hope I can take this passion into the start of my career so I can stop annoying my family and friends.

I would like to thank my committee for their guidance and their time during this thesis. I always enjoyed the discussions in our committee meetings, which always left me with a lot of energy to continue finishing this thesis. I appreciated all the feedback that has been given and I found it very interesting to see different views on discussed subjects resulting from each of your own expertise. A particular note of thanks to my daily supervisor Alexander Bakker, with whom I had great discussions in our weekly meetings and who was always available for questions or feedback.

I would like to express my love and thanks to my friends and family, which helped me through these, sometimes tough but mostly very special, student years. Thanks for bringing me a lot of happiness, fun and encouragement. I would like to give a very special thanks to my partner Stijn, for always having faith in me, giving me inspiration and for supporting me. I am very honoured to share this milestone with you. I read this old thesis joke that the only people who will actually read your thesis are: You, your supervisors, your assessment committee and your unlucky boyfriend who has to act as an unpaid proof reader for you. Because this last statement was definitely the case, I would like this thesis to be dedicated to you.

Lotte Bodelier,

Delft, 18th of May 2023

Abstract

Many Dutch infrastructure assets were constructed in the first half of the 20th century and by considering an average design life time of roughly 100 years, a lot of these structures will reach the end of their designed life in the upcoming decades. This results in a large replacement and renovation challenge in the nearby future. Assessing the end of life of individual critical hydraulic structures (case studies) and prolonging their lifetime by suggesting adaptive measures is of importance to better define and solve this challenge. In this research, the Haringvliet sluices are used as a case study.

The focus of this research is to apply two existing methods, the framework of Vader et al. (2023) and the Adaptation Pathway Approach of Haasnoot (2013), to the Haringvliet sluices, to make an estimate of the remaining life time and to propose suitable measures to elongate it. Next to this, this research aims to connect both methods mentioned above to create a new integral method. This full method aims to qualitatively and quantitatively analyse hydraulic structures and map out possible paths to elongate its remaining life time. The results of this thesis provide valuable insights in assessing the remaining lifetime of different hydraulic structures in the future. The Haringvliet sluices are an interesting candidate for this research due to the many functions it has to fulfil and the complexity of its interactions within the water system. Additionally, Rijkswaterstaat has highlighted the necessity to evaluate the Haringvliet sluices and requested an assessment of this system. The Haringvliet sluices are part of the Delta Works, which are the largest water defence projects in the Netherlands against high water levels at sea.

The first part of the analysis on the Haringvliet sluices describes the functional analysis as well as the technical decomposition performed on the Haringvliet sluices. The goal of the functional analysis is to define requirements for each of the functions. The goal of the structural decomposition is to identify the most important deterioration mechanisms of the structural elements, which in turn are important in estimating the remaining technical life. The functional analysis results in the description of eight different functions: (a) prevent extreme water levels in the hinterland, (b) provide a passage for navigation, (c) water level management, (d) water quality management, (e) allow for fish migration, (f) allow for an ecological beneficial environment, (g) provide a road connection, (h) maintaining National Monument status. For each of the functions, requirements are formulated, either qualitatively or quantitatively. For the structural decomposition the components were categorized into three groups: fixed, movable and electronic components. The main deterioration mechanisms are steel deterioration, concrete deterioration and erosion of elements affected by flowing water or debris like the stilling basin or the bed protection.

The next step in the analysis aims to either qualitatively or quantitatively describe the external drivers which influence the functional performance and technical state of the Haringvliet sluices. The external drivers to consider for the Haringvliet sluices, or hydraulic structures in general, can be subdivided into physical external drivers and economic, political and societal drivers. For the physical drivers, each driver is discussed regarding its possible consequences on the case study and an estimated severity of those consequences. From this analysis, the drivers which are expected to have the most severe influence on the Haringvliet sluices are defined. The most critical physical drivers to consider in further analysis are sea level rise, high river discharges, low river discharges and drought period. These drivers have the most influence on the flood protection function and the water management function.

For the Tipping Point analysis in the next part of the analysis, existing models are evaluated and used to quantify Tipping Points due to the expected most dominant driver and function combination. A Tipping Point is reached if the system fails to meets its technical or functional requirements due to changes caused by the external drivers. The dominant combination investigated in the analysis is the

effect of sea level rise on the flood protection function. The work of Ruessink (2019) is used to find an estimation for the Tipping Point. The goal of the work of Ruessink is in line with the first phase of this research: Determining the end of life of the Haringvliet sluices based on the effect of climate drivers. In the work of Ruessink (2019), water level simulations are performed for various locations within the system, by including various system characteristics and scenario inputs like: Failure mechanisms, behaviour of other barriers, sea water levels, river discharges, wind directions and climate scenarios. The Tipping Point is estimated to occur at 87 cm sea level rise when setting the criterium of failure for the flood safety to: 'The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter'. Using more recent climate projections, then the ones used in Ruessink (2019), the remaining life time of the barrier is decreased by roughly 12 to 26 years based on the defined Tipping Point. The Tipping Point analysis shows that there is a large dependence of the Tipping Points on the evaluation criteria. The analysis gives insight in how other evaluation criteria, like accepting more overflow discharge over a dike section, could impact the Tipping Point. For example: altering the allowed overflow discharge on the dike sections from the initial 1 L/m/s to 10 L/m/s causes the Tipping Point to shift from 87 cm to 137 cm sea level rise. The unit L/m/s refers to the volume of water per meter of width that flows over the dike section per second. In the used climate scenarios RCP4.5 and RCP8.5 the shift from 87 cm to 137 cm sea level rise results in an elongation of the life time of roughly 14 years. The used climate scenarios are on the extreme side. When looking at more moderate climate scenarios like SSP2-4.5 and SSP1-2.6 the shift from 87 cm to 137 cm sea level rise results in an elongation of 65 to 120 years respectively. Even though Tipping Points are sensitive to decisions on evaluation criteria and chosen climate scenarios, it does provide valuable insights in the response of the system to sea level rise when investigating different decision criteria.

In the last part of the analysis an Adaptation Pathway for the remaining lifetime of the Haringvliet sluices is presented by proposing life elongating measures. Life elongating measures for the Haringvliet sluices can be split into two different categories: Strategies for the bigger water system, i.e. future visions for the Dutch Delta, which could have either a positive or negative effect on the remaining life and life elongating measures focussed on the object or direct system. It is chosen to only investigate mitigation measures focused on the Haringvliet sluices and its direct system. The mitigations actions are comprised of dike elevations (action A and B), changes in requirements (action C) and expanding water storage elsewhere (action D). If action A, B and C are all implemented, their combined effect could potentially elongate the life of the Haringvliet sluices and its system to withstand 188 cm sea level rise (based on the evaluation criteria described earlier). By comparing this with the initial Tipping Point results (87 cm), it can be concluded that action A, B and C could postpone the Tipping Point by roughly 1 m additional sea level rise and thereby elongating the life time of the system. Including the fourth action (action D), the expansion of water storage possibilities, would lead to an additional 20 cm acceptable sea level rise, but the implications to surrounding areas of this fourth action need to be investigated further. How much the remaining life time can be elongated, expressed in years, is dependent on the chosen sea level rise projections.

It can be seen that the research approach consists out of multiple steps and each step can be viewed as its own analysis, contributing to the main research goal and the final results. Each sub-analysis has its individual results and therefore its individual assumptions, limitations and critical remarks. The assumptions and limitations of previous steps could have a significant impact on other steps in the analysis. One of the biggest uncertainties in the results of the remaining life time of the Haringvliet sluices is that there is a possibility that other critical combinations found from the driver analysis would reach a potential Tipping Point sooner than the one investigated in this research. Also, the impact of the proposed mitigation actions for the Adaptive Pathways needs to be revaluated on their impact on other function or technical requirements, i.e. an extra feedback loop is needed. The full analysis must be run through several times to create a more complete overview of the most critical ways a structure could reach its end of life and to indicate which measures could be best applied at what time.

Concluding, the full analysis on the estimation of the remaining life time of the Haringvliet sluices results in six key insights which are listed below, based on the mentioned simplifications and uncertainties:

- The functional end of life is more dominant than the technical end of life for the Haringvliet sluices.
- The most critical external drivers affecting the end of life of the Haringvliet sluices are sea level rise and changing river discharges.
- The most critical combinations of drivers and functions for the Haringvliet sluices are the combinations of; the flood safety and water management function with the driver sea level rise and the driver extreme river discharge situations.
- The Tipping Point in the analysis on the combination of the flood safety function and the rising sea levels is highly dependent on decisions on the evaluation criteria, such as acceptable overflowing discharges on dike sections or on criteria defining failure of the system for a specific function.
- If no mitigation actions would be implemented, the end of life of the Haringvliet sluices could be expected in roughly 50 to 70 years based on more extreme climate scenarios RCP4.5 and RCP8.5 respectively when looking at the middle-bound values.
- The four explored mitigation actions to elongate the life time of the Haringvliet sluices could make the system compliant up to 1 m extra sea level rise, in comparison to making no adaptations.

By applying the methodology proposed by this research to other case studies and by conducting more research on assessing the remaining life time of critical hydraulic structures, key insights can be found in how to manage our critical hydraulic infrastructure in an adaptive way to elongate their life time.

Nomenclature

Abbreviations

AP	Adaptation Pathways
Climate Signal'21	Climate change scenarios for the Netherlands released in 2021
HS	Hydraulic structures
IPCC	Intergovernmental Panel on Climate Change
KNMI	The Dutch Royal Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut)
KNMI'14	Climate change scenarios for the Netherlands released in 2014
NAP	Amsterdam Ordnance Datum (Normaal Amsterdams Peil)
PLM-HV	Performance level model Haringvliet sluices
SLR	Sea level rise
WOM-HV	Wave overtopping model

List of Terms and definitions

Accelerated ageing	Accelerated ageing of infrastructure assets can occur due to an increase in use, and thus technical wear, due to changes in physical boundary conditions or due to changes in demand or functioning. Each of these can be a direct consequence of climate change or societal developments.
Adaptation Pathway	Adaptation Pathways provide an analytic approach for exploring and sequencing a set of possible actions based on alternative external developments over time.
Adaptation Tipping Point (or Tipping Point)	An Adaptation Tipping Point is reached if the magnitude of the change is such that the current management strategy can no longer meet its objective.
Decision Point	A Decision Point is a point in time at which decisions have to be made on which course to follow on the Adaption Pathway to ensure a continuity of meeting the demands, preventing the object from fully reaching the Adaptation Tipping Point at which the object does not longer meet the demands.
Delta Works	The Delta Works are a response on the flood of 1953 (in Dutch referred to as the 'watersnoodramp' of 1953). An innovative plan to shorten the Dutch coastline drastically to prevent future flooding of the Netherlands.
Economic life	The time period over which the costs of owning and operating an asset are still less than the costs of equivalent alternatives.
Functional life	The time period during which an asset complies with the functional requirements. The end of the functional life could be reached due to changing physical conditions, societal developments, or altering functional requirements.

Goeree navigation lock	Navigation lock for vessels to pass the Haringvliet dam.
Haringvliet	The former estuary closed off by the Haringvliet dam on the West and the Haringvliet bridge on the East.
Haringvliet bridge	Traffic bridge over the Haringvliet, roughly 30 km East of the Haringvliet dam (not to confuse with the bridge deck on top of the Haringvliet sluices).
Haringvliet dam	The total object that closes of the Haringvliet from the North Sea, consisting of the Haringvliet sluices and a dike body on each side.
Haringvliet sluices	The object consisting of discharge sluices and concrete piers, including the abutments.
Kieren	Kieren is the activity of slightly opening the discharge sluices of the Haringvliet sluices at high tide to allow water flow from the North Sea into the Haringvliet with the main goal of promoting fish passage.
Life span	The life span of an infrastructure asset is referred to as the time that the asset will be expected to be able to fulfil its functions to the required performance level.
Rijkswaterstaat	Dutch term for the Dutch Directorate-General for Public Works and Water Management. Can also be found in documents as the acronym ‘RWS’.
Technical life	The time period until an asset is no longer able to fulfil its functions according to the original functional requirements due to deterioration of non-replaceable components or the use of outdated technologies.
The Delta Program	The Delta Program describes how the government should protect the Netherlands against flooding, now and in the future.
The Kier Policy	The Kier Policy (Dutch: Kierbesluit) has been launched in 2018 to promote the fish migration through the barrier.
Water Act	The Water Act regulates the management of the water system, i.e. the flood defences, surface water and groundwater. The standards for primary flood defences are set out in this Act.

Contents

1. Introduction

Many Dutch infrastructure assets, managed by the Dutch Directorate-General for Public Works and Water Management (Dutch: *Rijkswaterstaat*), were constructed in the first half of the 20th century (Vlist et al., 2016). Considering an average design life time of roughly 100 years, a lot of these structures will reach the end of their designed life in the upcoming decades. From this follows that in the nearby future a large replacement and renovation challenge will present itself. This challenge is amplified by the additional challenge of accelerated ageing of newer structures. Accelerated ageing of infrastructure assets can occur due to an increase in use, and thus technical wear, due to changes in physical boundary conditions or due to changes in demand or functioning. Each of these can be a direct consequence of climate change or societal developments. Ageing of a structure can thus be related to either technical ageing or functional ageing. Rijkswaterstaat is responsible for maintaining the technical quality, functioning and level of safety of these infrastructure assets. Timely assessment of these infrastructure assets is necessary to create enough time to collect proper funding, assign manpower and gather materials. It is estimated by previous research by Rijkswaterstaat that the required investment of tackling this challenge will be €6728 million for the first period of 2031-2040 and €7577 million for the second period of 2041-2050 (Klatter, 2019). As Rijkswaterstaat is responsible for the majority of these infrastructure projects, it is no surprise that for a long time already, replacement and renovation is on their agenda. Different research projects such as V&R (Replacement & Renovation), VONK (Replacement challenge wet infrastructure) and RINK (Risk inventory wet infrastructure) have all contributed knowledge and insights on this major renovation challenge over the last two decades.

A large part of the renovation and replacement program consists of wet infrastructure; e.g. hydraulic structures which are part of waterways, provide protection against flooding and regulate water levels etcetera. Storm surge barriers are an example of these hydraulic structures, which will require renovation or replacement in the near or distant future. These storm surge barriers are part of the primary flood defence system: the system of dikes, dunes and structures that protects the country against floods from the outside as stated by Rijkswaterstaat (Klatter, 2019). However, these storm surge barriers more often than not have more functions than solely a flood protection function, which makes them complex objects to evaluate in their entirety. Rijkswaterstaat manages a total of six storm surge barriers, five of which are also part of the well-known Delta Works[1]. Table 1 gives an overview of these storm surge barriers and their start of operation date. An overview of all the assets within the Delta Works and their location, can be found in Appendix A.

Table 1 List of storm surge barriers in the Netherlands managed by Rijkswaterstaat.

Name of object	Location of the asset	Year of start operation
Maeslant barrier*	Province of South Holland	1997
Hartel barrier*	Province of South Holland	1997
Hollandse IJsel barrier*	Province of South Holland	1958
Haringvliet sluices*	Province of South Holland	1970
Eastern Scheldt barrier*	Province of Zeeland	1986
Ramspol barrier	Province of Flevoland	2002

* Part of the Delta Works

Although the operational start dates of these storm surge barriers seem quite recent in comparison to the other group of aging infrastructure assets dating back to the first half of the 20th century, they

[1] The Delta Works are a response on the flood of 1953 (in Dutch referred to as the 'watersnoodramp' of 1953). An innovative plan to shorten the Dutch coastline drastically to prevent future flooding of the Netherlands.

demand a great deal of attention in the renovation and replacement challenge. As mentioned before, one reason for this is the phenomenon of accelerated ageing of structures: i.e. unplanned changes in hydraulic loading, changes in function performance, or changes in demand make that the life span of the barrier is reduced. This could cause a storm surge barrier to have a shorter life time than designed. An example to show the impact of accelerated aging on the life span of a storm surge barrier, caused by the effect of sea level rise, can be found in intermezzo 1 below.

Intermezzo 1: Example of the accelerated ageing of a storm surge barrier due to an accelerated sea level rise

To take as an example, an existing storm surge barrier is designed to have a life span of 100 years and is operational since 2000. In the design of this storm surge barrier, a sea level rise of 0.5 m per 100 years was taken into account, which proved to be sufficient according to the climate projections at that time. In the current year, new climate projections show a different scenario and predict that a sea level rise of 0.5 m is already expected 30 years from now, so in the first 50 years of the life of the barrier (fabricated values are used here). This would mean that the total life time of the storm surge barrier is roughly halved and the barrier will reach its expected end of life prematurely in 2050, caused by not being able to cope with the expected sea level rise. The example is further illustrated in Figure 1. This shows that changing (hydraulic) boundary conditions due to climate change itself, but also by the prediction techniques of climate change, could change the end of life of hydraulic structures and thereby decrease its life span.

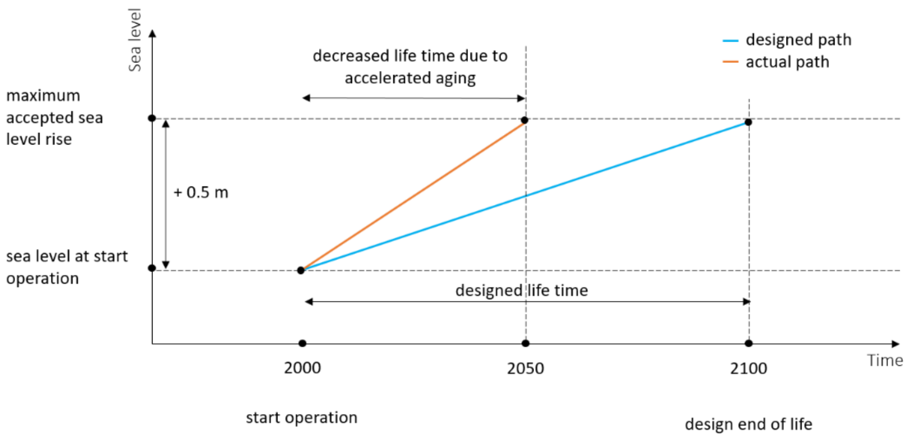

Figure 1 Fictive case of the decrease of the life time of a storm surge barrier due to accelerated aging.

Next to this example of functional accelerated ageing, the structure could also experience technical or material accelerated ageing triggered by more frequent storm closures due to the stated sea level rise.

Even though Rijkswaterstaat manages these storm surge barriers, they are not facing this challenge alone. Together with Rijkswaterstaat the national government, provincial and municipal authorities, waterboards and various other stakeholders work together on The Delta Program (Dutch: *het Delta Programma*). The Delta Program describes how the government should protect the Netherlands against flooding, now and in the future. Besides protection against flooding, the Delta Program defines two other missions. The first mission is being resilient to water shortages and the second is providing spatial adaptation to cope effectively with climate change. The Delta Program ensures periodical evaluation of critical hydraulic structures, updates on climate change knowledge and adaptation of future strategies for the Netherlands. The ultimate goal of the Delta Program is to have the

Netherlands climate-resilient and water robust by 2050. Before reaching this goal, a lot of research still has to be done to make it achievable.

As stated earlier, for managing these wet infrastructure assets it is not sufficient to rely on the end of life set by the initial design. To better describe and quantify the challenge ahead for Rijkswaterstaat, it is vital to map out all of these possible external factors and their influence on the life span of storm surge barriers. It is crucial to estimate *when* and *what* resources are needed to further protect the Netherlands from floods. This work aims to provide insight in the method on how to map out the *what* and the *when,* to assist Rijkswaterstaat in tackling the renovation and replacement challenge.

To achieve this goal, the Haringvliet sluices are selected as a case study. The framework of Vader et al. (2023) is applied to map out the functions and technical components of the Haringvliet sluices and to investigate how these are influenced by external drivers. This is done both quantitatively and qualitatively. Based on the output of this framework, quantitative Tipping Points of the Haringvliet sluices as an object, but also as a system, are analysed using the work of Ruessink (2019). In short, a Tipping Point refers to a state at which the object or the system does not meet its requirements anymore (either functional or technical requirements). After this, the Adaptive Pathway Approach of Haasnoot (2013) is used combined with life elongating measures to illustrate plausible future paths for the remaining life of the Haringvliet sluices. The framework of Vader and the Adaptive Pathway approach of Haasnoot will be further described in chapter 2. Also, the connection between the two methods and the different steps within the full methodology of this research are formally set up in chapter 3.

Using the Haringvliet sluices as the case study on the one hand serves as a direct and practical addition to replacement and renovation challenge as described, but also on the other hand serves as a test subject if the proposed methodology could serve the described overall challenge and could support in analysing all the critical hydraulic structures.

As a reader guide, the thesis structure is illustrated by Figure 2.

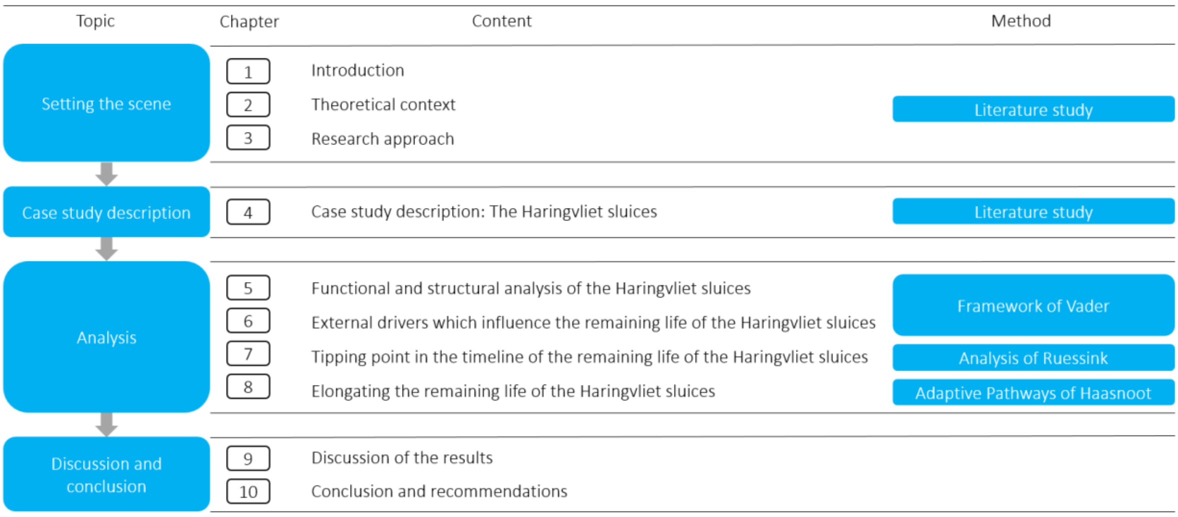

Figure 2 Reading guide

Chapter 2 provides the theoretical context related to the used concepts throughout the thesis and functions as a basis for the research approach. The research approach is mapped out in chapter 3. The case study description can be found in chapter 4. Chapter 5 to 8 represent steps in the analysis of the case study. As part of that analysis, in chapter 5, a functional analysis and a technical decomposition are performed. The results are used in chapter 6. In chapter 6, the external drivers which influence the case study system are examined and either qualitatively or quantitatively defined. By knowing the drivers and their effects, Tipping Points in the timeline of the remaining life time of the Haringvliet sluices can be estimated. These Tipping Points are estimated in chapter 7. In chapter 8, suitable life elongating measures or strategies are proposed and their influence on extending the life time of the case study will be presented in an Adaptive Pathway. The combined results of chapter 5 to 8 are discussed in Chapter 9, which is followed by concluding remarks and recommendations on further research in chapter 10.

2. Theoretical context

This chapter introduces the reader into the concepts which will be used throughout the thesis. It also provides a literature study, which forms the basis of the research approach of chapter 3. The topics discussed are: Life span concepts, frameworks to perform integral system analysis, concepts and terminology of Adaptation Pathways and lastly, prior research on using Adaptation Pathways on hydraulic structures.

2.1 Life span concepts

Different descriptions can be given for the life span (or life time) of an infrastructure asset. Definitions of the life span of a structure can vary between disciplines. In this research, the following definition of the life span is defined:

> *"The life span of an infrastructure asset is referred to as the time that the asset will be expected to be able to fulfil its functions to the required performance level"*

The evaluation of the required performance level can be based on different grounds: Technical state of the asset, political standards, economic considerations or societal demands. In a study performed by Vader (2021) on the assessment of the life time of the Hollandse IJsel barrier, three different life span categories are proposed: Technical life, functional life and economic life. These three life span categories are also applied by Rijkswaterstaat in their asset management. The definitions given by the study of Vader and by Rijkswaterstaat are presented in Table 2.

Table 2 Definitions of three categories of life spans as defined by the research of Vader (left column) and by Rijkswaterstaat (right column) (Vader, 2021).

Life span definitions of Vader	Life span definitions of Rijkswaterstaat
Technical life	
The time period until an asset is no longer able to fulfil its functions according to the original functional requirements due to deterioration of non-replaceable components or the use of outdated technologies.	Period over which an asset is technically capable of meeting the stated performance and risks for which it was designed (in theory, the technical life span can be extended indefinitely, but at high costs such as a VenR* measure).
Functional life	
The time period during which an asset complies with the functional requirements. The end of the functional life could be reached due to changing physical conditions, societal developments, or altering functional requirements.	Period over which an asset is of value for the purpose for which it was designed (when demand changes, requirements change and the asset no longer meets the changed requirements, there is an end of functional life).
Economic life	
The time period over which the costs of owning and operating an asset are still less than the costs of equivalent alternatives.	Period over which an asset can be maintained economically, while meeting the stated performance and risks for which it was designed.

* VenR = Replacement and Renovation

In this research, it is chosen to use the definition as proposed by Vader, as they are more explanatory than the ones of Rijkswaterstaat. For example, in the definition of the economic life stated by Rijkswaterstaat, the threshold of the economic life time is set at being 'maintained economically', whereas the definition of Vader also includes a description of what 'maintained economically' would consist of. It is described as; 'the costs of owning and operating an asset are still less than the costs of equivalent alternatives'. This extended specification can also be found in the definition of the technical end of life.

For the majority of this thesis, the economic end of life of the system is considered to be integrated into the functional and technical end of life. The argumentation for this can be found in Intermezzo 2.

Intermezzo 2: To include or not to include? Considering economic end of life.

As stated before, the economic life time can be defined as:

"The time period over which the costs of owning and operating an asset are still less than the costs of equivalent alternatives."

Since the initial cost of storm surge barriers are high in comparison to the maintenance costs, it can be considered unlikely that replacing the barrier will be a financially better option than an increase in maintenance costs, as also stated in the study of Vader (2021). Furthermore, there is no reason upfront to assume that the maintenance costs will drastically increase, substantiating the latter argument. A technical decomposition will show which elements of the system will be more vulnerable in their maintenance interval and which elements cannot be replaced, since it would mean that the structure would need to be replaced completely (like foundation piles). If such structural element would not meet its quality standards or other requirements anymore, it could be either considered technical end of life (because the element does not fit its technical requirements anymore) or it could be considered economic end of life (because replacing the element would imply replacing the whole structure, which would not be economically feasible). From this we can conclude there is some kind of overlap between the economic and technical end of life. Therefore, excluding the economic end of life when considering the life time of a storm surge barrier can be considered a justified simplification. This overlap can also be found between economic and functional end of life. For example: large system alterations in the water systems could make the contribution of an existing barrier obsolete. In other words: the function it fulfils would no longer be a demand of the larger system. It could be considered economic end of life based on the ground that there are no benefits to gain which could be weight against the cost of keeping the structure or it could be considered functional end of life, because simply the function does not exist anymore.

2.2 Framework to perform integral system analysis

Various studies have looked at the technical, functional or economic end of life of hydraulic structures and systems separately. Studies investigating at the technical end of life mostly focus on specific element deterioration and on preventing end of life on a single driver basis. For example, in Heutink et al. (2004), the maintenance approach of the paints on the steel of the Haringvliet sluices using the LEM model (Life time Extending Maintenance) is investigated. Thus, only focussing on a single element of the total structure. Furthermore, deterioration modelling is performed by Nicolai et al. (2007), who looked at the deterioration of steel elements by comparing three different models. The functional life-time has not extensively been considered in the past and only in recent years studies have started to investigate the consequences of climate change on the functional performance of hydraulic structures. Yet these studies primarily focus at the flood safety function of the structure and thereby neglect other functions, such as the navigation availability, ecology, fresh water supply or socio-economic changes. Defining measures to improve the flood safety function can lead to problems with other functions and as stated before, these hydraulic structures have to fulfil various functions.

Combining technical and functional end of life analyses simultaneously, allows for an integral approach to improve decisions and strategies in the long run. To further illustrate this statement, a fictive case can be taken, in which a pumping station in need of renovation activities is considered. After a few years of service, the pumps need to be replaced for the system to maintain its pumping capacity and operational reliability. One can choose to only look at the technical element and instal new updated pumps with the same total capacity. However, this assumes that the demands, i.e. the functional requirements, have not changed and will not change in the future. With current climate change conditions and other drivers, this assumption might be unrealistic. From this can be concluded that it is more logical to include a functional life time analysis of the structure in the decisions considering updates to prevent the technical end of life. The challenge here is not only combining the technical and functional end of life analysis, but also to integrate all the different elements and functions of larger hydraulic systems. Detailed integral analyses could be necessary for these larger hydraulic structures to achieve completeness in assessing their end of life and to be able to make confident decisions regarding the elongation of the remaining life.

Considering all the different types of life spans simultaneously for hydraulic structures, as discussed in section 2.1, is done by Deltares[2] in a report assessing the Hollandse IJsel barrier(van Baaren et al., 2022). Vader (2021) further developed this report into a framework to assess both the technical and functional performance simultaneously of storm surge barriers (Vader et al., 2023). The framework describes a systematic approach to assess all the different ways a structure can reach its end of life. The schematization of the framework is shown in Figure 3.

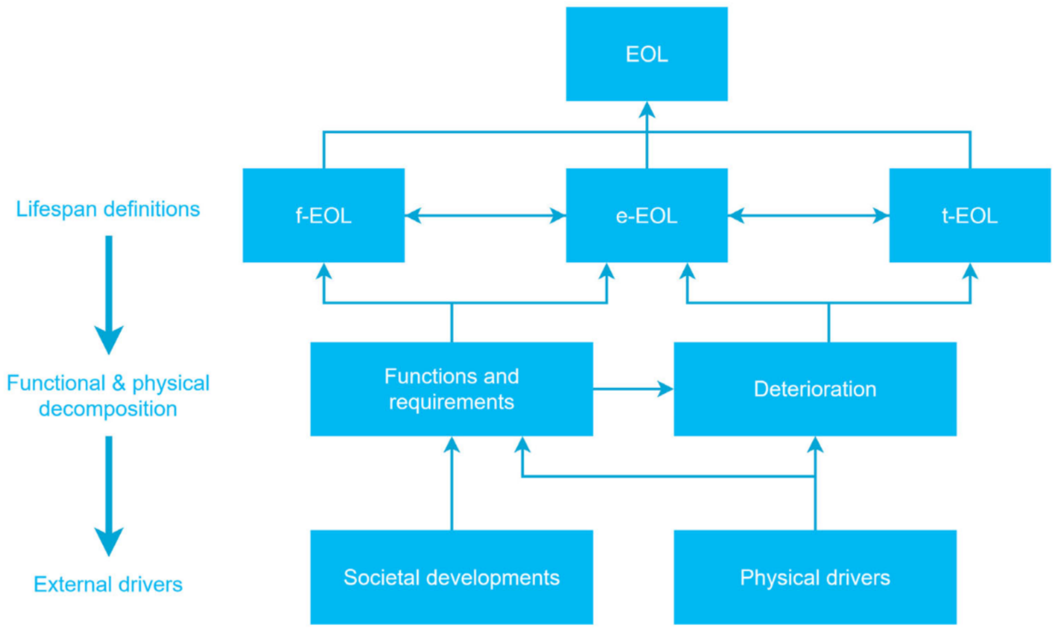

Figure 3 Flow chart of the framework for assessing the remaining life span of storm surge barriers EOL = End of Life, f-EOL = functional End of Life, t-EOL = technical End of Life, e-EOL = economic End of Life. (Vader et al., 2023)

Also following an integral approach, but focussing more on quantitative results in the assessment of the life time of a storm surge barrier, is the study of Ruessink (2019). In this study, not only the technical state in the present and future is considered, but also the resilience of the structure against increased loads on critical elements. This study takes the Haringvliet sluices as its case study, similar

[2] Deltares is an independent institute for applied research in the field of water and subsoil

to this thesis. Comparing similarities and differences could lead to interesting results on how details and extensiveness could lead to different results for the remaining life time of a structure.

2.3 Concept and terminology of Adaptation Pathways

A highly uncertain future due to changes in climate, socio-economic conditions and technology has led to the realisation that identification of the 'best-guess' future conditions might no longer be appropriate (Maier et al., 2016). The use of Adaptation Pathways is proposed as a strategy to make an existing or new object flexible, in order to be able to react to future changes instead of making a robust object based on a 'best-guess' or conservative future projection. The term 'objects' in the latter can range in this context from a single hydraulic infrastructure object to larger river systems.

An Adaptation Pathway, which can also be denoted with an Adaptation Policy Pathway or Dynamic Adaptation Policy Pathway, can be defined as follows:

> *"Adaptation Pathways provide an analytic approach for exploring and sequencing a set of possible actions based on alternative external developments over time"* (Haasnoot et al., 2013).

This definition, i.e. the core of the use of Adaptation Pathways, can best be explained by an illustration of an example Adaptation Pathway (see Figure 4). The Adaptation Pathway in Figure 4 looks similar to a metro map of a city, including a starting point (current policy) and different routes through transfer stations (coloured actions paths) to reach your desired destination (target) (Haasnoot, 2013).

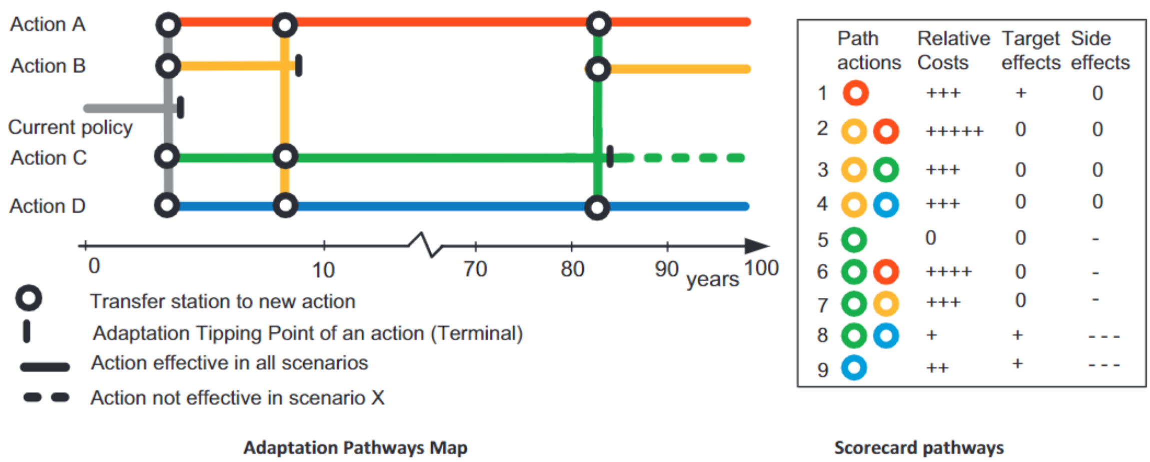

Figure 4 Example of an Adaptation Pathway (left) and a scorecard (right) (Haasnoot et al., 2013)

In Figure 4 the terminology of Adaptation Tipping Point is introduced in the legend, which takes the form of a terminal station following the analogy of a metro map, and can be defined as follows:

> *"An Adaptation Tipping Point is reached if the magnitude of the change is such that the current management strategy can no longer meets its objective"* (Kwadijk et al., 2010).

Beyond such a Tipping Point, an alternative strategy is needed, i.e. the system needs to change in order to comply to its demands or the demands have to be modified. By applying the Adaptation Pathway, the critical questions of decision makers and asset managers are visualized: *what* are the first bottle necks the structure will encounter as a result of climate change and maybe more important, *when* can we expect this to be reached. The scale on the x-axis of the Adaptation Pathways of Figure 4 is dependent on the chosen climate scenario. Multiple x-axes could be included to illustrate different climate scenarios influencing the '*when*' of the Adaptation Tipping Points. As for the y-axis, in which the possible actions are listed, it can be said that these actions are not limited to physical changes to the object but could also imply policy changes or an alteration in function demands.

Looking at the example Adaptation Pathway shown in Figure 4, one can see that starting from the current policy, performance targets will not be met anymore after the first years: The first Adaptation Tipping Point would be reached if no measures are taken. The example proposes four different actions. One can choose to implement action A, C or D to be able to comply to set targets for another 80 years or one can choose to implement action B after which another Adaptation Tipping Point is expected to be reached in 6 years. Before reaching this second Adaption Tipping Point, one can still switch to implement the other actions (A, C or D). The decision on which path to follow and thus, when to implement which action, is dependent on a variety of factors. Costs, political environment and urban planning are an example of main drivers for decision making here. To illustrate a preferred path, a scorecard can be supplemented to the Adaptation Pathway as can be seen on the right side of Figure 4. Different criteria can be used to evaluate paths. In case of the example in Figure 4, the following criteria are used; costs, target effect and side effects.

Adding to the definitions of Adaptation Pathways and Adaptation Tipping Points is the concept of Decision Points. The following definition for a Decision Point is proposed:

> *"A Decision Point is a point in time at which decisions have to be made on which course to follow on the Adaption Pathway to ensure a continuity of meeting the demands, preventing the object from fully reaching the Adaptation Tipping Point at which the object does not longer meet the demands."*

From this definition it can be said that a Decision Point happens before an Adaptation Tipping Point and has to allow for sufficient time to gather information and resources to be able to adapt the object to meet the demands before an Adaptation Tipping Point would be reached otherwise.

As a last remark on Adaptation Pathways, it can be said that this approach serves as a method to deal with uncertainty in climate change or other external drivers when considering the life time of a system, but one has to keep in mind that the preferred pathway might change over time considering these uncertainties and thus does not propose a fixed solution. An Adaptation Pathway illustrates multiple future lives for the object in which it can continue to meet its demands.

2.4 Prior research on using Adaptation Pathways for hydraulic structures

Whereas the previous section focusses on literature regarding Adaptation Pathways in a more theoretical and explanatory manner, this section focusses on analysing different implementations of the method. This is further specified by investigating only master theses at the TU Delft focussed on hydraulic structures. How the scope of this literature study is handled in a more practical way is described in Appendix B. Also, in this appendix more detailed remarks or less substantial findings are presented.

Applying the method of Adaptation Pathways has become increasingly popular in the last few years as a tool to cope with uncertainties in the design, renovation or assessment phase of assets and systems (Werners et al., 2021). The Adaptation Pathways approach has the most added value when the moment in time of reaching Adaptive Tipping Points is uncertain, as explained in section 2.3. A reason to use this approach for hydraulic structures is that it provides a method to deal with the uncertainty of climate change and the thereby influenced hydraulic boundary conditions. Examples of hydraulic conditions are water levels, storm surges, wave characteristics and river discharge. Table 3 aims to include all the relevant master theses at the TU Delft regarding the application of Adaptation Pathways for hydraulic structures.

Table 3 Overview of relevant master theses at the TU Delft on the application of Adaptation Pathways for hydraulic structures (abbreviations: HS = Hydraulic Structures, AP = Adaptation Pathways)

Author	Type of HS	Application	Main conclusions
Rowbottom, 2020	Port infrastructure	AP are created for two different port case studies. Multiple actions are proposed to elongate the life time of different elements of the ports (berms, breakwaters and quay walls). AP are supplemented with scorecards. Also, a distinction between preferred paths and avoided paths is given.	AP a suitable tool to map out and analyse all the effects of different actions to elongate the life time of ports. It is discussed that a simplification made in combining Tipping Points leads to an under or overestimation of the combined efficacy of actions.
Huijsman, 2021	Navigation lock	AP are created for a navigation lock distinguishing minor and drastic adaptation measures. Cost, benefit and efficacy are used to determine the optimal path.	AP a suitable tool to compare the consequences of minor or drastic adaptation measures on costs and availability. Criticised is that the scoring of AP can be rather vague.
Vrinds, 2021	Multiple HS (dike, sluice & barrier)	Uses AP to find the best combination of structures for a robust preliminary design, after which a variant study is done based on the output of the chosen pathway.	Stated that AP provide crucial quantified information for decision makers, connection short- and long-term goals, considering the uncertainties of sea level rise.
Hadders, 2021	Pumping station	Uses AP to investigate the performance of three different designs for a pumping station, including multiple climate scenarios. Each of the designs has a specific character defined by their adaptability.	Designing alternatives using AP can illustrate the benefits of an adaptable design in comparison to a robust design. It allows for a guided discussion with decisions makers on how different designs perform under uncertainty, including decision parameters like costs or initial investments.
Hogeveen, 2021	Breakwater	Evaluates the best AP for the overtopping of different breakwater characteristics for both breaking and non-breaking waves, which result in different preferred paths.	AP a suitable tool to compare different actions. States that choosing a path based on costs has to be done with caution (be aware of which type of cost is taken into account and be sure to look at the local conditions).
Trommelen, 2022	Multiple HS (flood wall variations)	Uses AP as part of a new framework to develop and evaluate AP for a fictive as well as a real case study considering the flood safety of a set area using different HS as an action in the AP. The framework aims to evaluate AP with an incorporated scenario-based economic evaluation and performs a probabilistic assessment of the performance of the paths.	The framework created automizes the process of creating AP and also includes the process of economically evaluating them. The study concludes that AP can be used to select a robust flood risk strategy.

Considering the implementation of Adaptation Pathways in the studies presented in Table 3, it can be said that it is variable which criteria are used to evaluate the different pathways. The most common criterion that is used for evaluation is the cost of different actions. The study which looks at evaluating the different pathways based on costs in the most detail is the study of Trommelen (2022). Rowbottom

(2020), on the contrary, uses multiple other criteria besides costs. This study also considers the hindrance on port activity as an evaluation criterion caused by the proposed actions. Next to this, the study looks at compatibility, sustainability and durability as criteria to define a preferred pathway. In Vrinds (2021) the criterion of hindrance to the system when evaluating the pathways is included, similar as in Rowbottom (2020), which makes it a considerable criterion to include in evaluating preferred pathways.

A distinction that can be made between the studies presented in Table 3 is that four out of six studies investigating extending the life time of already existing objects and two out of six do not. From this can be concluded that for these type of studies for the majority, Adaptation Pathways is used to evaluate existing systems. Different from looking at upgrading existing structures are the studies done by Vrinds (2021) and Hadders (2021). Both use Adaptation Pathways to verify the best design alternative for a new structure or new system. In this, Hadders (2021) looks at a new design for a pumping station and evaluates different alternatives using Adaptation Pathways. Instead of comparing different design alternatives similar to Hadders, Vrinds (2021) looks at combining different elements or components to create a flexible total design. The best combination of components is found by using Adaptation Pathways.

What stands out when considering the conclusions drawn in the studies presented in Table 3 is that the majority of the studies discusses the generalization of the used approach for similar hydraulic structures. The joint conclusion on this is that using the approach with similar adaptation measures is suitable to use when considering similar hydraulic structures and will give insightful information about different paths. However, it is stated that the preferred path will be different for similar hydraulic structures. This can best be seen in the study of Rowbottom (2020), in which the same approach with corresponding proposed actions leads to a different preferred path for both of the port case studies considered. Rowbottom (2020), as well as other authors from Table 3, mention that the preferred path is highly dependent on local conditions and thereby making a generalized pathway for similar hydraulic structures unlikely. From this can be concluded that, using a similar set up (i.e. considering similar mitigation actions) for similar hydraulic structures is a solid approach, but will possibly lead to different preferred pathways due to local conditions. The study done by Trommelen (2022) even proposes to automate the evaluation of the pathways for similar case studies using his framework. This framework focusses on flood safety measures in flood risk areas.

Besides the studies presented in Table 3, which focus on hydraulic structures only, other interesting studies are mentioned in Table 4 , which focus on other types of engineering systems. All these studies apply Adaptation Pathways in their methodology to analyse the system. Again, only master theses from the TU Delft are considered.

Table 4 Overview of other relevant master theses of the TU Delft on the application of Adaptation Pathways

Author	Year	Type of structure / system
Wienk	2020	Waterways
Frölke	2020	Polder management
Savvidis	2020	Road tunnels
Krijnen	2021	Flood prevention of national highway network
Zhang	2019	Managing stormwater in urban environment

A quite different use of Adaptation Pathways can be seen in the work of Wienk (2020) , in which the use of a navigation channel is analysed by determining when different vessel types using the channel reach an Adaptation Tipping Point. On the Y-axis different vessel types are listed instead of mitigation actions to extend the life time of the system. The Adaptation Tipping Points of the vessels type is dependent on the performance indicator of transportation costs per ton kilometre, i.e. the moment when a vessel cannot use the navigation channel anymore in an economically feasible way.

As stated earlier, a generalised pathway does not follow from using adaptation pathways on similar hydraulic structures. Despite that this generalization is not found in the studies presented in Table 4, in the work of Frölke (2020) , it is agreed upon that adaptation pathways are a very helpful tool to inform authorities and stakeholders about expected problems, current system limitations and the efficacy of different mitigations. Frölke (2020) investigates pathways for polder management and concludes that the path is dependent on local conditions, as well as governmental and stakeholder influences. Agreeing with the dependence on local conditions for the preferred pathways is the thesis of Krijnen (2021), in which flood proofing a national highway network is investigated. Here it is also concluded that a generalised approach is not achievable on a national level. However, the study argues that an outcome of a preferred path can lead to helpful international guidelines for floodproofing highway networks.

Summarizing, Adaptation Pathways can be used as a tool to investigate different design options and can test the performance of designs when looking at renovating or (re)designing hydraulic structures. It can provide many useful insights, but the outcome of a preferred pathway is very dependent on the evaluation criteria. Although often costs are considered, other relevant criteria are helpful to make a better choice on the preferred pathway. A generalised preferred pathway for similar structures cannot be achieved due to the dependence on local conditions. From the last two statements, it can be suggested that defining and scoring a preferred pathway is not always the output to strive for, but perhaps an overview of all the possible pathways should be the end product, to which scoring options can be supplemented. Lastly, it can be concluded that as far as the studies considered are concerned, some hydraulic structures are not yet analysed using Adaptation Pathways. Examples of this are storm surge barriers or weirs. In the research performed by Vader (2021), a storm surge barrier, the Hollandse IJsel barrier, is analysed for its remaining life time and life elongating measures are proposed. However, Vader does not make use of the Adaptive Pathway approach, which could be a valuable addition to this work.

3. Research approach

This third chapter defines the focus of the research and composes the research objectives and questions. The chapter also proposes a methodology to reach these objectives and to answer these questions.

3.1 Research focus

The previous chapters have shown the overarching challenge this research aims to address (chapter 1) and the theoretical frameworks that are available to address this (chapter 2). The main challenge referred to is the large renovation or replacement task of critical hydraulic infrastructure, resting among others on the shoulders of Rijkswaterstaat. Assessing the end of life of individual critical hydraulic structures (case studies) and prolonging their lifetime by suggesting adaptive measures is of importance to better define and solve this challenge.

In this research, the Haringvliet sluices are used as a case study, one of the storm surge barriers listed in Table 1. As the Haringvliet sluices have plenty of intricate structural components and multiple functions to fulfil, a structured approach, taking into account both the technical and functional end-of-life, has to be applied. A systematic assessment is necessary to take all the important influential factors, structural elements and functions into account when making an estimation of the remaining life time of the Haringvliet sluices. Such a systematic approach is introduced in the study of Vader et al. (2023), which investigated the remaining life time of the Hollandse IJsel barrier. The study proposes a framework to assess all the different ways a structure can reach its end of life, looking at the technical, functional or economic end of life. The intended result of this framework is a list of the most important drivers influencing the remaining life time. A different method, which can be used to set out the different points in time at which a structure does not meet its requirements anymore (technical, functional or economical end-of-life), is the method of Adaptation Pathways (Haasnoot et al., 2013). In Haasnoot et al. (2013) it is proposed to use Adaptation Pathways and Adaptation Tipping Points as a preferred strategy to robust decision making, especially in situations with large uncertainties. In short, there is a need for validation on other storm surge barriers of the framework of the study of Vader et al. (2023), as it is only applied to the case study of the Hollandse IJsel barrier. Testing, validating or improving the framework by using the Haringvliet sluices case study provides valuable information in assessing other hydraulic structures in future research. Furthermore, the use of Adaptation Pathways as a follow up to the framework of Vader, could potentially lead to a method for a full object analysis in which the possible courses for the life time of hydraulic structures could be mapped out.

The focus of this research is therefore to apply both methods, the framework of Vader and the Adaptation Pathway Approach, using the Haringvliet sluices as a case study, to make an estimate of the remaining life time and to propose suitable measures to elongate it. Next to this, this research aims to connect both methods mentioned above to create a new integral method to be able to fully analyse hydraulic structures and map out qualitatively and quantitatively possible courses to elongate its remaining life time. The results of this thesis could provide valuable insights in assessing different hydraulic structures in the future.

3.2 Research questions

The central research question for this research is defined below.

(RQ) *How can the remaining life time of critical hydraulic structures be assessed and what methods can be used to elongate its remaining life?*

To answer the central research questions as stated above, multiple sub-questions are proposed to provide a structured approach.

(a) *What and when are expected Tipping Points in the life time of the Haringvliet sluices which could lead to end of life decision?*

(b) *Can the framework of Vader et al. (2023) also be applied to other critical hydraulic structures?*

(c) *How can adaptive pathways support in maximizing the remaining life of critical hydraulic structures?*

(d) *Can a combination of the framework of Vader et al. (2023) and adaptive pathways of Haasnoot et al. (2013) lead to a full system analysis of critical hydraulic structures to determine plausible courses for the remaining life time?*

3.3 Research methodology

The approach for this research can be divided up into two different phases, divided in a total of nine steps. The phases and steps are illustrated in Figure 5.

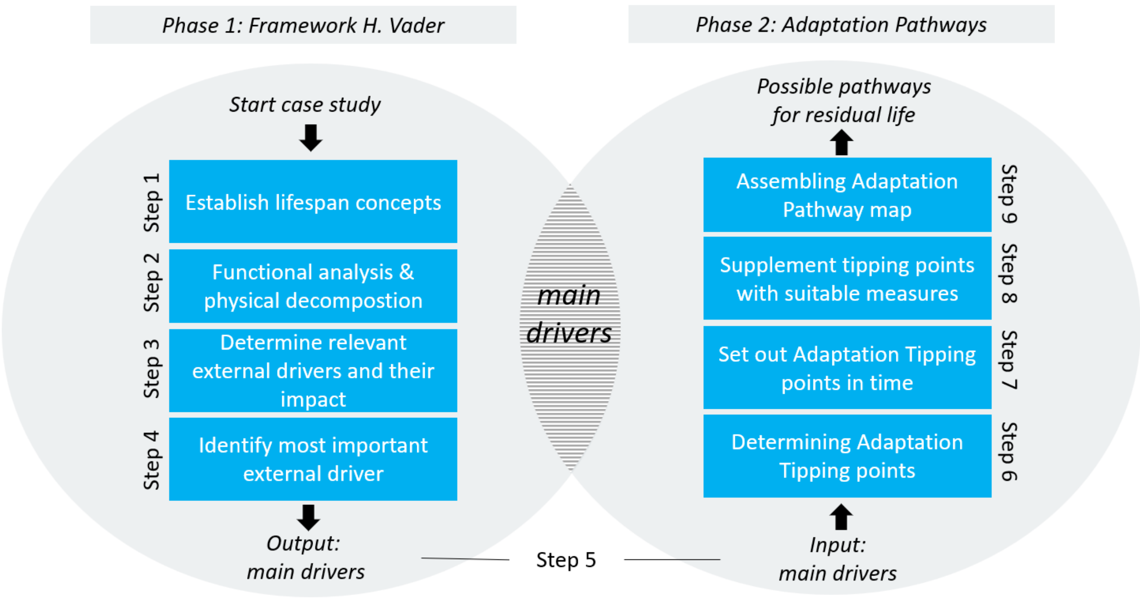

Figure 5 The two different phases within the research approach showing their most important steps and their overlap.

In the first phase a framework is used to ultimately identify the main drivers affecting the functional performance and technical state of the Haringvliet sluices. The framework used to reach this goal is the framework composed in the research performed by Vader et al. (2023) . This framework provides a 'top-down' method characterised by four different steps. The framework by Vader is a direct result of a life time assessment of the Hollandse IJselkering (Vader, 2021). By using this framework to assess the remaining life time of the Haringvliet sluices it allows the framework to be validated or supplemented if necessary. This can be useful for future use of the framework, when analysing different case-studies. In the second phase the approach of Adaptation Pathways is used. The Adaptation Pathways are used to map out the Tipping Points in the timeline of the remaining life of the Haringvliet sluices and to show the effect of different measures to elongate the remaining life.

In Figure 6 , the different steps in the research approach are linked to the chapters of this thesis as well as to their corresponding method.

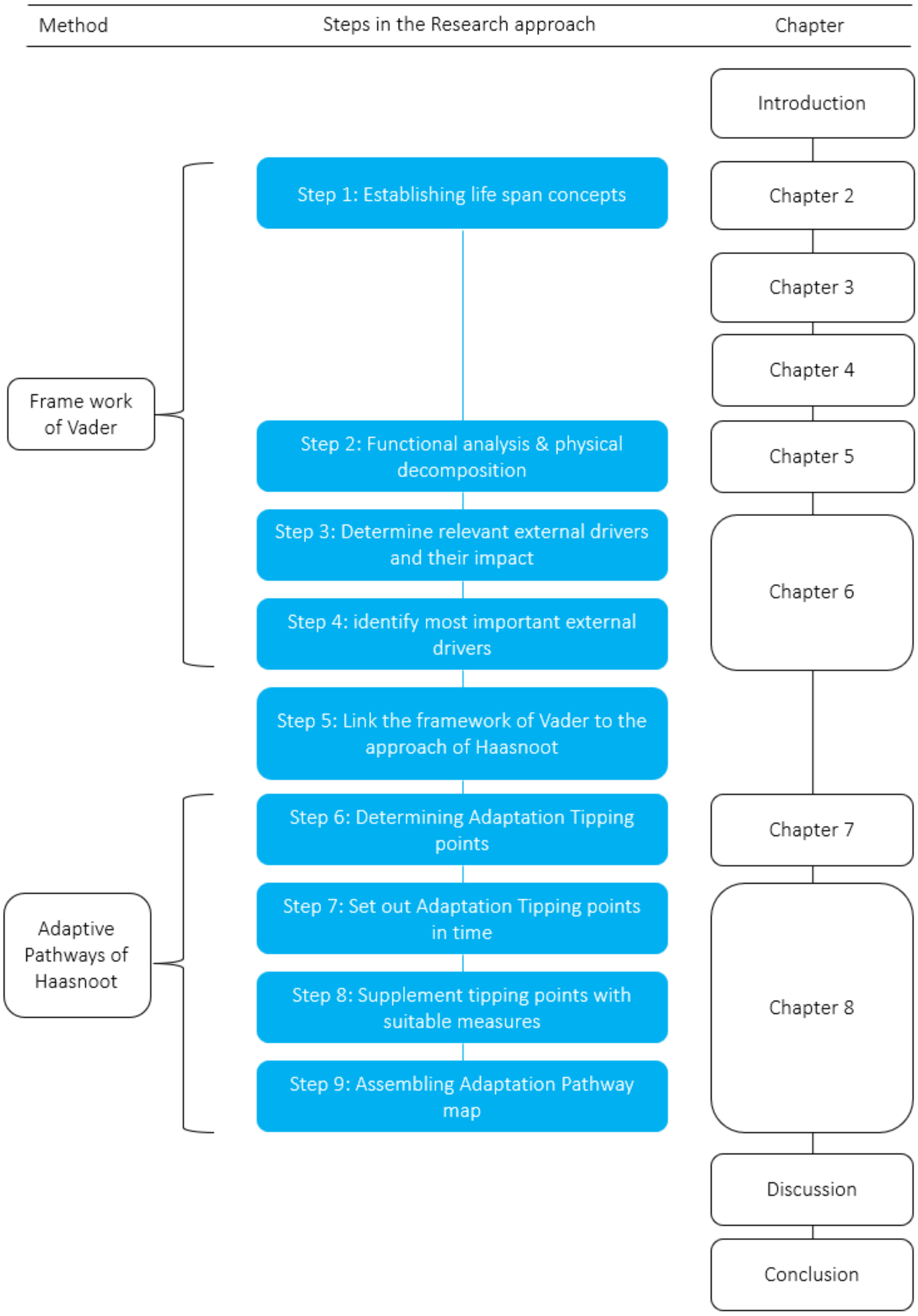

Figure 6 A visualization of the link between the research steps and the chapters of this thesis

The nine steps shown in both Figure 5 and Figure 6 are further elaborated below. The intention of this step-by-step plan is to provide a robust system for analysing the case study of the Haringvliet sluices. This way important details like functions, technical aspects and external drivers are not overlooked. Step 1 to step 4 follow directly from the work of Vader, whereas step 6 to 9 is meant to form the basis to create the Adaptive Pathways.

Step 1 **Establishing life span concepts:** For easy and clear reference in the remainder of the analysis it is necessary to clearly define the lifespan concepts in order to avoid misconception of the definition.

Step 2 **Functional analysis & physical decomposition:** The functional analysis is intended to obtain an overview of the functions of the Haringvliet sluices and establish the requirements the object and the system must meet. The physical decomposition should be carried out for the Haringvliet sluices only. By decomposing the Haringvliet sluices into different structural components, the dominant deterioration mechanisms can be identified, which later can be linked to the effect of the external drivers.

Step 3 **Determine relevant external drivers and their impact**: For each function, one should analyse which external drivers could affect the functional performance and to what extent these drivers could do so. A similar analysis should be performed to identify the external drivers that effect the technical deterioration. This step aims to obtain a complete overview of all potentially relevant external drivers and their impact.

Step 4 **Identify most important external drivers**: Once all relevant external drivers are listed, their impacts can be evaluated to identify the most important/dominant ones. For some effects of external drivers, the evaluation can be done either qualitatively or quantitatively, based on information available. The results of this step can be presented in tables that summarize the effects of the drivers on the functions or structural components. These tables allow for composing a short-list of the dominant external drivers which could be valuable to further asses in next steps of the analysis.

Step 5 **Link the framework of Vader to the approach of Haasnoot:** This link is established by using the output of step 4 as input for step 6. Their link is thus formed by the most important external drivers influencing the system.

Step 6 **Determining Adaptation Tipping Points:** This step aims to estimate the end-of-life thresholds for the Haringvliet sluices based on the dominant driver and system requirements combinations, which follow from previous steps. When the structure or the system fails to meet the objectives, this moment, can be defined as a Tipping Point. To quantify these Tipping Points existing analysis on the Haringvliet sluices are used (the work of Ruessink (2019) will be elaborated in chapter 7).

Step 7 **Set out Adaptation Tipping Points in time:** Using current climate scenarios to translate the limit values of the Tipping Points to end of life points in time. Different climate scenarios can be used for this.

Step 8 **Supplement Tipping Points with suitable measures:** For each Tipping Point a suggestion for suitable measures can be made. Depending on the function or technical aspect which fails to meet the set objective, multiple measures can be given. These measures can range from short term solutions to long term solutions.

Step 9 **Assembling Adaptation Pathway map:** Connections between the Tipping Points and proposed measures can be illustrated in an Adaptive Pathway. Possible interaction between measures and Tipping Points has to be considered.

Step 6 to 9 could be repeated in future research for different combinations of drivers and functions or drivers and technical state. For this research it is chosen to only select a single critical combination, which gives the research a ‘from coarse to fine’ character in the second phase, fitting the scope of the research.

4. Case study description: the Haringvliet sluices

To serve as the case study for the research design, as stated in chapter 3, the Haringvliet sluices are selected. The Haringvliet sluices are an interesting candidate for this research due to the many functions it has to fulfil and the complexity of its interactions within the water system. Additionally, Rijkswaterstaat has highlighted the necessity to evaluate the Haringvliet sluices and requested an assessment of this system. The Haringvliet sluices are part of the Delta Works, which are the largest defence projects in the Netherlands against high sea water levels. The Delta Works consist out of 5 storm surge barriers, 2 sluices and 6 dams. In this definition of the Delta Works, the Haringvliet sluices fall under the Haringvliet dam. More about the difference in definitions later. For the location and names of all the assets within the Delta Works the reader is referred to Appendix A. The Delta Works are a response to the North Sea flood of 1953 (in Dutch referred to as the “watersnoodramp”). In short, this defence system shortened a jagged coastline of 700 km to a straight coastline of roughly 80 km. The Haringvliet sluices where build between 1956 and 1970. This chapter introduces the Haringvliet sluices themselves and its interaction with its surroundings, before starting any formal analysis regarding the end of life estimations.

The Haringvliet sluices are located in the province of South Holland, connecting the peninsula of Goeree-Overflakee and Voorne-Putten. The sluices are able to cut off the interaction between the North Sea and the Haringvliet. The discharge of the rivers the Rhine and the Meuse is collected in the Haringvliet, after which the Haringvliet sluices discharges this water into the North Sea using the waterhead difference. This waterhead difference occurs due to the difference between the water level in the Haringvliet and low tide of the North Sea, both of which fluctuate. The Haringvliet provides a place for water storage, recreational navigation and fresh water intake points. The Haringvliet sluices combined with two dike bodies on both sides of the sluices are called the Haringvliet dam. The different objects within the Haringvliet sluices case study and their abbreviations are defined in Table 5. These abbreviations have no official status within Rijkswaterstaat and are for reference purposes only. The locations of the objects of Table 5 are illustrated in Figure 7.

Table 5 Object clarifications within the Haringvliet sluices complex and its direct vicinity

Haringvliet dam	(HVD)	The total object that closes of the Haringvliet from the North Sea, consisting of the Haringvliet sluices and a dike body on each side
Haringvliet sluices	(HVS)	The object consisting of discharge sluices and concrete piers, including the abutments.
Haringvliet bridge	(HVB)	Traffic bridge over the Haringvliet, roughly 30 km East of the Haringvliet dam (not to confuse with the bridge deck on top of the Haringvliet sluices)
Haringvliet	(HV)	The former estuary closed off by the Haringvliet dam on the West and the Haringvliet bridge on the East.
Goeree navigation lock	(GNL)	Navigation lock for vessels to pass the Haringvliet dam.

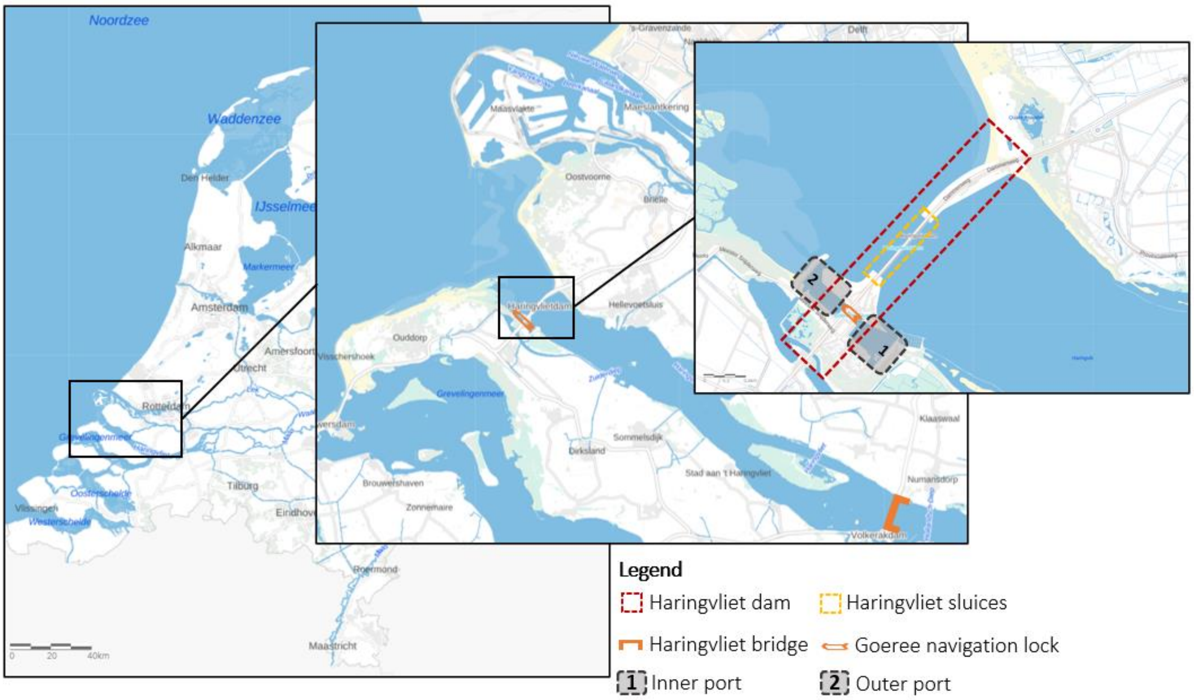

Figure 7 The Haringvliet sluices and its components located in the West delta of the Netherlands

The case study description is further extended by considering the following subjects: The water system, the flood protection system and the different components of the system.

4.1 Water system

The primary function of the Haringvliet sluices, which is to prevent the hinterland from flooding, is two-sided, i.e., in two directions. On one hand the sluices have to close to prevent high waters of the North Sea from getting in and on the other hand the sluices have to open to discharge the river water of the Rhine and the Meuse to prevent flooding from the inland side. This means the barrier has to deal with the characteristics of the water body on the outside (the North Sea) as well as the waterbody on the inside (the Haringvliet filled by the rivers Rhine and Meuse). Adding to this interaction of in- and outland water systems is the salt and fresh water balance.

The largest quantity of water input within the system comes from the river the Rhine, about 90%. The other 10% enters the system via the river the Meuse. Not all of the combined water of both rivers is discharged into the North Sea via the Haringvliet sluices. The volume of water is divided between the Haringvliet sluices (70%) and the New Waterway (30%). This distribution is created by many hydraulic structures situated along the trajectory of the rivers. The 30% discharged through the New Waterway prevents the saltwater of the North Sea to penetrate too deep into the hinterland of Rotterdam, where it could influence fresh water intake points for agriculture, industry and the general population. If the river discharge is expected to drop below critical levels, water can be let into the Haringvliet by the Volkerak sluices. This not only helps to reduce the salt water intrusion but is also beneficial in guaranteeing certain navigational depths. The use of the Volkerak sluices can also be reversed: When the Haringvliet sluices are closed due to high waters at sea, excess water builds up by the closing of the discharge sluices, the Volkerak sluices then can be used to discharged water into the Volkerak lake and the Eastern Scheldt. It is also possible to discharge water through the Spui and the Oude Maas. This implies that the Measlant barrier, which is located here, has to be open. The interactions and routes of discharging are clarified by Figure 8.

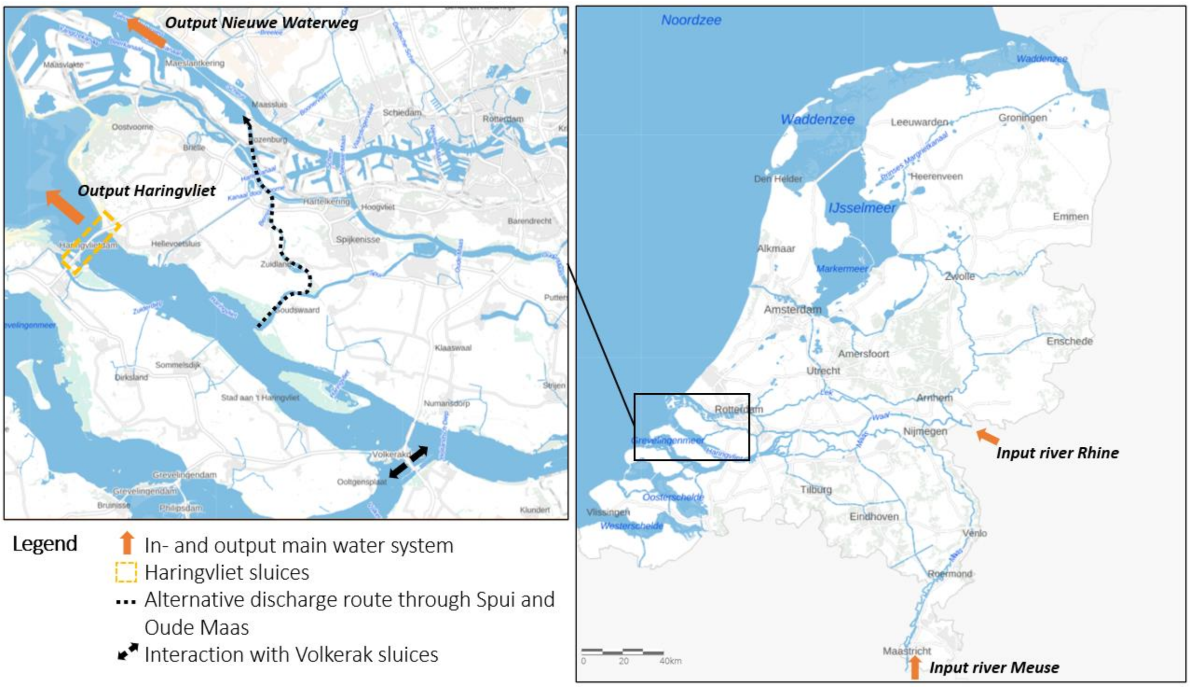

Figure 8 Illustration showing the main characteristics of the water system concerning the Haringvliet sluices

The Kier Policy (*Dutch: Kierbesluit*) has been launched in 2018 to promote the fish migration through the barrier. This Kier Policy means that the Haringvliet sluices are partly open, allowing water into the Haringvliet during high tides when the river water is not being discharged. This activity of allowing water back in is called *kieren*. Since there is no direct translation for the Dutch verb it is chosen to use the word *kieren* for the remainder of this report. The word and its concept are explained in Intermezzo 3 below. The degree of *kieren*, i.e., how much the sluices are opened, depends on the river discharge. The higher the river discharge, the more seawater is allowed to come in through the sluices, as the river discharge can push back the salt water. The balance between available river discharge and the amount of sea water that is allowed back in is driven by guaranteeing fresh water conditions at the intake points in the Haringvliet. These are drinking water intake points for the surrounding peninsulas, but also for agriculture in those locations (Voorne-Putten and Goeree-Overflakkee). Due to this opening decision of the Kier Policy, the Haringvliet sluices are now classified as a storm surge barrier by Rijkswaterstaat.

Intermezzo 3: Explanation on the concept of the Dutch word *kieren*

As explained in the main text, since the launch of the Kier Policy in 2018 the Haringvliet sluices do not only discharge river water, but now also allow seawater back in. Since there is no direct appropriate translation for the Dutch word *kieren* it is chosen to use the Dutch word in the remainder of the report. The use of the Dutch word is chosen to make a clear difference between discharging water to the sea and allowing water back in. Using ‘discharging’ for both directions of waterflow could lead to confusion. The definition of *kieren* is defined below and illustrated in Figure 9 in comparison to the discharging of river water.

“Kieren is the activity of slightly opening the discharge sluices of the Haringvliet sluices to allow water flow from the North Sea into the Haringvliet with the main goal of promoting fish passage”

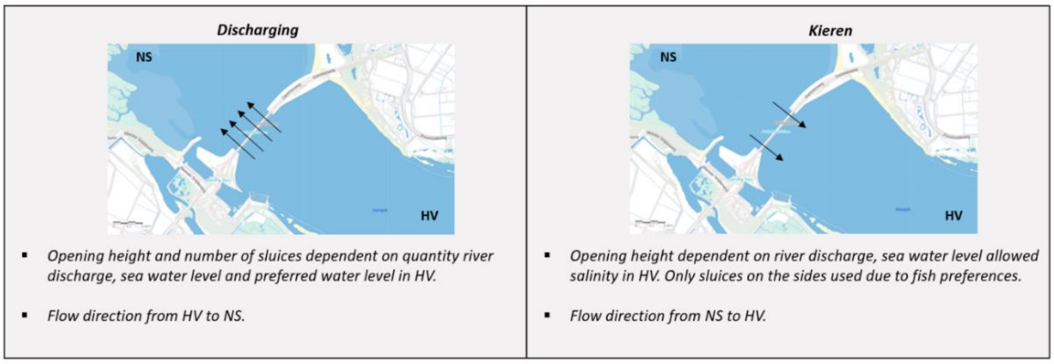

Figure 9 Illustration to show difference between discharging and kieren. (NS = North Sea, HV = Haringvliet)

In Figure 9 can be seen that when the Haringvliet sluices are discharging river water this can be done by opening any number of sluices at any of the 17 openings to create the required surface to discharge the amount of river water. However, when the sluices are in the activity of *kieren* only the sluices and openings adjacent to the abutments are used, following the preference of the fish.

As last remark on the water system of the Haringvliet it can be stated that during all activities, such as discharging river water and *kieren* of sea water, the average water depth withing the Haringvliet is kept at NAP + 0.50 m. This water level is dependent on the river discharge entering at Lobith and the movement of the tide at the North Sea.

4.2 Flood protection system

The Haringvliet dam connects the dike trajectory 25-1 and 25-2 in the South (Goeree-Overflakee) with the dike trajectories 20-1 and 20-4 in the North (Voorne Putten). The dike trajectory of the Haringvliet dam according to the Water Act[3] is section 211. A large part of this trajectory is then formed by the Haringvliet sluices. An overview of the dike trajectories of the Netherlands can be found in Appendix C, including their safety requirements. The goal of the Haringvliet dam is to reduce the hydraulic loads on dike trajectories in the hinterland. The legal required failure probability (lower limit) is 1:1,000 per year and the signal value is 1:3,000 per year. The characteristics of trajectory 211 according to the Water Act are summarized in Table 6.

Table 6 Characteristics of trajectory 211, the Haringvliet dam, according to the Water Act

Characteristics	Dike trajectory 211
Signal value	1:3,000 per year
Lower limit	1:1,000 per year
Length section	3.5 km
X_{begin} [RD-coordinates] *	64432
Y_{begin} [RD-coordinates] *	429234
X_{end} [RD-coordinates] *	61801
Y_{end} [RD-coordinates] *	426806

** The Dutch abbreviation 'RD-coordinates' stands for the 'Rijksdriehoekscoördinaten', which are the coordinates in the geodetic coordinate system that is used at national level for geographical indications.*

[3] The Water Act (the Dutch water law) mainly regulates the management of water systems, including flood defences, surface water and groundwater bodies.

4.3 Components of the Haringvliet sluices

This subchapter aims to briefly describe certain characteristics of components of the Haringvliet sluices. The components addressed are the navigation lock, the dike body of the Haringvliet dam and lastly, the discharge sluices. These and other components can be seen in Figure 10.

Figure 10 Overview of the components of the Haringvliet sluices. Photo edited from (Land+Water, 2020)

4.3.1 Navigation lock

To be able to pass the Haringvliet sluices, vessels have to use the Goeree navigation lock. Logically, it is built at the same time as the Haringvliet sluices. The schematization of the layout of the navigation lock can be seen in Figure 11 . The lock has a single locking chamber, providing passage in both directions, with a width of 16 meters and a length of 144 meter.

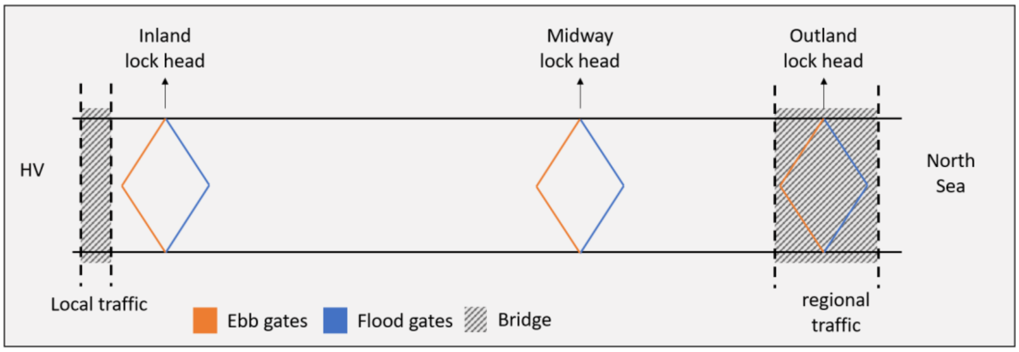

Figure 11 Schematized gate layout of the Goeree navigation lock, indicating the position of the two crossing roads.

When the main bridge over the navigation lock is closed there is a draft limit of NAP + 6.1 m (indicated in Figure 11 with 'regional traffic' bridge). This makes the available draft dependent on the water level out- or inside the lock. When a vessel approaches the navigation lock exceeding the maximal draft, the bridge deck is lifted and thereby opened. The traffic over the Haringvliet dam can temporarily not pass the bridge anymore. The sill of the navigation lock is located at NAP – 5 m, creating another boundary condition for passing vessels. The navigation lock consists out of six sets of mitre gates, which comes to a total of 12 gates, as shown in Figure 11. The retaining height of the gates differs per lock head. The retaining height of the outland lock head and the midway lock head are NAP + 6.5 m. This holds for both the flood and ebb gates. The inland lock head has a retaining height of 4 m.

As can be seen from Figure 11, there are two bridges crossing the navigation lock. The bridge limiting the draft of vessels to a height of NAP + 6.1 m, described earlier, is the bridge for the regional traffic.

The regional traffic is assumed to be a constant flow of vehicles, whereas the bridge for local traffic is used infrequent. For this research, only the regional traffic bridge is taken into account. In intermezzo 4, more detailed information is given on the use of the navigation lock and the bridges. This intermezzo also aims to substantiate the decision to not take into account the local traffic bridge.

Intermezzo 4: More information of the use of the Goeree navigation lock

From personal communication with Rijkswaterstaat, general statistics of the lock system were retrieved to give insights in the usage of the lock, bridges and the ports.

On average a total of 8000 ships per year pass the navigation lock, 85% of which are recreational vessels. The lock is at its busiest during the summer season, caused by the increase of recreational vessels in higher temperatures. The other main users of the navigation lock are fishing boats (Dutch: *kotters*). These fishing boats mostly dock at the outer port, where the fisheries are located. The inner port mostly accommodates shipyards and other fish related businesses.

When the closing water level of the Haringvliet sluices is reached and the discharge sluices are closed, it is possible for the ships to still use the lock. However, a wind limitation of winds up to force 6 prevents the regional traffic bridge from being opened, which leads to a draft limitation for ships.

As can be seen from Figure 11, there are two bridges crossing the navigation lock. Only the regional traffic bridge will be taken into account in the analysis of the case study. In Table 7 the characteristics of the bridges are summarized.

Table 7 Overview of the two crossings over the Goeree navigation lock.

Type	Users	Use intensity	Consideration
Regional traffic	Regional traffic: car and truck traffic with a regional destination	Continual and regular	Taken into account when considering external impacts
Local traffic	Local traffic: cars, public transport, bicycles and pedestrians with a local destination	Incidental and regular	Impact considered not governing for this research

An explanation why the local traffic bridge will not be further considered is the following: The draft of this bridge will be lower than the earlier stated NAP + 6.1 m, which means that this bridge will form a strict threshold on the locking operations. Since this bridge is only used by local destination-oriented vehicles and local bicycles and pedestrian traffic, it is assumed that the negative effect of opening the bridge more often is assumed to be negligible in terms of the negative effect of opening the regional traffic bridge. Taking into account the draft limit of the lower bridge would form unnecessary strict demands.

Lastly it can be said that there is no alignment between being allowed to use the navigation lock, thereby opening the bridge, and traffic rush hour.

4.3.2 The dam

The dam bodies connecting the Haringvliet sluices to the land at either side have roughly a length of 2 km. For the purpose of this research, it is assumed sufficient to only elaborate the longest dike section in more detail. This is the dike section on the North side of the Haringvliet sluices. During the construction of the Haringvliet sluices the gap between the sluices and the land was initially closed by stacking concrete cubes of a single cubic meter using a cable cart system. This concrete block dam has a height of NAP + 3 m and a slope of 1:1. Its profile is still recognizable in the final cross section (see Figure 12 righthand side).

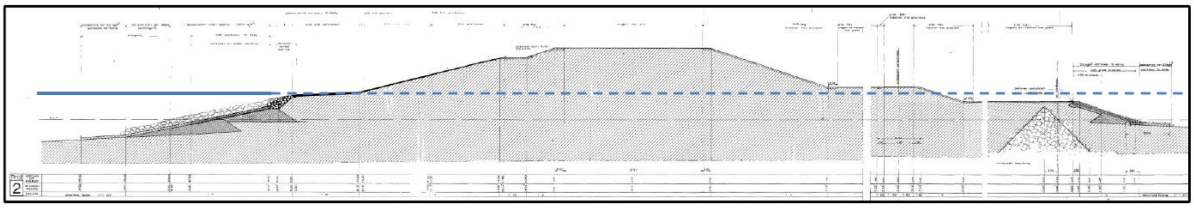

Figure 12 cross section of dam body North of the Haringvliet sluices. Primary concrete block dam still recognizable at the right-hand side (line in blue is the water level at the norm requirements).

The height of the dam body varies over its length with a height of NAP +18 m at the connection with the Haringvliet sluices to NAP +7 at its lowest point land inwards. According to the preliminary verdict on the safety of this dike trajectory (internal RWS document), all the dike bodies have been found to be able to comply to the required signal value. All dike sections are also described as very robust in their cross section and revetment quality.

4.3.3 The sluices

The Haringvliet sluices have a total of 17 openings. At the openings, the sluices consist out of steel gates, making a total of 34 gates with a width of 56.5 m. The set of gates consists of sea-side gates with the top located at NAP + 3 m when closed and river-side gates with the top located at NAP + 5 m when closed. The gates can be opened or closed (also partially), depending on the operational demand. The total length of the structure is 1050 m, excluding the length of the dike bodies. The maximum discharge capacity of the sluices is 25.000 m^3/s.

Since the sluices will be the main objective for the functional analysis and the technical decomposition of Chapter 5, this shorter description will suffice for the case study introduction. The functions which the sluices have to fulfil can be found in section 5.1, and the more detailed technical components of the sluices can be found in section 5.2.1.

5. Functional and structural analysis of the Haringvliet sluices

This chapter describes the functional analysis as well as the technical decomposition performed on the Haringvliet sluices, this in line with step 2 of the framework of Vader et al. (2023) (section 3.3). The goal of the functional analysis is to define requirements for each of the functions of the case study. This can be used in the next steps of the analysis of the estimation of the remaining functional life of the Haringvliet sluices. In turn, the goal of the structural decomposition is to identify the most important deterioration mechanisms of the structural elements, which in turn are important in estimating the remaining technical life.

In section 5.1, the functions of the Haringvliet sluices are defined, including its corresponding requirements, either quantitatively or qualitatively. In section 5.2, the structural elements of the Haringvliet sluices are decomposed and the most important deterioration mechanisms are identified. Chapter 5 concludes with section 5.3 in which the findings of both the functional and structural analysis are summarized.

5.1 Functional analysis

Large hydraulic structures, like the Haringvliet sluices, do not just fulfil a single function. It is a multi-functional object which fulfils different requirements, needs or wishes. The functions of the Haringvliet sluices can be categorised based on their importance level or overarching functional categories. In this thesis it is chosen to categorise the functions into primary, secondary and additional functions to indicate their level of importance. The importance level of each function is based on the original intentions of building the hydraulic structure. It has to be noted that the functions themselves or their importance could change or already have changed over time. For each function a short explanation is given as well as a definition of the proposed performance requirements. These requirements are either formal or estimated requirements and can be used in the estimation of the remaining life time of the Haringvliet sluices in later stages of this thesis. An overview of the functions can be found in Table 8.

Table 8 Functions of the Haringvliet sluices

Function category	Function	Importance category
Flood protection	(a) Prevent extreme water levels in the hinterland	Primary
Navigation	(b) Provide a passage for navigation	Secondary
Water management	(c) Water level management	Primary
	(d) Water quality management	Primary
Ecology	(e) Allow for fish migration	Secondary
	(f) Allow for an ecological beneficial environment	Secondary
Traffic	(g) Provide a road connection	Secondary
Monument	(h) Maintaining National Monument status	Additional

(a) Prevent extreme water levels in the hinterland

One of the primary reasons for building the Haringvliet sluices, is to protect low lying parts of the country against high water levels from the North Sea. The closing of the former estuary with the Haringvliet dam meant that a much shorter structure could prevent flooding along all of the circumference of the estuary. The dikes along the estuary were primary defences before the build of the Haringvliet sluices, which makes them quite high and strong in comparison to other inland dikes. The gates of the Haringvliet sluices can withstand water levels up to NAP + 5 m. Waves or higher water levels then this threshold level will cause overtopping or in extreme cases even overflow. The Haringvliet sluices are a double gate system in which the first and lower gate acts a wave breaker, removing energy and height from incoming waves. Some degree of overflow or overtopping is allowed in the system, since the Haringvliet acts as water storage buffer, assuming that the overtopping and overflow does not lead to structural failure. Prior to an expected storm, the sluice operator can choose to pre-discharge water from the Haringvliet to temporarily lower the water level to accommodate for potential overflow and overtopping water. The average water level in the Haringvliet is around NAP + 0.50 m. Pre-discharging the water from the Haringvliet is not only done to accommodate for overflow or overtopping water, it can also be done to act as a buffer for incoming river water which can temporarily not be discharged during predicted closed conditions.

The Haringvliet sluices perform a storm closure when a threshold water level of NAP +2.2 m is expected at Hoek of Holland. For comparison, the Maeslant barrier, which is active in the same water system as the Haringvliet sluices, has a closing threshold of NAP +3.0 m (expected at Rotterdam). Together they aim to protect the hinterland against flooding, but they can also influence each other's effectiveness in case one of them fails to close. Function (a) only focusses on preventing extreme water levels caused by high sea water levels at the North Sea, but as explained in section 4.1, the threat of high waters in this case study is double sided. High waters caused by extreme river discharges is treated in function (c).

According to the Water Act, the lower limit of the failure probability of the Haringvliet sluices is a failure probability of 1:1,000 per year. As there are 17 openings, each sluice gate can fail individually. The failure of a single opening, one of the 17 pairs of gates, can be assumed to not have a significant effect on the total performance of the barrier. A study by HKV was performed to show the influence on the water retaining function in the case of different numbers of gates not closing in comparison to the correct functioning of all the gates (Kuijper et al., 2022).

The functional performance of the function to prevent extreme water levels caused by the North Sea can be defined by the following statements.

(a.1) The failure probability of the Haringvliet sluices must be less than 1:1,000 per year.

(a.2) The overflow and overtopping volumes should not increase the water level in the Haringvliet to such extent that the inland dikes are not sufficient anymore.

(a.3) The overflow and overtopping volumes should not significantly increase water levels in more upstream critical locations.

Since there is no criteria set for the allowed overtopping or overflow volumes, the function criteria can be related to the allowed consequence. In this case the consequence is elevated water levels in the Haringvliet and at critical more upstream locations.

(b) Provide passage for navigation

Every time a vessel needs to pass the barrier, they have to use the navigation lock, independent of the state of the sluices (opened or closed). Users of the lock are mostly recreational vessels, but fishing boats also use the lock frequently. The use of the lock increases in summer, mostly due to the increase in recreational vessels. An average yearly trend can be seen in Figure 13. The Goeree navigation lock is not part of any major shipping route for inland or seawards transport. A requirement for the navigation lock is to be able to accommodate its users in the future.

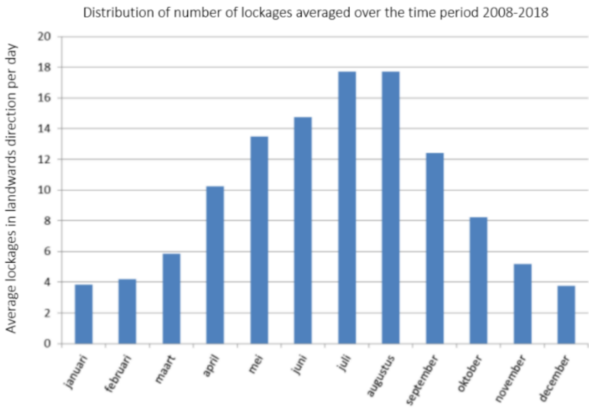

Figure 13 Trend of distribution of number of lockages in landwards direction using the Goeree navigation lock (adapted from (Krielen, 2019))

The sill of the navigation lock is located at NAP – 5m and the average water level at the Haringvliet is NAP + 0.5 m. When this is combined with an average low tide water level at sea of NAP -1 m, the average maximal vessel draft that the lock can accommodate ranges from 4 to 5.5 m. Another limiting factor, besides the maximal depth, is the maximal available height. The regional traffic bridge poses a height limiting factor when passing the navigation lock. This bridge is able to open if this limited height of NAP + 6.1 m is exceeded by incoming vessels.

The functional performance of the function to provide a passage for navigation can be defined with the following statements.

(b.1) The navigation lock has to accommodate its users in the future regarding its size.

(b.2) In a period of drought, the water level in the Haringvliet should be sufficient enough for ships to enter and exit the lock.

(b.3) The navigation lock has to comply to an availability requirement.

The availability threshold is set to 98% according to agreement between Rijkswaterstaat and the maintenance company. This availability threshold is not a strict requirement, but more of less a goal. Furthermore, because the navigation lock is not part of a busy shipping route, the topic of waiting times is neglected in the functionality requirements.

(c) Water level management

Not only do the Haringvliet sluices have to protect from water levels at the North Sea, they also have to manage the water level inside the Haringvliet influenced by the incoming river discharge of the rivers the Meuse and the Rhine. The average target water level in the Haringvliet is set at NAP + 0.50 m. The sluices have to discharge the water of the rivers to maintain the target water level. The size of the opening of the sluices is dependent on the discharge measured at Lobith. The water measured at Lobith takes an average of 30 hours to reach the Haringvliet sluices. The sluices are opened when the outside and inside water levels are the same.

Threshold values in the Haringvliet consist of a maximum water level at Hellevoetsluis of NAP + 2.60 m, at Dordrecht of NAP + 3.00 m and at Moerdijk of NAP +2,70 m according to the Water Act. There are also minimum water levels at the location Moerdijk to ensure navigation and to benefit the ecological system. The minimal water level for navigable depth at Moerdijk is NAP + 0 m and the threshold for the breeding season (15th of March – 15th of July) is a minimal water level at NAP + 0,80 (Rijkswaterstaat, 2020b).

To show how the water level fluctuates in the Haringvliet influenced by the river discharge entering the Netherlands at Lobith, a plot of these parameters over a period of 28 days is shown in Figure 14. The water level at Hellevoetsluis is also influenced by the tidal window in which it is possible for the sluices to discharge the water.

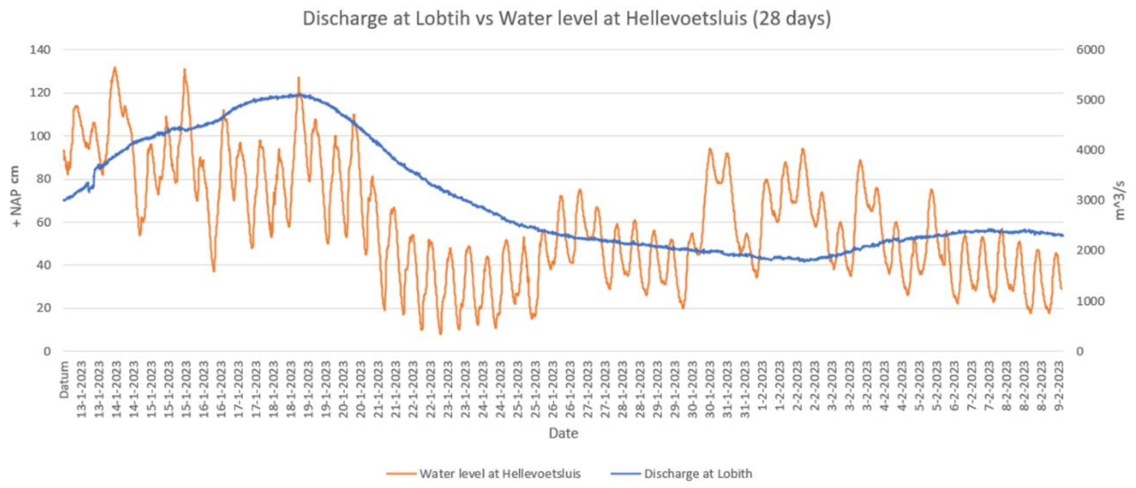

Figure 14 Plot of discharge measured at Lobith versus the water level measured at Hellevoetsluis over a period of 28 days (Rijkswaterstaat, n.d.-c)

At extreme discharges the Haringvliet sluices must have enough discharge capacity to maintain an acceptable water level in the Haringvliet. The functional performance of the function to manage water levels in the Haringvliet can be defined with the following statements.

(c.1) The maximum water level at Hellevoetsluis may not exceed NAP + 2.60 m.

(c.2) The maximum water level at Dordrecht may not exceed NAP + 3.00 m.

(c.3) The maximum water level at Moerdijk may not exceed NAP + 2.70 m.

(c.4) The minimum water level at Moerdijk may not fall below NAP + 0 m to ensure navigability.

(c.5) The minimum water level at Moerdijk may not fall below NAP + 0.80 m during breeding season.

From these functional performance statements, it can be concluded that the discharge capacity of the sluices, combined with the storage capacity of the Haringvliet should be sufficient to guarantee the threshold values.

(d) Water quality management

When considering the water quality, the most governing function is to maintain fresh water thresholds at certain locations. This function can be quantified in two ways. Firstly, using the location of the fresh water intake point used by water company Evides or secondly, using the fresh water thresholds line defined by the Kier Policy.

In the Netherlands there are eight important fresh water intake points at national waterways. One of those intake points is located in the Haringvliet. Before the Kier Policy (chapter 4.1), the intake point was located at only 3 km upstream of the Haringvliet sluices, as no salt water was allowed in the Haringvliet. To realise the Kier Policy the water intake point was relocated to about 16 km upstream of the Haringvliet. The old and new locations can be seen in Figure 15 (Rijkswaterstaat, 2006) .

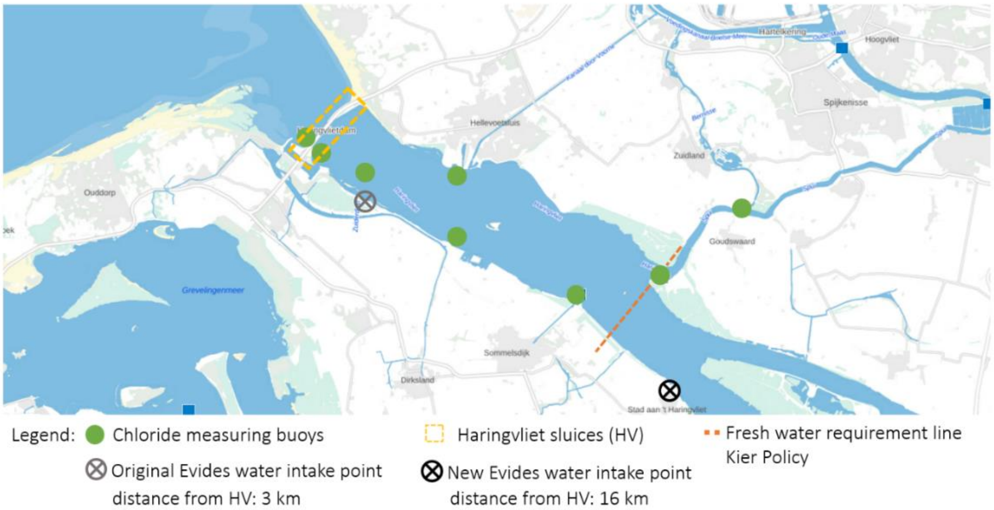

Figure 15 Old and new location of the Evides water intake point in the Haringvliet area and fresh water line of the Kier Policy.

The owner and stakeholder of this water intake point is Evides. Evides is a water utility company ensuring drinking water for the population and the industry. Evides requires fresh water with a maximum chloride content of 150 mg/l at this intake point. It can be concluded that the requirement following from this can be defined as follows:

(d.1) 16 km upstream of the Haringvliet sluices, at the fresh water intake point of Evides, the maximum acceptable chloride content of the water is 150 mg/l.

After the Kier Policy the Haringvliet is introduced again to salt water intrusion. From the Kier Policy it follows that the guarantied fresh water line is located at the location Spui – Middelharnis (this is indicated as the orange line in Figure 15) (Rijkswaterstaat, 2020b). The thresholds for which chloride content the water is considered fresh or salt can be seen in Table 9.

Table 9 Water categorization regarding chloride content (Rijkswaterstaat, 2020b)

Water categorization	Chloride content [mg/l]
Fresh water	< 150
Brackish water	150 – 1,000
Strongly brackish to salt water	> 1,000

To ensure the threshold value for fresh water (< 150 mg/l) is not exceeded, multiple chloride measuring buoys are located in the Haringvliet. The location of these buoys can be seen in Figure 15. The chloride content is being measured every 10 minutes at all 8 measuring buoys and at each buoy three different depths are considered (Rijkswaterstaat, 2020a). From Figure 15 it can be concluded that the current water intake point of Evides, is located upstream of the fresh water line from the Kier Policy. The requirement to control salt intrusion according to the Kier Policy can be formulated as follows:

(d.2) At the location of Spui – Middenharnis the chloride content of the water has to be smaller than 150 mg/l during reverse discharging or other salt intruding events.

Since requirement (d.2) poses quite a strict threshold on the chloride content of the water, the notion can be made that when the water is used for agriculture, a higher chloride content is acceptable and usable (Deltares, n.d.). Therefor a new water category, called 'agricultural fresh water', is introduced in Table 10.

Table 10 Water category for agriculture purposes (Deltares, n.d.)

Water categorization	Chloride content [mg/l]
Agricultural fresh water	< 1000

(e) Allow for fish passage

In the design of the Haringvliet sluices fish channels were included to make passing the barrier possible for all types of fish. In total, six fish channels are located in six of the concrete piers. Since the Kier Policy, fish can also pass the barrier through the gates. It is also looked into the possibilities of using the Goeree navigation lock as a fish migration route in the study of Krielen (2019) at the request of Rijkswaterstaat.

Since the Kier Policy works with the concept of 'Implement while learning', there are no specific functional requirements and therefor the requirement is simplified to the statement below.

(e.1) Fish passage should be possible for the desired species and the required frequency.

(f) Allow for an ecological beneficial environment

The Haringvliet provides another ecological function beside allowing for fish migration. After all, ecology is more than just fish. Different water parameters like temperature, concentration of chloride or chemicals and tidal range are important factors in defining an ecological environment. Also, morphology changes could alter the ecological environment. This research will not further define a requirement for this function, as it is dependent on a lot of different variable factors and sensitive to decision making, which is outside the scope of this research.

(g) Provide a road connection

On top of the Haringvliet dam there is a regional road as well as a local one. The usage of these different roads was defined in Table 7. These roads provide a connection between Voorne-Putten and Goeree-Overflakee. This can be generalised by saying that it provides a connection between the cities South of Rotterdam with the peninsula Goeree-Overflakkee and the other peninsulas of the province of Zeeland. There is another parallel optional route using the Haringvliet Bridge. For the difference between the bridge over the Haringvliet sluices and the Haringvliet bridge the reader is referred to Table 5 and Figure 7.

The functional performance of the function to provide a road connection can be defined with the following statement.

(g.1) The Haringvliet dam should provide a road connection between the North and South end of the dam.

It is chosen to not set a requirement for the number of times a day it is allowed to open the bridge over the navigation lock, which means that the bridge over the navigation lock temporarily halting the traffic flow. There is no strict law or set guideline for this disturbance to the traffic flow. When in further analyses this function seems critical, it can be further looked into defining an acceptable delay allowed on this traffic section.

(h) Maintaining National Monument status

In 2016 the Haringvliet sluices became the first structure of the Delta works to receive the status of being valued as a national monument. There are several reasons why the Haringvliet sluices have become a national monument, based on their remembrance value, engineering excellence and architectural value. In intermezzo 5, these reasons are elaborated further.

Intermezzo 5: Four reasons the Haringvliet sluices gained monumental status.

This intermezzo lists and explains the reasons the Haringvliet sluices have gained monumental status since the year 2016.

Remembrance value	The Haringvliet sluices act as a token for remembering the devastating flood of 1953. The fact that the Delta Works were rushed after this catastrophic flood and to this day help in the fight against high waters in the Netherlands, make the Haringvliet sluices an icon in keeping intact the historic importance of the 1953 flood.
Engineering excellence (building)	While in current day the Haringvliet sluices are not the only structure of this size and greatness that is being build, at the time of construction this was an extraordinary engineering challenge. The building methods ranging from combining prefab and in-situ elements to the needed equipment to build this large structure, makes the Haringvliet special in its engineering excellence.
Engineering excellence (components/ elements)	Not only the engineering excellence in the construction is worth mentioning, but also the technical highlights of the components themselves. This refers to structural elements like the concrete NABLA-beams connecting the piers and which hold the load of the steel gates, but also the gates themselves with special welding techniques and rivet works.
Architectural value	As far as architectural value goes, one does not have to be an engineer to appreciate this large structure. Its robust exterior provides that visual safety that compliments its primary functions. Furthermore, its scale of magnitude gives it a unique character. Contributing to the architectural value are the shape of the concrete piers in combination with the NABLA beam and the bridge deck. The piers, entirely made of reinforced concrete, are designed as ships. In combination with the bridge deck, the structure mainly refers in top view to the old ship bridge pattern, consisting of a bridge deck on boats which was used in bridge building before the 19th century.

Being designated as a national monument means that adjustments require permission, which could complicate future changes needed to maintain the functions of the system. How this exactly influences the decision regarding replacement of elements is assumed to be non-governing for this research. What can be stated is that the Haringvliet sluices have to comply to both safety laws and monumental laws (‘Wet op waterkeringen 1996’ and ‘Monumentenwet 1996’). Conflicting requirements could arise from this and can be resolved by taking all the concerns into account and come to the best solution. When drastic changes are necessary, all different requirements have to be taken into account. One of these requirements will be maintaining cultural historic value.

The functional performance of the function to maintain monumental status can be formulated in the following statement.

(h.1) Monumental status has to be included in considerations regarding renovation or replacement plans. This refers to the specific elements on which the monumental status is based on as well as thematic or architectural value of the Haringvliet sluices as whole.

Summary of functions of the Haringvliet sluices

In section (a) to (h), the functions of the Haringvliet sluices were described and requirements were stated. The functions and requirements are summarized in Table 11.

Table 11 Functions and requirements of the Haringvliet sluices

Function category	Function	Requirements
Flood protection	(a) Prevent extreme water levels in the hinterland	(a.1) The failure probability of the Haringvliet sluices must be less than 1:1,000 per year.
		(a.2) The overflow and overtopping volumes should not increase the water level in the Haringvliet to such extend that the inland dikes are not sufficient anymore.
		(a.3) The overflow and overtopping volumes should not significantly increase water levels in the more upstream critical locations.
Navigation	(b) Provide a passage for navigation	(b.1) The navigation lock has to accommodate its users in the future regarding its size.
		(b.2) In a period of drought the water level in the Haringvliet should be sufficient enough for ships to enter and exit the lock.
		(b.3) The navigation lock has to comply to an availability requirement.
Water management	(c) Water level management	(c.1) The maximum water level at Hellevoetsluis may not exceed NAP + 2.60 m.
		(c.2) The maximum water level at Dordrecht may not exceed NAP + 3.00 m.
		(c.3) The maximum water level at Moerdijk may not exceed NAP + 2.70 m.
		(c.4) The minimum water level at Moerdijk may not fall below NAP + 0 m to ensure navigability.
		(c.5) The minimum water level at Moerdijk may not fall below NAP + 0.80 m during breeding season.
	(d) Water quality management	(d.1) 16 km upstream of the Haringvliet sluices, at the fresh water intake point of Evides, the maximum acceptable chloride content of the water is 150 mg/l.
		(d.2) At the location of Spui – Middenharnis the chloride content of the water has to be smaller than 150 mg/l during reverse discharging or other salt intruding events.
Ecology	(e) Allow for fish migration	(e.1) Fish passage should be possible for the desired species and the required frequency
	(f) Allow for an ecological beneficial environment	Non defined
Traffic	(g) Provide a road connection	(g.1) The Haringvliet dam should provide a road connection between the North and South end of the dam.
Monument	(h) Maintaining National Monument status	(h.1) Monumental status has to be included in considerations regarding renovation or replacement plans. This refers to the specific elements on which the monumental status is based on as well as thematic or architectural value of the Haringvliet sluices as whole.

5.2 Structural analysis

By decomposing the Haringvliet sluices, its current technical state and its potential vulnerable points can be evaluated. Each structural component can have its own critical deterioration mechanism, therefore, a physical decomposition of the Haringvliet sluices is done to identify and categorize individual elements. Once the physical decomposition is made, the main deterioration mechanism per element can be investigated and quantified if possible. In chapter 6, the main external drivers influencing the life time of the Haringvliet sluices can be linked to this structural analysis.

5.2.1 Structural decomposition

For the structural decomposition, only the Haringvliet sluices themselves are taken into account, as it is assumed that for other elements of the system, like the navigation lock, their functional requirements are most critical. This assumption can be substantiated with the fact that the scale and costs of replacement or increased maintenance of the Haringvliet sluices is an order of magnitude larger than that of the other components (i.e. Goeree navigation lock, Haringvliet bridge and the dike body of the Haringvliet dam). The goal of the structural decomposition of the structure is to identify important components of the Haringvliet sluices. Different components can have different mechanisms influencing their life time and thus will have different vulnerabilities to different external factors. This leads to varying maintenance or replacement strategies per structural element. It is chosen to divide the different elements of the Haringvliet sluices into three categories: Fixed structures, movable parts and electronic components. This subdivision is chosen as it is assumed that these categories will have similar life spans or similar maintenance intervals and can therefore be grouped together when discussing impacts or mitigation measures in further sections of this thesis. Figure 16 shows the main structural elements of the Haringvliet sluices in an aerial picture as well as a cross-section originating from the technical drawings.

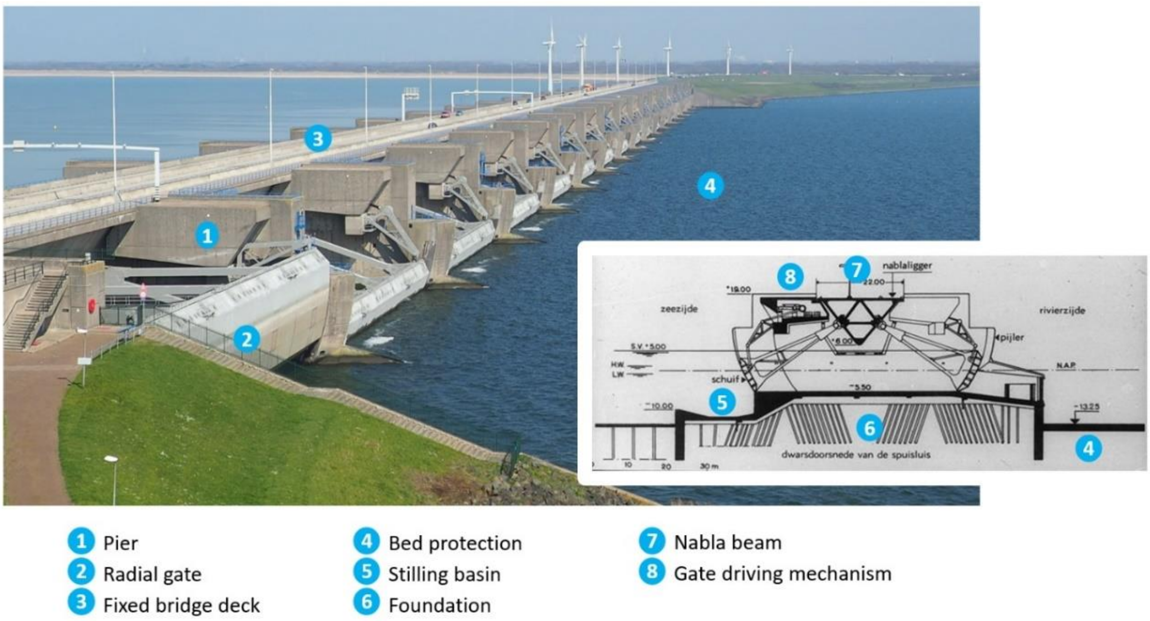

Figure 16 Overview of the main elements of the Haringvliet sluices (Riverside right, Sea side left).

In Figure 17 a breakdown of the elements of the Haringvliet sluices is shown, divided in the three categories as mentioned before. The breakdown also indicates structures which are part of the Haringvliet sluices system, but are assumed out of scope for the technical decomposition. A more detailed description of each of the components of the Haringvliet sluices and the bridge on top can be found in Appendix D.

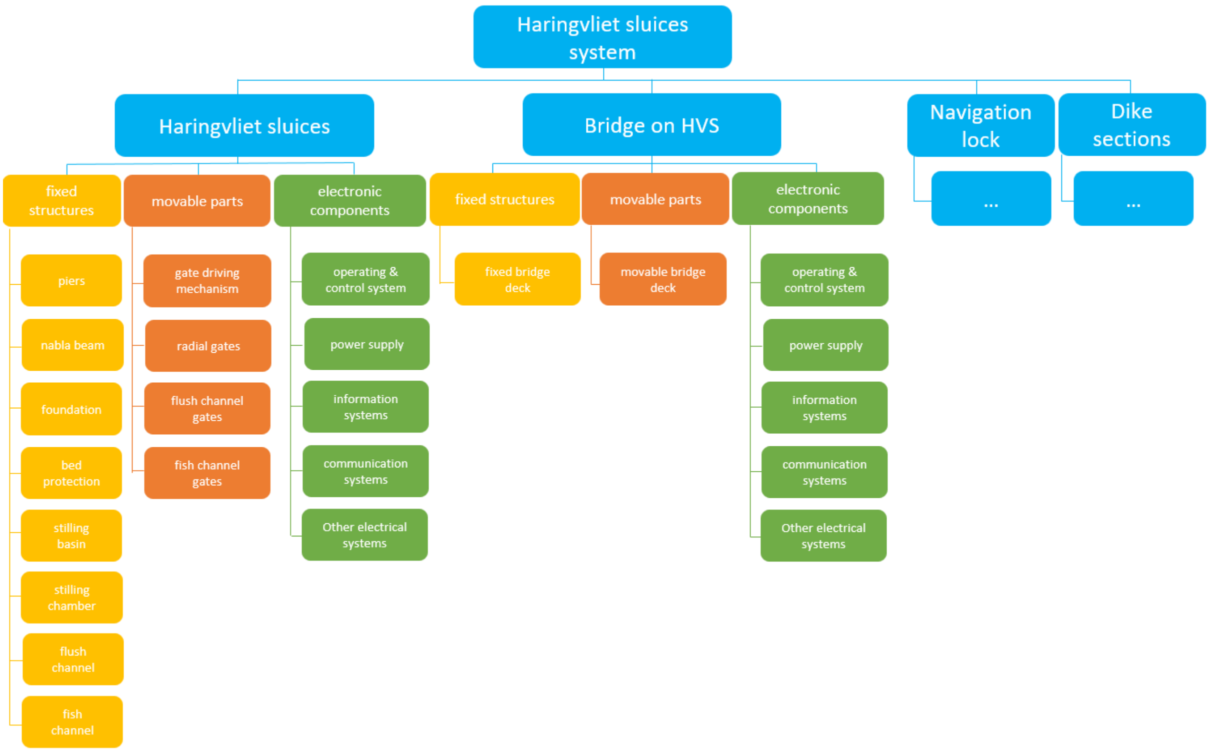

Figure 17 Breakdown of the structural elements of the Haringvliet sluices complex

5.2.2 Identifying dominant deterioration mechanisms and potential consequences

The different elements following from the technical decomposition of the Haringvliet sluices are affected by various material aging as well as element specific deterioration processes. Not only do the elements have different external effects influencing them, but also the severity of the consequence of ageing can be different. This subchapter aims to describe the main deterioration process per element and the extent of the consequences. The same categorization is applied (fixed, moveable, electronic).

In Table 12, the fixed elements of the Haringvliet sluices are shown, including their main deterioration mechanisms and the corresponding consequence. A more detailed explanation of the results from Table 12, can be found in Appendix E. From Table 12 it can be concluded that the majority of the fixed structures are made out of reinforced concrete. Therefore, one of the main deterioration mechanisms for the fixed elements of the Haringvliet sluices is concrete deterioration. The concrete elements are situated above water as well as below water. Salt water conditions are applicable here. An increase in the drivers which lead to concrete deterioration, has consequences on the technical life time of these elements. Another one of the common deterioration mechanisms is erosion, which are mainly related to the flow of water for this case study. Erosion in this context means the damage of concrete elements, like a stilling basin, by wear of that concrete element or the loss of stone material in the bed protection. All the flow related wear of the material or damage is categorized as erosion.

Table 12 Main deterioration mechanisms and their consequence for the fixed structures category

Element	Deterioration mechanism	Consequence
Piers	Concrete deterioration	Repairing of deteriorated concrete
NABLA beam	Concrete deterioration	Repairing of deteriorated concrete
Bed protection	Erosion	Repair by placing new or additional bed protection (stones or concrete slab)
Foundation	Settlements	If pile foundation fails, implies technical end of life

Stilling basin	Erosion	Repairing of concrete under water slab
Stilling chamber	Concrete deterioration	Repairing of concrete under water and above water
Flushing channel	Concrete deterioration, erosion	Repairing of deteriorated and eroded concrete
Fish channel	Concrete deterioration, erosion	Repairing of deteriorated and eroded concrete
Fixed bridge deck	Road surface deterioration	Repairing or replacing road surface

As can be seen from Table 12, the technical life time of the fixed elements is mostly dependent on repairs. Only a damaged foundation would lead to full replacement and therefore immediately lead to technical end of life. Regular inspection on repairable visible elements could prevent end of life based on technical grounds. Current maintenance intervals might have to be reconsidered in the future.

The overlapping deterioration mechanism for the movable parts are mechanisms related to steel deterioration and are related to wear in the moving or driving mechanisms, as can be seen from Table 13. Only full replacement of all radial sluice gates would lead to technical end of life based on economic grounds. Replacement of a single radial gate could still be an option if it would impact the remaining end of life enough. The other elements in Table 13 can either be repaired or replaced dependent on the severity of the deterioration.

Table 13 Main deterioration mechanisms and their consequence for the movable parts category

Element	Deterioration mechanism	Consequence
Gate driving mechanism	Mechanical wear	Repairs or replacement of parts
Radial Sluice gates	Corrosion Debris damage	Repairs of coating Local repair of damage
Flushing channel gates	Corrosion	Repair of coating (locally or fully) or full gate replacement
Fish channel gates	Corrosion	Repair of coating (locally or fully) or full gate replacement
Movable bridge deck	Corrosion Mechanical wear	Repair of coating (locally or fully) or full bridge replacement Repairs or replacement of parts

It can be stated that for the movable parts also regular inspection on repairable visible elements could prevent end of life based on technical ground. Current maintenance intervals might have to be reconsidered in the future.

From Figure 17, it can be seen that there are multiple electronic components to consider, however their deterioration mechanisms can be considered the same, which is shown in Table 14. The general life time of electronic components can be short due to developments in the technological industry, i.e. components can become outdated and need to be replaced.

Table 14 Main deterioration mechanisms and their consequence for the electronic components category

Element	Deterioration mechanism	Consequence
Electronic components	General ageing	Repairs are replacement of electronic components, hardware and software

From Table 12 to Table 14, it can be concluded that the most frequent deterioration mechanisms to be considered are the ones related to steel and reinforced concrete. Additionally, erosion due to flow velocity and turbulence is the cause for multiple elements to deteriorate.

5.2.3 Summary of the technical decomposition of the Haringvliet sluices

As presented in section 5.2.2, the most important deterioration mechanisms of the elements of the Haringvliet sluices are the ones related to steel deterioration, reinforced concrete deterioration and erosion. The influences of external drivers on these deterioration mechanisms have to be taken into account when exploring the different external drivers in chapter 6 in line with steps 3 and 4 of the framework of Vader et al., (2023). Table 15 shows the contributing drivers for each of the main deterioration mechanisms.

Table 15 Deterioration mechanisms and their contributing drivers

Deterioration mechanism	phenomena	Contributing drivers
Steel deterioration	Corrosion	O_2 and (sea) water exposure
Concrete deterioration	Carbonation Chloride ingression	CO_2 Sea water exposure
Erosion	Material wear	Flow velocity and turbulence of water

The deterioration mechanisms will mainly lead to an increase in maintenance. In further steps of the analysis, it has to be considered if the increase in maintenance could be problematic. A potential problem could be that the maintenance window, due to safety conditions, could become too small to be able to accommodate for all the required maintenance. Another problem that could arise is that due to the maintenance, and their impact on the operational hours, could lead to incompliance of functional requirements.

5.3 Conclusions of the functional and structural analysis

This chapter has defined all the functions of the Haringvliet sluices and has decomposed the structure in all its elements. A functional analysis was performed on the case study to define all the functions and their requirements. This resulted in eight different functions, which were categorized in six different function groups. The main functions are: (a) prevent extreme water levels in the hinterland, (b) provide a passage for navigation, (c) water level management, (d) water quality management, (e) allow for fish migration, (f) allow for ecological beneficial environment, (g) provide a road connection, (h) maintaining National Monument status. For each of the functions, requirements were formulated, either qualitatively or quantitatively. Some requirements follow from formal regulations, others are based on allowed consequences. A structural decomposition was performed to identify the main structural components of the Haringvliet sluices and their corresponding main deterioration mechanism. The components were categorized into three groups: fixed, movable and electronic components. The main deterioration mechanisms are steel deterioration, concrete deterioration and erosion of different elements.

The functions, together with their stated performance requirements, and the main deterioration mechanism will be the main focus for the next step of the analyses where impact of external drivers on the Haringvliet sluices are investigated.

6. External drivers which influence the remaining life of the Haringvliet sluices

In chapter 5, the functions and the technical components of the Haringvliet sluices are discussed and the most important characteristics of the system are summarized. This next chapter aims to either qualitatively or quantitatively describe the external drives which influence the functional performance and technical state of the Haringvliet sluices. This chapter is in line with step 3 and step 4 of the framework of Vader et al. (2023) (section 3.3). The relevant external drivers and their impact are considered (step 3) and the most important drivers are stated (step 4).

In section 6.1, an overview on which drivers to consider for hydraulic structures are given. This overview is focussed on storm surge barriers. Local conditions of the case study will show which external driver to further analyse and which can be assumed negligible in their effect. An introduction to climate change scenarios is given in section 6.2. Many of the external physical drivers are influenced by climate change, making their impact dependent on current climate change projections. In section 6.3, the potential impact of physical drivers on the Haringvliet sluices is elaborated. In section 6.4, the potential impact of socio-economic drivers is investigated. In section 6.5, the chapter concludes on which drivers to consider in further steps of analysis on the Haringvliet sluices.

6.1 External drivers to consider for hydraulic structures

A list of external drivers to consider for hydraulic structures can be found in Figure 18. This list is focussed on the Netherlands and does not include drivers like severe earthquakes and ice loads. The drivers are categorized in physical drivers or non-physical drivers like economic, political and societal related drivers.

Form local conditions of case study location follows which drivers could have a significant effect and needs to be investigated further, and which drivers are negligible in their impact. The drivers which need to be analysed further can be described either qualitatively or quantitively. This depends on the available information, the amount of impact or the severity of the consequence. The effect of each driver will be linked to a function or a technical component described by chapter 5.

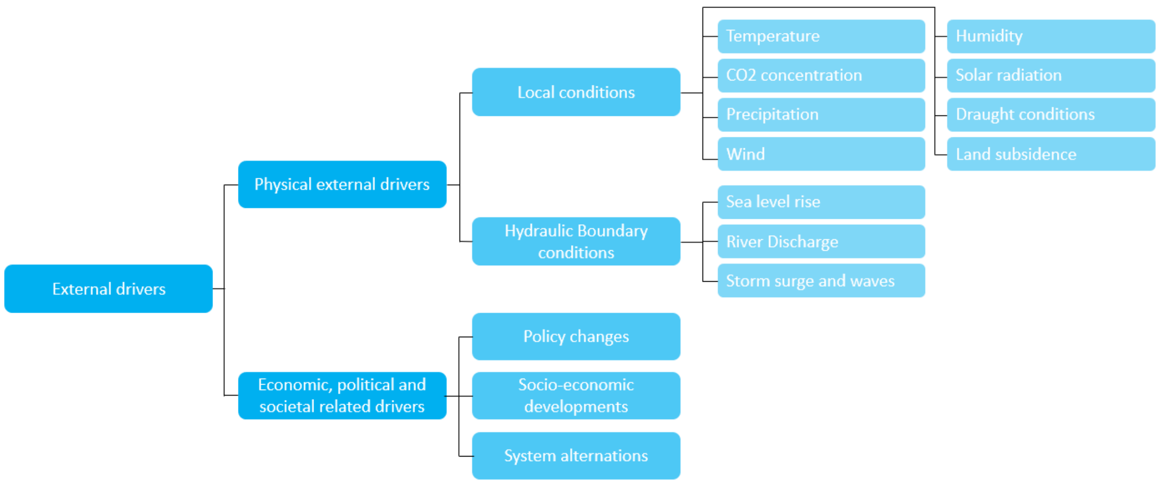

Figure 18 Overview of the external drivers to consider for critical hydraulic structures in the Netherlands

6.2 Climate change scenarios

Two main sources for climate change scenarios are elaborated; One focussed on the global representation of climate change (IPCC) and one more tailored to the Netherlands (KNMI). Some key figures regarding current information on climate change in the Netherlands are elaborated in section 6.2.3.

6.2.1 IPCC scenarios

Every six to eight years the IPCC (Intergovernmental Panel on Climate Change) releases an assessment report on the current status and future projections of climate change. Currently, the IPCC is in their sixth assessment cycle in which a new assessment reports will be published (AR6). The final report, the synthesis report, has been released in march 2023. The previous assessment, AR5, dates back to 2013/2014. The IPCC focuses on the global representation of climate change. The key difference between the fifth (AR5) and sixth (AR6) assessment cycle of the IPCC is the climate data used and the application of newer climate models, underlying many of the findings and projections (Gannon & Boonvanich, 2021). The AR5 climate projections were based on so-called Representative Concentration Pathways (RCPs). In short, they were used as sample trajectories of radiative forcing, which can be related to the greenhouse gas effect and the trapping of heat in the earth's atmosphere, resulting in global temperature increase. These trajectories were used to understand and project a variety of climate impacts, based on these different emission pathways. However, it turned out that it was difficult to link these RCPs with real world conditions for emissions, political interventions and land use (Gannon & Boonvanich, 2021). For AR6 it was decided to use new climate models in which the RCPs are coupled with Shared Socioeconomic Pathways (SSP), which include factors like urbanization, population growth and technologic advancement mitigating climate change, which can be coupled to the real world. Five SSP-RCPs are considered in the new IPCC scenarios.

6.2.2 KNMI scenarios

The KNMI (the Dutch Royal Meteorological Institute) translate every assessment cycle of the IPCC to the Dutch local climate. The new KNMI'23 climate scenarios are not yet published and will follow eventually from the sixth assessment cycle of the IPCC (AR6). The previous released climate scenarios of the KNMI date back to 2014 (KNMI'14 scenarios). Since then, an updated report on climate change is released, named Climate Signal'21 (KNMI, 2021). This report is based on the new knowledge and insights of AR6 which are released earlier.

6.2.3 Key figures on climate change in the Netherlands

Before diving into the external drivers which could influence the Haringvliet sluices (climate change driven or not), it is valuable to get some first insights on what climate change means for the Netherlands. This, to analyse up front which drivers could be more important than others. Some key figures of KNMI'14 are presented in Table 16. Table 16 presents four climate scenarios and their predictions for two time periods (around 2050 and around 2085). Some newer predictions regarding sea level rise (SLR), three scenarios from Climate Signal'21, are presented in Table 17. One can already see that there is in increase in predicted SLR when comparing the KNMI'14 and Climate Signal'21 predictions.

Table 16 Key figures of climate change in the Netherlands according to KNMI'14 scenarios (KNMI, 2015)

parameter	Climate change scenarios for 2050 (2036-2065)				Climate change scenarios for 2085 (2071-2100)			
	G_L + 1°C Low value	G_H + 1°C High value	W_L + 2°C Low value	W_H + 2°C High value	G_L + 1.5°C Low value	G_H + 1.5°C High value	W_L + 3.5°C Low value	W_H + 3.5°C High value
SLR (absolute level)	+15 to + 30 cm	+15 to + 30 cm	+20 to + 40 cm	+20 to + 40 cm	+25 to + 60 cm	+25 to + 60 cm	+25 to + 80 cm	+25 to + 80 cm
SLR (speed)	+1 to +5.5 mm/year	+1 to +5.5 mm/year	+3.5 to +7.5 mm/year	+3.5 to +7.5 mm/year	+1 to +7.5 mm/year	+1 to +7.5 mm/year	+4 to +10.5 mm/year	+4 to +10.5 mm/year
Temperature (average)	+ 1°C	+ 1.4°C	+ 2.0°C	+ 2.3°C	+ 1.3°C	+ 1.7°C	+ 3.3°C	+ 3.7°C
Precipitation (average amount)	+4%	+2.5%	+5,5%	+5%	+5%	+5%	+7%	+7%
Solar radiation	+0.6%	+1.6%	-,8%	+1,2%	-0,5%	+1,1%	-0,9%	+1,4%
Evaporation	+3%	+5%	+4%	+7%	+2,5%	+5,5%	+6%	+10%

Table 17 Key figures for SLR from Climate Signal '21 KNMI (KNMI, 2021)

Jaar	2050	2050	2050	2100	2100	2100
Scenario	SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
SLR (absolute water level)	14-38 cm	15-41 cm	16-47 cm	30-81 cm	39-94 cm	54-121 cm
SLR (speed)	2.8-8.7 mm/year	5.2-10.6 mm/ year	5.8-12.1 mm/ year	2.9-9.1 mm/ year	4.4-10.5 mm/ year	7.2-16.9 mm/ year

One of the first findings that Climate Signal'21 presents is that the climate panel of the new IPCC report has established that the heating of the earth is indeed caused by humans. Climate Signal'21 gives already an indication for the Netherlands of IPCC findings regarding six topics: Sea level rise, river discharge, drought conditions, weather, precipitation and consequences in cities. The report states that, if we do not reduce the emissions of greenhouse gasses, the sea level on the Dutch coast could rise up by 1.2 meters by the year 2100 (compared to the sea level at the beginning of this century). An extremer scenario would be if the Antarctic ice sheets would become unstable, resulting in estimation of a sea level rise of up to 2 meters. For the river discharges of the Meuse and the Rhine is stated that in summer the chances of low river discharges increases and in winter the chances of high river discharge increase. Also, the risk of drought period in spring and summer increases due to the increase of evaporation caused by higher temperatures and more solar radiation. It is found that the warming in the arctic regions is stronger than in the tropics. This can lead to a weaker jet stream and as a result, the chance of longer persistent weather situations such as periods of dry, wet, hot or cold may be longer. Another influence in weather conditions, is the difference in precipitation characteristics. Because the air in a warmer climate can contain more moisture, more extreme rain showers can occur. These extreme rain showers can also be accompanied by large wind gusts. All these implications of climate change are noticeable in both rural and city environments, although cities tend to be more vulnerable to the results of climate change. Cities are usually warmer than the rural environments, thus an increase in global temperature causes these cities to heat up even more. In addition, cities are more problematic in dealing with extreme precipitations and drought conditions.

6.3 Potential impact of physical external drivers on the Haringvliet sluices

The physical drivers addressed in this thesis are illustrated in Figure 19. For each of the drivers the potential impact and consequences are discussed concerning the Haringvliet sluices and the surrounding system.

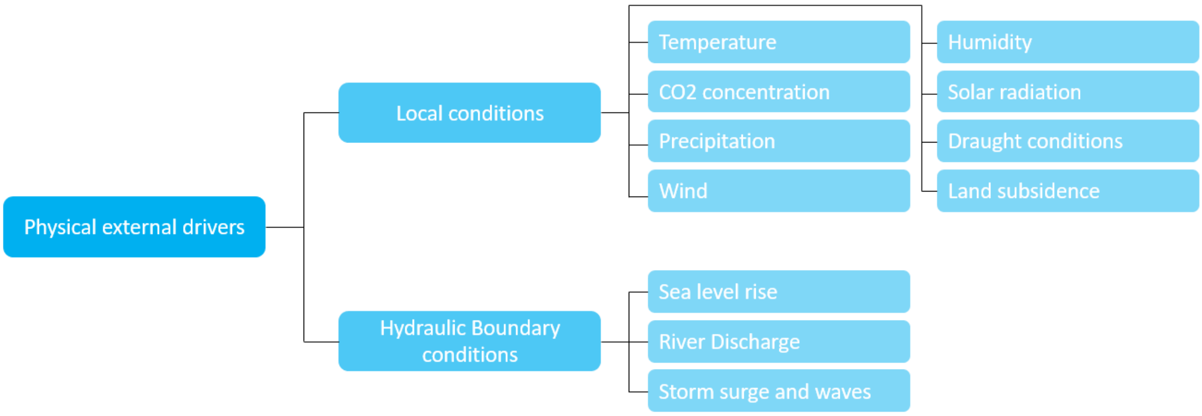

Figure 19 Physical external drivers considered in this thesis

6.3.1 Local conditions

The external drivers related to the local conditions can be characterised by the following parameters: temperature, CO_2 concentration, precipitation, wind, humidity, solar radiation, drought conditions and land subsidence.

Temperature

Due to climate change, future average temperatures will increase. It is expected that for the Netherlands the local average temperature changes are proportional to the global temperature increase. Besides average temperature changes, the possibility of extreme high temperatures increases, whereas the possibility on extreme cold temperatures decreases (KNMI, 2021). Both the increase in average temperature and in extreme high temperatures could influence the Haringvliet sluices and its system. The expected temperature change in Europe for two different climate scenarios is shown in Figure 20.

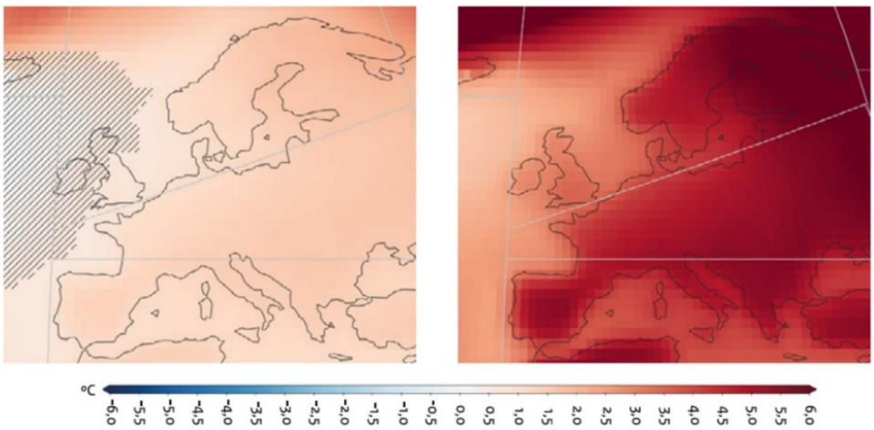

Figure 20 Climate projections for 2081-2100 relative to 1995-2014 for two scenarios, SSP1-2.6 (left) and SSP5-8.5 (right). Temperature change is presented in °C. (Edited from KNMI, (2021))

These expected temperature characteristics can affect the Haringvliet sluices in various ways. One of the impacts it can have is on temperature sensitive materials, like steel. Steel materials expand in high temperatures and shrink again when the temperature drops. This expansion could become problematic if moving elements would jam as a result. This is mostly relevant for the bridge deck, navigation lock gates and the discharge sluices. The expansion of these could influence the functioning of the respective element as well as cause the material to fatigue by obstructed expansion. The effect of temperature change on the functioning of the navigation lock gates and the discharge sluice gates is assumed to be negligible, as they are partially cooled by the water. However, there could be a significant effect when considering the opening and closing of the bridge deck. From an interview with the asset manager of the Haringvliet sluices can be concluded that there is enough room for the bridge deck to expand. Therefore, this effect is also considered negligible and these assumptions are strengthened by no jamming of sluice doors, bridge deck or navigation lock gates caused by high temperatures occurring in the past. Another way that higher temperatures could affect materials is the accelerating affect it has on deterioration mechanisms like carbonation and thus corrosion. Temperature, in combination with CO_2 concentration and humidity, accelerates the carbonation process and thus affects the carbonation resistance of the concrete. Besides carbonation resistance, the resistance of concrete against chloride penetration is also reduced at elevated temperatures as stated in Xu et al. (2022). The significance of the effect of carbonation on the Haringvliet sluices is further elaborated on in the discussion of the driver CO_2 concentration.

More frequent extreme high temperatures could cause overheating, and thus malfunctioning, of the operation systems or other instrumentations. This could easily be prevented by cooling the affected systems or upgrading to more temperature resilient equipment. Therefore, the impact is assumed to be negligible.

Besides material or other physical impacts, increased temperatures could also lead to functional impacts. This could either be functional change in demands or increased use of some functions. For example, fresh water demands could increase in periods of high temperatures. Also, the navigation lock could be used more, as higher temperatures could imply an increase in the use of recreational vessels. As a result, the bridge has to be opened more often, which in turn could lead to stagnation of traffic. Mobility goals, for traffic as well as recreational vessels, are assumed outside of the scope of this research and are not further investigated qualitatively.

CO^2 concentration

As already mentioned in the temperature driver section, increased CO_2 concentrations accelerate material deterioration processes like carbonation and corrosion. Temperature and humidity also influence this process. In recent research done by TNO a quick scan of the concrete state of four storm surge barriers in the Netherlands has shown that the concrete is in excellent condition and the barriers are expected to reach their designed life without major problems (TNO, 2022). It is assumed that the quality of the concrete of the Haringvliet sluices is comparable to the storm surge barriers analysed in this study. The contribution of carbonation and corrosion to end of life of the Haringvliet sluices is therefore assumed non governing.

Precipitation

More extreme rain showers, longer periods of rain or lack of rain are expected in current climate models (KNMI, 2021). Rain showers can be more extreme, because the air in warmer weather can contain more moisture and rain periods can elongate because of expected weaker jet streams. The effect of precipitation is only regarding local precipitation. The influence of more rain in the catchment of the Rhone and the Meuse is taken into account in the change of hydraulic boundary conditions in section 6.3.2. The implication of more acid rain is not taken into account.

An increase in local precipitation will not have a significant effect on the water levels of the Haringvliet. These water levels will most likely be governed by the discharge of the rivers and the discharge capacity of the sluices. Local extreme precipitation could lead to insufficient drainage capacity of the bridge deck, causing aquaplaning, but this is assumed not to be a leading consequence in this research.

Wind

From Climate signal'21 (KNMI, 2021) can be concluded that there is no significant increase in wind speed or other wind characteristics in the Netherlands. These small changes can be seen in Figure 21.

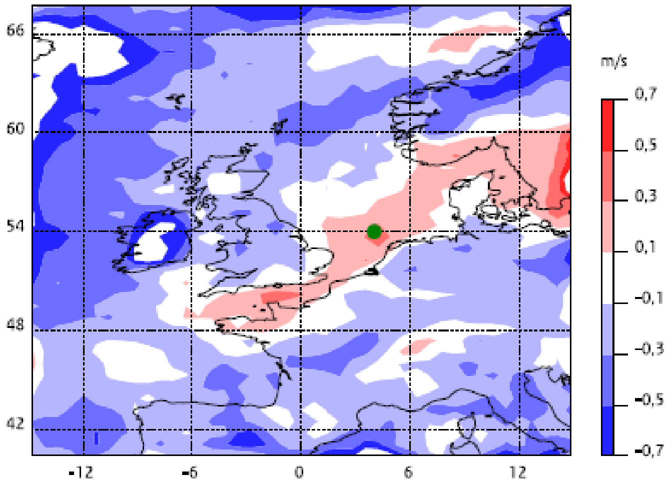

Figure 21 Change of the annual maximum of the wind speed (m/s) in winter (December -February) in Western Europe between 1991-2020 and 2071-2100 based on a high emission scenario (SSP5-8.5). Increase in red, decrease in blue. The green dot presents the location where the most changes in windspeed are estimated (From KNMI, (2021))

Humidity

As mentioned before, humidity contributes to accelerating material deterioration processes. Changes in relative humidity are expected to be low or are expected to decrease (KNMI, 2015). Therefore, the effect of humidity is not further taken into account.

Solar radiation

The most important impact of solar radiation on the Haringvliet sluices, is the increase in temperature caused by the increase in solar radiation. This is already discussed in the temperature driver section. Other solar radiation effects are assumed to have no effect on this case study.

Drought conditions

Climate predictions expect an increase in the duration of weather conditions, as such longer periods of drought are also possible. Drought periods increase the demand for fresh water and could apply stress on the ability to maintain the fresh water boundaries. Longer drought periods could also impact the water quality of the Haringvliet due to a low refresh rate and low water depths. Lower water levels in the Haringvliet and less water supply from the rivers also means less room to implement the Kier Policy and allowing water back into the Haringvliet. This implies that the fish passage by *kieren* could be blocked for multiple days at a time to ensure the required water quality at intake points.

Low water levels in the Haringvliet could also be problematic for vessels if the draught of the ships is too large for the water level. It would mean that vessels could not pass the Haringvliet or even enter the lock. Dikes could also be vulnerable when water levels would suddenly rise again after a long period of drought. An analysis on the quality of the dikes is outside of the scope of this research.

Depending on the length and the severity of the drought periods it could have n significant impact on the life span of the Haringvliet sluices, due to the wide spread of consequences.

Land subsidence

Land subsidence could not only have an effect on structural components of the Haringvliet sluices and its surrounding system, but could also induce a change in functional demands (e.g., lower allowed water levels in the Haringvliet). The underlying processes of land subsidence are not directly related to climate change. However, climate change does impact or accelerate these processes. Climate parameters which influence land subsidence are temperature, drought conditions and precipitation. The main causes for land subsidence in the Netherlands can be summarized in three categories according to the Climate Effect Atlas (Klimaateffectatlas, n.d.). The first being the drainage of water within soft soils, such as peat and clay, leading to oxidation of the soil and the start of consolidating processes. Secondly, the extraction of minerals, such as natural gas or salt from deep-lying rock, causes subsidence of the ground surface. Thirdly, land subsidence can be caused by applying a surcharge load on soft soils.

Damages to a structure can occur due to settlements of the soil. Especially uneven settlements beneath the foundation of a structure could lead to an increase of internal forces, for which the structure is not designed. However, the Haringvliet sluices are fully founded in a sandy soil on prefab foundation piles, which makes the structure significantly less vulnerable to potential settlements. Being more susceptible to land subsidence and thus more vulnerable to the effect of this driver, are the dike trajectories along the Haringvliet. Land subsidence along these dike trajectories would mean a lower absolute dike height and as a direct consequence a lower allowed water level within the Haringvliet. This could lead to an increase in discharge capacity demands through the Haringvliet sluices.

For an estimation of the future changes of land subsidence, the maps of Climate Effect Atlas can be used (Klimaateffectatlas, n.d.). In Figure 22, the estimated land subsidence of the case study area is presented using the low impact scenario as well as the high impact scenario following the climate change predictions of KNMI'14. The low impact scenario is based on mild climate change predictions (KNMI'14 GL scenario) and water level fixation. The high impact scenario is based on strong climate change predictions (KNMI'14 WH) and water level indexation. From Figure 22 it can be seen that at the location of the case study the expected land subsidence is limited to 3-10 cm in the timespan of 80 years, which comes down to a maximum of 8 mm/year land subsidence in the high impact scenario.

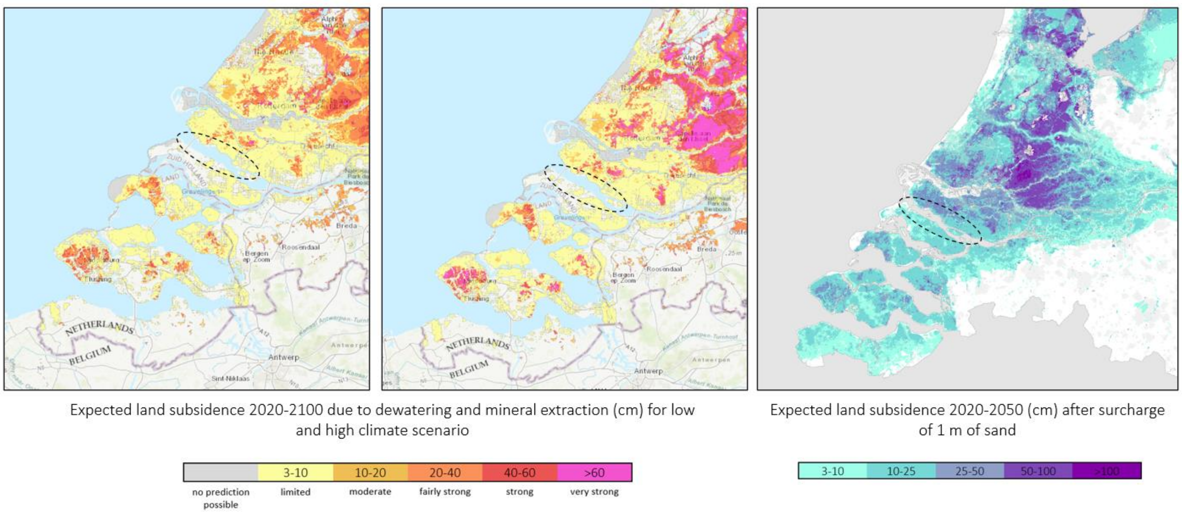

Figure 22 Estimated land subsidence in the Netherlands for the time period of 2020-2100. the left figure represents the low scenario (water level fixation and limited climate change) and the middle figure represents the high scenario (water level indexation and strong climate change), both taking into account dewatering and mineral extraction. The right figure shows the estimated land subsidence in the Netherlands for the time period of 2020-2050 when applying a 1-meter sand surcharge layer (Klimaateffectatlas, n.d.)

For future land subsidence conditions in the case study area, it can be said that it is governed by water level management choices. In Figure 22 can be seen what the expected land subsidence is for the project location. It can be seen that the case study area is located in a region with a lower vulnerability to settlements caused by surcharge loads. Lastly, it can be said that areas which already have been loaded by an extra surcharge load in the past react different to further additions of load in comparison to unloaded locations. Nevertheless, Figure 22 provides a good estimate on the sensitivity to land subsidence due to surcharge loads.

The effect of land subsidence on the Haringvliet sluices themselves is assumed to be negligible, as the vulnerability to land subsidence is minimized by the pile foundation used beneath the foundation and protection. The estimated land subsidence for the dike sections along the Haringvliet is assumed to be in a manageable order of magnitude (8mm /year). The term manageable here is referring to the rate of land subsidence in comparison with monitoring and maintenance intervals of these dike trajectories.

6.3.2 Hydraulic boundary conditions

For the drivers that influence hydraulic conditions it is chosen to group sea level rise, river discharge, storm surge and wave characteristics together, as the water system of the Haringvliet is influenced by sea and river conditions simultaneously.

Sea level rise

Sea levels are expected to continue to rise. Depending on which climate scenario is used, the future sea level rise rate predictions differ. From Table 33 in Appendix H, it can be noted that sea level rise could be in the order of a meter by the year 2100.

The rise of sea levels implies that the closure threshold of the Haringvliet sluices will be reached more often. This implies less room for *kieren*, which impacts the ecology and fish passage function. Frequent closure or longer closure periods also lead to higher water levels in the Haringvliet, because the river water cannot go elsewhere. Higher water levels at sea also cause larger overtopping or even overflow volumes in storm conditions, which is not only increasing the load on the actual structure, but also increases water levels in the Haringvliet.

The discharge capacity is also influenced by sea level rise. If it is assumed that the base water level in the Haringvliet is kept the same, and levels at the North Sea rise, there is a decrease in hydraulic head. Less hydraulic head indicates a lower discharge capacity.

On the mobility side of things, higher sea levels also imply that the maximum draft for passing the bridge deck is reached more often. That means that the bridge is opened more frequent and that traffic is disrupted more. Both, the more storm closures of the Haringvliet sluices and the more opening of the bridge deck could cause for wear of movable elements.

From this can be concluded that the influence of sea level rise is quite significant, as its effects cause a kind of domino effect of consequences.

River Discharge

River discharges are expected to have more extreme discharge volumes, due to climate change. The expected trend can be seen in Figure 23 for both high and low waters in the river Rhine and the Meuse.

High river discharges could cause the sluices to not have enough discharge capacity, after which the water level in the Haringvliet could rise to extreme levels. This could be amplified by a decrease in hydraulic head over the sluices caused by sea level rise. The effect of low river discharges is described in the discussion of the drought driver section. More research on the influence of the discharge capacity is needed (also in combination with sea level rise).

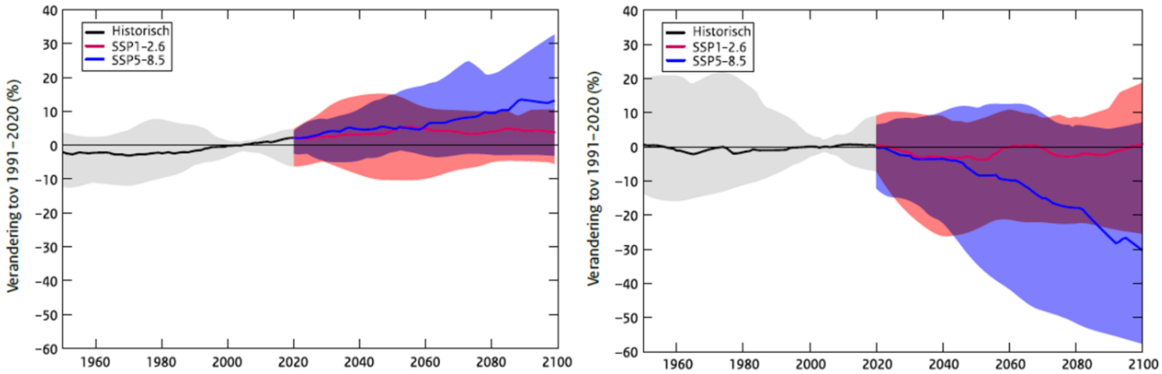

Figure 23 Relative changes per year in the high water indicator (left) and the low water indicator (right) compared to the average over the period 1991-2020. Black is for the historical period (up to 2020), and the colors are for the future projections according to the low (SSP1-2.6; red) and the high (SSP5-8.5; blue) emission scenario (KNMI, 2021).

In Klerk et al. (2015) it is investigated if there is any dependence between a storm surge at Hoek van Holland and a peak discharge at Lobith. If these processes would happen simultaneously, it would lead to extreme hydraulic conditions at both sides of the Haringvliet sluices. The study concludes that the dependence between the two processes is highest at a phase delay of 6 days, i.e. the time lag between the peak of the storm surge at Hoek of Holland and the peak discharge at Lobith is 6 days. There was no significant dependence found for a time delay of zero. Klerk et al. (2015) also concludes that more extreme river discharges, as predicted due climate change, does not lead to a difference in magnitude of dependence of the two processes.

Storm surge and wave characteristics

As presented earlier, there is not a significant predicted increase in wind speeds for the North Sea. Despite the fact that there is hardly an effect of the wind on the highest water levels, these water levels will increase in the future because of average sea level rise. Research on the wave characteristics do not show a significant change in wave statistics. The results are highly dependent on the climate models used and even though there are some similarities, no general significant results for the North Sea are predicted. (Bonaduce et al., 2019; Grabemann et al., 2015; Groll et al., 2014).

6.3.3 Summary on potential impact of physical drivers

In Table 18 and Table 19, an overview is shown of the potential impact of the discussed drivers on the functions and the technical state of the Haringvliet sluices. A colour index is used to easily identify the most important driver-function or driver-element combination. The colour index is introduced in Figure 24. The assigned colour to the driver and function or element combination is assigned based on expected effect, severity of the consequences and expert judgement.

The green colour indicates that the impact is investigated by a quick scan and was thereby assumed to have a minor or negligible effect. The yellow colour indicates that either the effect is assumed to be moderate based on literature or expert opinion, but that it is advised to look into to impact or stakeholder inclusion before fully excluding it from a full analysis, i.e. could either be green or orange after further research. The orange colour indicates that these combinations are expected to have a severe effect on the end of life of the Haringvliet sluices. Empty boxes in the matrices indicate either a non-existing impact relation or an assumed negligible impact before investigation.

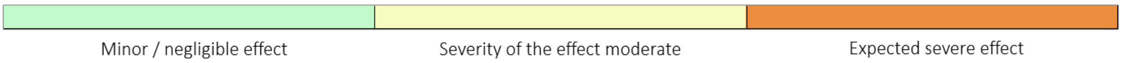

Figure 24 Colour index used in Table 18 and Table 19

Table 18 Overview of the impact of physical drivers on the functions of the Haringvliet barrier

Functions \ Drivers	Temperature	Precipitation	Land subsidence	Sea level rise	High river discharges	Low river discharges	Drought conditions	CO2 concen-tration	Storm surge and waves
General conse-quence	Installations malfunction and increased use of lock by recreational vessels	Average and extreme precipitation increases causes river discharge to increase	Lowering of dike crests at soft soil locations, sandy soils less impacted	Closing level reached more often	Discharge sluices need to discharge more water	Lower water levels in the Haringvliet	Increase in fresh water demand and risk of instability of dikes	Accelerati-on of CO_2 sensitive processes	Minimal change in storm frequency and wave characteri stics
Flood protection	Extreme storm conditions and high temperatures are related to opposite wind directions implying little impact		Decrease of dike height increases chances of flooding	More frequent closure and more wave over-topping and overflow	Increased risk of flooding *from the back side*				
Navigation	Hindrance due to malfunctioning installations at the lock or bridge			Bridge must be opened more frequent due to height restriction reached more often		Possibility of too low water depths, entrance to lock could be hindered			
Water manage-ment	Increase in risk of not being able to discharge or kieren of water and increase in risk of salt intrusion influencing the quality of water	More water to discharge through the sluices, possible change in water quality	Decrease of dike height causes changes in water level manageme nt	Discharge capacity influenced by decreased hydraulic head over the sluices also window to be able to kieren becomes smaller	Risk on not being able to discharge all the river water	Quality of the water could be difficult to maintain and smaller windows for *kieren*	Changes in water level and water quality manageme nt required		
Ecology	Hindrance due to malfunctioning installations on *kieren* and fish corridors			More frequent closure of HV leads to less opening of corridor					
Traffic	Hindrance due to malfunctioning installations if bridge is not able to close	Not sufficient drainage capacity to prevent risk of aquaplaning							
Monumen-tal					Need for changes in monument protected elements to be able to fulfil functions				

Table 19 Overview of the physical drivers impacting the technical state of the Haringvliet barrier.

Category \ Driver	Temperature	Precipitation	Land subsidence	Sea level rise	High river discharges	Low river discharges	Drought conditions	CO2 concentration	Storm surge and waves
General consequence	Installations malfunction and increased use of lock by recreational vessels	Average and extreme precipitation increases causes river discharge to increase	Uneven settlements of structural components	Closing level reached more often	Discharge sluices need to discharge more water	Lower water levels in the Haringvliet	Increase in fresh water demand	Acceleration of CO_2 sensitive processes	Minimal change in storm frequency and wave characteristics
Fixed structures	Accelerated carbonation of concrete elements	Accelerated carbonation of concrete elements	Uneven distributions of forces could cause minor cracking of concrete elements	Higher flow velocities could cause erosion	Higher flow velocities could cause erosion			Accelerated carbonation of concrete elements	Splashing on concrete elements increases, accelerating chloride ingression
Movable parts	Accelerated corrosion of steel components, expansion of steel and overheating of driving mechanisms	Accelerated corrosion of steel components		Fatigue caused by increase of use	Fatigue caused by increase of use				Splashing on steel elements increases, accelerating corrosion
Electronic components	Overheating of electronic components								
Navigation lock	Accelerated carbonation of concrete elements, accelerated corrosion of steel components and overheating of driving mechanisms	Accelerated carbonation of concrete elements and accelerated corrosion of steel components		Higher water levels cause the bridge to be opened more frequently	Higher water levels cause the bridge to be opened more frequently	Water levels too low to use the lock	Water levels too low to use the lock		

6.4 Potential impact of economic, political and societal external drivers on the Haringvliet sluices

The non-physical drives which will be addressed in this thesis are illustrated in Figure 25. For each of the drivers the potential impact and consequences are discussed concerning the Haringvliet sluices.

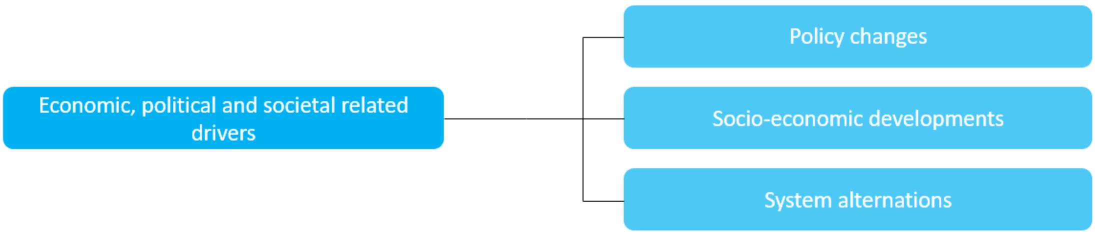

Figure 25 Non-physical external drivers considered in this thesis

6.4.1 Policy changes

Policy changes and changes in laws could affect the end of life of the Haringvliet sluices, as many of the requirements of the system result from formal laws and policy. In 2017 the safety standards for hydraulic structures were revised. Formerly, hydraulic structures such as dikes were designed on withstanding certain water levels based on a required probability of exceedance. Since 2017, the safety standards are based on an acceptable probability of flooding. Hereby taking into account different failure mechanisms that could lead to flooding. As these standards are quite recently defined, it is not expected that such an impactful revision will happen in the near future. Furthermore, the waterboards and Rijkswaterstaat have until 2050 to make sure all the flood defences comply to their assigned standard. However, the assigned standard per dike section could change, due to socio-economic growth.

6.4.2 Socio-economic developments

It is important to be aware on how social or economic developments in the country or the more local region could impact the functional demands and requirements or the technical state of the Haringvliet sluices. Socio-economic growth could lead to a higher expected safety level of the sluices themselves, but also of the dike rings around the Haringvliet, due to the possible damages or other consequences a flood would have. It could also be the case that the needed dike elevation, to realise the new requirements, is not achievable due to the development of buildings and infrastructure to close to the dike ring. The most likely solution in such a scenario would be to construct more technically challenging and expensive dike reinforcements.

Socio-economic growth also causes intensified use of certain functions. For example, the traffic intensity over the bridge could increase by growing cities in the south. The road surface or the bridge deck itself could age quicker than expected, increasing the maintenance. The intensified use of the bridge deck could also make requirements on the opening of the bridge stricter to comply to mobility demands. From these examples can be concluded that socio-economic growth could have a domino effect on function demands as well as structural ageing. Another example could be that the ratio of recreational vessels and commercial shipping changes, which could lead to totally different preferred water levels in the Haringvliet and could potentially alter requirements for the navigation lock.

The impact the socio-economic developments is dependent on the rate of growth in combination with pressures of other external drivers like sea level rise, as they both would cause pressure on similar aspects.

6.4.3 System alterations

Large changes within the water system of the Haringvliet sluices could result in changes in hydraulic boundary conditions or required functions and their required performance level. The large changes referred to here, are engineering changes, i.e. artificial changes which could have an influence on the case study. Changes could have either a positive or negative effect on the remaining life time of the Haringvliet sluices. This research does not aim to quantitatively describe the impact of these artificial changes outside of the direct vicinity of the Haringvliet sluices, but will create an overview of these possible changes and qualitatively describe their impact. Awareness of possible changes is a valuable addition to this research without quantifying possible impacts. Possible system alternations are listed below and differ in location and scale.

Replacement of current storm surge barriers – Just like the Haringvliet sluices, other storm surge barriers in the Netherlands experience accelerated aging and might be reaching their end of life earlier than expected. One of the current storm surge barriers which could influence the Haringvliet sluices would be the Maeslantbarrier. Changing the functioning of the Maeslantbarrier could change the hydraulic boundary conditions of the Haringvliet sluices. The Maeslantbarrier is located in the New Waterway at Hoek van Holland. It was built during 1991 to 1997 and has a retaining height of NAP + 5 meters. The barrier is fully open in normal operation, which allows for ships to enter and leave the port of Rotterdam. During storm conditions the barrier floats into the waterway, after which it sinks itself to the bottom closing of the waterway. Under these conditions ships cannot leave or enter the port anymore. Sea level rise caused by climate change enforces the storm surge barrier to close more often, causing problems in port availability and increasing wear of the structure by the unforeseen number of closures. This might give reason to an early replacement of the storm surge barrier. Dependent on the type of replacement the boundary conditions for the Haringvliet sluices change. The rivers the Meuse and the Rhine are mainly discharged to the North Sea by the Haringvliet and the New Waterway. In other words, water is discharged by the Haringvliet sluices and through the Maeslantbarrier. Making changes in the volume of water discharged through the New Waterway could have a severe impact on demands on the Haringvliet sluices. The severity of the impact is amplified by the fact that ensuring enough discharge capacity is already considered one of the main drivers, as stated in section 6.3.3. Changes within the delta system of one if the hydraulic structures, influences the other hydraulic structures.

The Haakse Zeedijk (DHZ) **–** The DHZ plan entails a robust, sand-sprayed dike, at a maximum of 25 km off the coast from Den Helder to Walcheren. The dike is intersected with two passages to the sea: At Rotterdam and at Ijmuiden. Between the current coastline and the new dike, three basins are planned with a permanent average water level of NAP + 0 m, independent of sea level rise. The river discharge flows freely into the basins. The basins discharge the river water into the sea by means of discharge sluices. In the first decades this will be possible at low tide, later on, taking into account sea level rise, pumping stations will have to be used to pump out the water to the sea. The dike could be extended further along the coast of other countries. The plan does not elaborate on the use of existing storm surge barriers, but the main goals of the plan are to not reinforce current dikes and infrastructure in the future. From this we can assume that there will be no longer a need for the Haringvliet sluices. This does imply the DHZ would be a plan to consider when the Haringvliet sluices or other storm surge barriers along the coast reach their end of life based on sea level rise.

Northern Europe Enclosure Dam (NEED) **–** The Nort European Enclosure dam is a proposed plan to be able to deal with sea level rise, not only for the Netherlands, but also other North European countries. It consists out of three massive dams, respectively 331, 145 and 161 km long, turning the entire North Sea in a massive basin. The plan would cause a lot of changes in the boundary conditions and demands of delta situated hydraulic infrastructure all across Northern Europe. As a lot is yet unknown about the details of the plan, no direct consequence for the Haringvliet sluices can be defined. As the plan would have an influence on a various number of critical hydraulic structures in the Netherlands, their functions and demands would have to be altered to a totally new situation. The feasibility of this plan and the severity of the impact on ecological systems are still questioned, but it shows a plan which focusses on an area larger than just the Netherlands in strategies to deal with increasing sea level rise.

Delta21 **–** Delta21 aims to be a future-proof solution for the southwestern delta, which is also the area of the case study. The Delta21 plan includes topics like flood safety, energy storage and nature restoration. Between the coast of Maasvlakte 2 and that of the island of Goeree Overflakkee, it is planned to construct a flood defence in the form of a row of dunes, a pumping station and a storm barrier. The flood defence creates a lake of approx. 20 km2. The pumping station in the flood defence would have sufficient capacity to pump the excess water into the sea at the very highest expected river water levels. The dunes and the storm surge barrier together provide sufficient protection against high seawater levels. If there are no high-water levels, the pumping station can be used to give the lake the function of an energy storage lake. The plan aims to permanently open the Haringvliet sluices reintroducing the Haringvliet to a salty tide. This plan would drastically alter the demands of the Haringvliet sluices in regards to flood protection, discharge of river water and ecology.

The location of these system alterations and their potential impact area can be found in Appendix F.

6.4.4 Summary on the potential impact of economic, political and societal external drivers

The main conclusion on the impact of socio-economic developments, policy changes and system alterations is that it could impact the life time of the Haringvliet sluices on a variety of functional demands and requirement or structural state. However, it is not possible to quantify or anticipate on the possible impacts of these drivers, due to their large uncertainty. Quantifications of this or qualitative scenario descriptions based on these types of drivers are assumed to be out of the scope of this research. What is important is to realise that the impact could be significant, thus awareness of possible changes in the future is key.

6.5 Conclusions on the external drivers influencing the remaining life of the Haringvliet sluices

The external drivers to consider for the Haringvliet sluices, or hydraulic structures in general, can be subdivided into physical external drivers and economic, political and societal drivers. For the physical drivers, each driver is discussed regarding its possible consequences on the case study and an estimated severity of that consequence. From this analysis, the drivers which are expected to have to most severe influence on the Haringvliet sluices are defined (orange sections in Table 18). The most important physical drivers to consider in further analysis are sea level rise, changes in high or low discharges and drought conditions. These drivers have to most influence on the flood protection function and the water management function.

For the non-physical drivers it is concluded that in the remainder of this analysis, these will not be taken into account qualitatively, even though they could have drastic consequences. It is not possible to quantify or anticipate on the possible impacts of these drivers, due to their large uncertainty. Nevertheless, it is important to stress that changes in the system can negatively affect the life span of the Haringvliet sluices. This step in the analysis could be used to anticipate on non-physical drivers: when a system alteration is proposed, it can be estimated what the impact would be on the Haringvliet sluices and which boundary condition it will influence. Then, from Table 18 and Table 19 can be derived which function or element the system alteration would influence, and more important, if this driver and function combination was already estimated to be dominant in the end of life of the Haringvliet sluices.

7. Tipping Points in the timeline of the remaining life of the Haringvliet sluices

The previous chapter concludes that sea level rise and changes in extreme river discharges (either high or low) are expected to be dominant external drivers, affecting the remaining life of the Haringvliet sluices. These external drivers mainly have an effect on the flood protection function and water management function. The water management function consists of both the water level and water quality management. The previous chapter (chapter 6) has analysed *what* could be the cause of the most dominant Tipping Points for the Haringvliet sluices, this chapter (chapter 7) aims to estimate the *when* of these Tipping Points. A Tipping Point is reached if the system fails to meets its technical or functional requirements due to changes caused by the external drivers. If both the *what* and the *when* of the Tipping Points are determined, the next chapter (chapter 8) can continue to set out the different courses for the remaining life time of the Haringvliet sluices by proposing life elongating measures.

This chapter is the first step in illustrating the possible courses in the remaining life of the case study using Adaptation Pathways and corresponds to step 6 of the research approach (chapter 3). In section 7.1, the considered critical combinations of external drivers and case study requirements are defined. In section 7.2, the method of analysis for quantifying the Tipping Points is described. In section 7.3, the results of the analysis of the Tipping Points are shown as well as an additional representation of the data which aims to show the effects of decisions on important parameters. Lastly, section 7.4, will provide a conclusion on the analysed Tipping Points in the life of the Haringvliet sluices.

7.1 Considered critical combination of external drivers, functional requirements or technical components

The most critical combinations of external drivers and functional requirements or technical components are summarized in Table 20. Table 20 shows a qualitative description of the impact of the driver on the function and is a reduced version of Table 18 in chapter 6. Only combinations of drivers and functions are shown, as from chapter 6 it can be concluded that the technical state of the Haringvliet sluices is expected not to be a governing factor in respect to the functional life time.

Table 20 Overview of the critical combinations of external drivers and functions by describing their consequences on the functions of the Haringvliet sluices (empty boxes indicate an either non-existent or negligible effect).

Functions vs. drivers	Sea level rise	High river discharges	Low river discharges	Drought conditions
Flood protection	More frequent closure, more wave overtopping and more overflow	Increased risk of flooding *from the back side*		
Water management	Discharge capacity influenced by decreasing hydraulic head over the sluices. Additionally, the window to be able to kieren becomes smaller	Risk of not being able to discharge all the river water	Quality of the water could be difficult to maintain and smaller windows for *kieren*	Changes in water level and water quality management required

This thesis will only investigate the effect of sea level rise and high river discharges on the flood protection function (and partly the water management function), to limit the scope of the Tipping Point analysis. These combinations are represented by the left side of Table 20. The effect on the water management function is taken into account by investigating the consequences of rising sea levels on the (extreme high) water levels in the Haringvliet, and thus neglecting other criteria of the water management function (such as salt water ingression, or availability to *kieren*). A similar analysis can be done for the omitted critical combinations, which would lead to different Tipping Points and results in additional branches in the Adaptive Pathways illustrated in chapter 8.

7.2 Method of determining the Tipping Points in the timeline of the remaining life of the Haringvliet sluices

The goal of this chapter is to give quantitative estimations on the expected Tipping Points in the remaining life of the Haringvliet sluices. Quantitative analysis can be carried out in various ways. In this research it is chosen to combine existing models of the Haringvliet sluices to determine an estimation of the Tipping Points. This choice is based on the fact that detailed and recent models for the case study are available and would fit within the scope of this step in the research methodology. In total three models are used and originate from a master thesis done at the TU Delft under the supervision of HKV by Ruessink (2019), a report by HKV at the request of Rijkswaterstaat (Kuijper et al., 2022) and a report done at Rijkswaterstaat internally (Kortlever et al., 2008). The models and a short description are presented in Table 21 and corresponding abbreviations are assigned.

Table 21 Existing models of the Haringvliet sluices and their assigned abbreviations (It is chosen to not assign an abbreviation to the work of Ruessink)

Model / Report	Abbreviation	Description
The future of the Haringvliet sluices (MSc thesis) (Ruessink, 2019)	-	The aim of this research is to determine the end of life of the Haringvliet sluices based on the effect of climate change scenarios. Four different life times are considered: regarding strength and stability, regarding flood protection, regarding fresh water availability and regarding ecology.
Performance level model Haringvliet sluices (Kuijper et al., 2022)	PLM-HV	The aim of this model is to determine performance water levels, for different locations in the water system, for the Haringvliet sluices in a probabilistic way, taking into account the relevant failure modes. Performance water levels are water levels that are expected in different combinations of river discharge and storm conditions under different failure mechanisms of the barrier.
Wave overtopping model (Kortlever et al., 2008)	WOM-HV	The aim of this model is to schematize the geometry and characteristics of the Haringvliet sluices in such way that overtopping and overflow volumes can be calculated accurately.

The majority of the results presented on the Tipping Points for the Haringvliet sluices in section 7.3 will be based on the work of Ruessink. The PLM-HV model (abbreviation found in Table 21) will be used to support the results or schematizations of the work of Ruessink, whereas the WOM-HV model (abbreviation found in Table 21) is already integrated in the model of Ruessink. The intended use of the existing models for this research and their interaction is summarized by Figure 26.

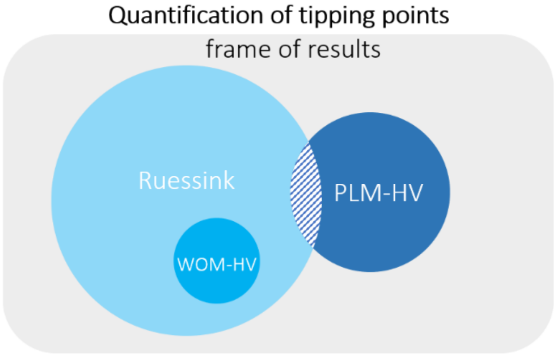

Figure 26 Intended use of existing models for quantifying Tipping Points for the Haringvliet sluices. The grey 'frame of results' space refers to calculations made, data and results presented in this work.

An elaboration of the main goal, used methods, type of results and main take aways of all three models can be found in Appendix G. The discission in the following sections is mainly focussed on what the implications are of using the work of Ruessink as the core of the results for the Tipping Points, i.e. what are important simplifications or assumptions made in the calculations and how valid are they for this research.

Before discussing the simplifications or assumptions made in the work of Ruessink, the research method of this work is explained in more detail. The goal of the work of Ruessink is in line with the first phase of this thesis: Determining the end of life of the Haringvliet sluices based on the effect of climate drivers. The analysis starts by looking into the boundary conditions of the system of the Haringvliet sluices. Important boundary conditions here are the water levels at the North Sea and the river water, which is discharged by the Haringvliet sluices. Water level simulations are performed by SOBEK-RE[4] for various locations, by including various system characteristics and scenario inputs like: Failure mechanisms, behaviour of other barriers, sea water levels, river discharges, wind directions and climate scenarios. Then, Hydra-BS[5] is used to calculate the corresponding return period for the various water levels resulting from the SOBEK-RE model. To determine the end of life of the structure, system requirements and failure mechanisms are described. The effect of overtopping of the sluice gates on the water levels in the Haringvliet is taking into account by using the WOM-HV model (see Table 21). The calculations are supplemented with literature and information gathered from interviews with experts. Some of the results of the research will be shown directly, whereas other results follow from own calculations based on output of the work of Ruessink in section 7.3.

The first simplification to discuss is that in the model used by Ruessink the failure mode 'not opening' and the failure mode 'not closing' are modelled by a fully open or fully closed sluice gate. This implies that the bottom of the gate is either at NAP – 5.0 meter or at NAP + 6.0 meter. In the case of 'not closing' this is quite a conservative assumption, as the initial opening position of the gates is dependent on the required opening height to discharge the river water. This does not only hold for the opening position of the gates, but also for the number of gates which are open. All 17 openings are rarely fully opened. This occurs at discharges larger than 9500 m^3/s according to the discharge regime of the sluices. The actual level of the bottom of the sluice doors, which is dependent on the discharge at Lobith, is taken into account in the simulations performed in the PLM-HV model. The dependence of the opening position of the gates on the discharge are schematized in Figure 27.

[4] SOBEK is a powerful modelling suite for flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, river morphology, salt intrusion and surface water quality (*SOBEK Suite | Deltares*, n.d.)
[5] Hydra-BS (similar to Hydra-NL) is a probabilistic model that calculates the statistics of the hydraulic loads (water level, wave conditions, wave overtopping) for the assessment of the primary dikes and structures.

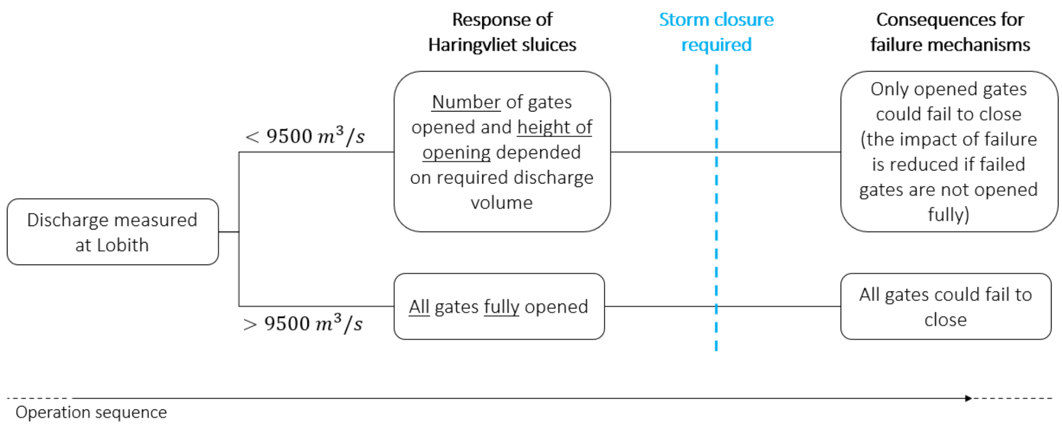

Figure 27 Schematization of the dependence of the position of the gates of the Haringvliet sluices on the discharge measured at Lobith, with the corresponding consequence for the failure mechanisms.

To show the effect of taking into account the actual height and number of sluices gates prior to storm closure, Figure 28 is shown below, which originates from PLM-HV. Figure 28 illustrates the difference in maximum water level between correct functioning of the Haringvliet sluices and the failure mode of 17 gates not opening. At the higher water levels at sea (the right side of both figures), there is a clear jump visible at the 9500 m^3/s mark, at which all gates would be opened prior to a storm closure to discharge the river water. It can be concluded that for the same sea water level, the water level difference between correct functioning and all 17 gates failure, is smaller for river discharge values below the 9500 m^3/s mark. Below the 9500 m^3/s mark, not all the gates are in use or fully opened. As such, for the failure mode of all doors failing this would indicate a lesser affect due to not all gates being fully open in the first place. If the discharge increases more than the 9500 m^3/s mark, it can be seen that the water level difference stabilizes or even decreases. This can be explained by the fact that in cases of high river discharge and closed (correct functioning) Haringvliet sluices, the water level would already rise behind the barrier as the river water cannot go anywhere. Also contributing to this could be that in the case of large river discharges, the large water body could 'push back' the water from the sea in the case of 17 gates not closing.

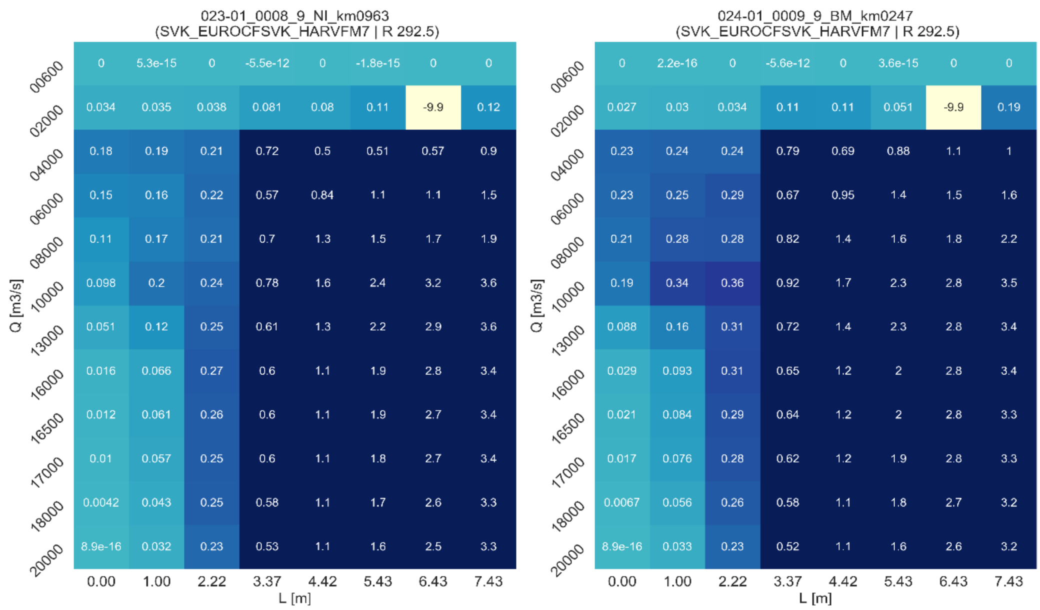

Figure 28 Display of the difference in maximum water levels (in m) at Werkendam (left) and Keizersveen (right) between correct functioning HV and the failure mode of 17 doors not closing. The horizontal axis represents different storm surge scenarios at the North Sea and the vertical axis represents different river discharges measured at Lobith. Results taken from PML-HV model (Kuijper et al., 2022).

It can be concluded that the simplification of Ruessink would only have a significant effect in the low and medium discharge regime and since we are mostly interested in extreme conditions the simplification of Ruessink is deemed a justified simplification. Even more so, in the case of 'not opening' the simplification represents the reality as is, as the 'not opening' failure mode only occurs after a storm closure in which all the gates are at their lowest bottom level.

A second point of discussion regarding the model of Ruessink is that in the SOBEK calculations, the failure of not opening of the Volkerak sluices is not taken into account. This means that for the results of the maximum water level for each return period, there is a small underestimation, as the effect of not opening of the Volkerak sluices could have a significant effect on the water levels. To quantify this effect, we look again at the results of PLM-HV shown in Figure 29. Figure 29 shows the opening and closing level of the Volkerak sluices (blue), the water level in the Haringvliet (green) and the water level in the Volkerak-Zoomlake (dark red). The solid lines represent the case of the failure mode, which in this case is the 'non closure' of two gates of the Haringvliet sluices. The dotted lines represent the case of correct functioning.

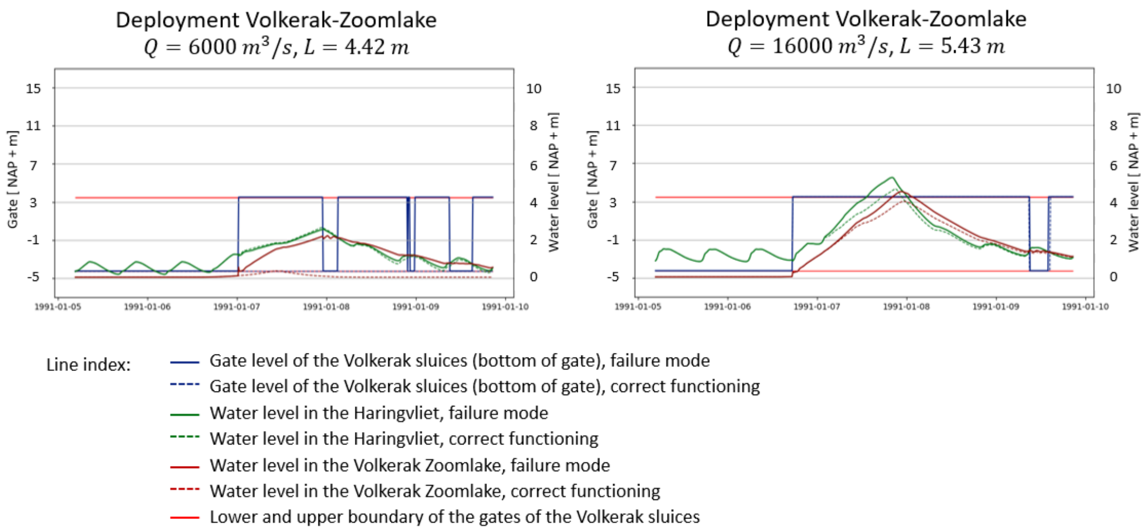

Figure 29 Representation of the difference in gate height and water levels on the Haringvliet and Volkerak side at Volkerak sluices between mode 'correct functioning' and 'non closure' of 2 gates of HV (Q = 6000 and L4.42 in the left figure and Q = 16000 and L5.43 in the right figure). From PML-HV (Kuijper et al., 2022).

It can even be seen in the left plot of Figure 29 that the effect of the failure to close 2 gates of the Haringvliet sluices in moderate storm and discharge conditions is completely eliminated by the deployment of the Volkerak sluices (dotted line and solid line are close to each other). In this case, the blue dotted line is a horizontal line, meaning that in these discharge and storm conditions the Volkerak-Zoomlake would not have been used if the Haringvliet sluices would have functioned correctly. This is not the case in the right plot of Figure 29, in which the Volkerak sluices would have been deployed whether or not the Haringvliet sluices would have functioned correctly or two gates would have failed (illustrated by the two lines being on top of each other). The plots in Figure 29 do not directly show the water level difference between the 'not opening' or 'correct functioning' mode of the Volkerak sluices. To illustrate this difference, an overview showing the effect of using the Volkerak sluices or not on the estimated water level is shown in Figure 30. From this can be seen that the effect is mostly present at the south western part of the Delta and could be a significant contribution in reducing the water levels in the Haringvliet.

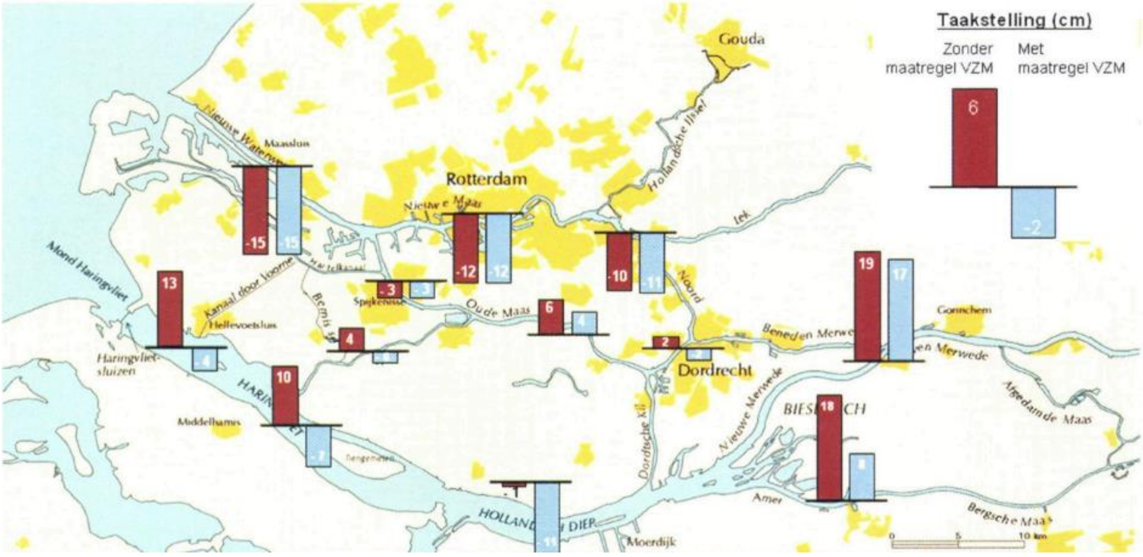

Figure 30 Difference in water level in the Hinterland of the Haringvliet sluices due to using or not using the Volkerak Zoomlake (VZM) as water storage (red= not using, blue = using). From Slootjes & Hesselink (2005). 'Taakstelling' refers to the intended result or target values for the water levels in governing conditions.

To conclude, not including the failure of the Volkerak sluices, like in the model of Ruessink, could lead to an underestimation of water levels in the HV. For the Europoort barrier the failure of non-closure is taken into account in the calculations, but the failure mode of 'not opening' is not. This simplification is assumed to not have a significant effect on the water levels in the Haringvliet since the distribution of the river discharge is already leaning more heavily towards the Haringvliet sluices (roughly 70% goes through the Haringvliet sluices).

Looking more into the failure mechanisms and probabilities of the Haringvliet sluices themselves, some important assumptions are made. Ruessink reports that there is no current available data on the current failure probabilities of the sluices. Therefore, the required probabilities of the sluices are used as the actual probabilities in the calculations. In PLM-HV the current realized failure probabilities are presented and can thus be compared with the used required failure probabilities. In Table 22 the failure probabilities of PLM-HV are shown and in Table 23, the failure probabilities used in Ruessink are shown. The required failure probabilities used in these works, are the same, as they follow from formal requirements.

Table 22 Failure probabilities as used in PLM-HV for the required failure probability and the current realized failure probability (Kuijper et al., 2022).

Code	Description of the failure mode	Failure probability requirement	Failure probability realization
FM1	9 gates do not open	1,00E-02	2,13E-05
FM2	17 gates do not open	1,00E-04	4,07E-05
FM3	1 gate does not close	5,00E-03	2,77E-03
FM4	2 gates do not close	1,05E-03	7,66E-04
FM5	5 gates do not close	1,00E-04	1,97E-05
FM6	9 gates do not close	1,80E-05	2,13E-05
FM7	17 gates do not close	2,00E-04	4,09E-05
Code	Description of the mode	Reliability requirement	Reliability realisation
CF	correct functioning	9,84E-01	9,96E-01

Table 23 Failure probabilities for the required failure probability as used in Ruessink (2019).

Description of the failure mode	Failure probability requirement
1 gate does not open	0,5
2-5 gates do not open	0,1
6-10 gates do not open	0,01
11-17 gates do not open	1,0E-04
1 gate does not close	5,0E-03
2 gates do not close	1,05E-03
3-5 gates do not close	1,0E-04
6-10 gates do not close	1,8E-05
11-17 gates do not close	2,0E-04

By comparing Table 22 and Table 23, it can be noted that the actual realised failure probability is lower than the required failure probability for all failure modes except for the case of 9 gates failing to close (FM6). Even though the failure mode of FM6 is currently not meeting its requirements, the difference is negligible and the probability of correct functioning (CF) is higher than the requirement as a result of combining all the failure modes and their current realised probabilities. This indicates the structure complies to its standard and shows that the calculations of Ruessink might be on the conservative side. Calculations using the current realised failure probability could lead to lower estimated extreme water levels for the same return period. It is not expected that this would lead to significant difference in water levels, as the failure probability of all doors failing, which is used in the results of Ruessink, is already very low. From the work of Ruessink it can be concluded that the water level frequency lines in the case of 8 doors failing is in the same order of magnitude as the case of correct functioning and therefore in final calculations only the dominant mode of all doors failing is taken into account.

It can be concluded that the simplifications or schematizations made in the research of Ruessink align with the scope of this work's analysis of the Haringvliet sluices. The results can give a first estimation of the end of life of the Haringvliet sluices based on the dominant driver and function combination. However, it is good to be aware of the implications of simplifications.

7.3 Results of the Tipping Points in the timeline of the remaining life of the Haringvliet sluices

The results on the estimation of the Tipping Points in the life time of the Haringvliet sluices are presented in this subchapter. First, the system functional requirements following from this research are compared with the requirements used in the analysis of Ruessink. After this, the final Tipping Point results of Ruessink are translated to the current climate scenarios. In addition to these Tipping Point results, the sensitivity of different decision parameters is evaluated (parameters such as threshold values or criteria). This additional evaluation aims to provide a better understanding of how the system reacts to different levels of sea level rise.

7.3.1 System requirements comparison between existing models and this research

Before getting into the quantitative results of the Tipping Points, the functional requirements of Ruessink have to be compared to the requirements from this research. In doing this, possible necessary translation steps of the results can be identified. Both the requirements of the flood safety function for this research as well as the work of Ruessink are presented in Table 24.

Table 24 Functional performance requirements as stated by the analysis of this research and the work of Ruessink (2019)

Result from functional analysis	Ruessink
- *The overflow and overtopping volumes should not increase the water level in the Haringvliet to such extend that the inland dikes are not sufficient anymore.* - *The overflow and overtopping volumes should not significantly increase water levels in the more upstream critical locations*	- *The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter.*

From Table 24 can be concluded that both requirements are focussed on the result of overflow of the gates of the Haringvliet sluices and on the water level of the Haringvliet. The difference is that in the requirement of Ruessink performance values are assigned, whereas in this research the requirements are defined qualitatively. The assigned values to the criteria of end of life in the work of Ruessink are stated to be based on costs, available space and safety of the hinterland. As the requirements are similar in their goal, no translation step in the results of Ruessink is required and they can be used directly.

7.3.2 Existing model results in newer climate scenarios

The work of Ruessink concludes that the system of the Haringvliet sluices can withstand 87 cm of sea level rise. After this the sluices are not able to comply to the set requirements. Ruessink takes into account two climate scenarios from the KNMI'14 report (Klein Tank et al., 2015), but to get a more updated view on the end of life of the Haringvliet sluices, in this work more recent climate data is used. The data in the projections of Le Bars is selected, which is also used in Haasnoot et al. (2018). These projections could chronologically be placed in between the KNMI'14 report and the Climate Signal'21. More information on the projections used, like the extrapolation type after the year 2100, can be found in Appendix H.

The results of Ruessink are shown in Figure 31, showing the Tipping Points at an 87 cm sea level rise in the year 2105 and 2185 for both used climate scenarios respectively (middle values used here). The same amount of acceptable sea level rise in the system is plotted into the newer climate scenarios (Figure 32), showing the corresponding Tipping Points. The estimated years of the Tipping Points for all climate scenarios are summarized in Table 25.

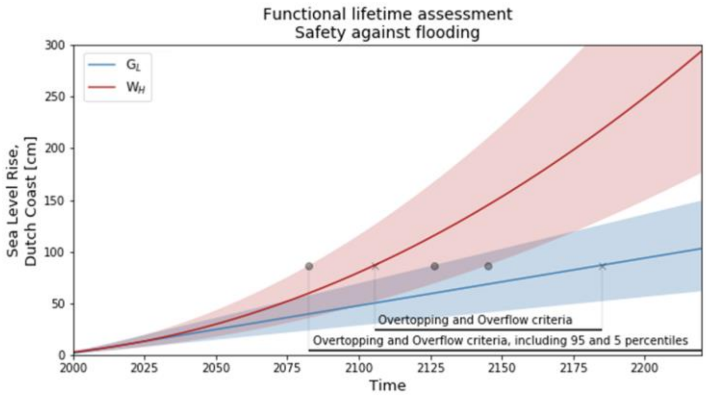

Figure 31 Climate plots used by Ruessink showing the Tipping Points of 87 cm sea level rise. (Ruessink, 2019)

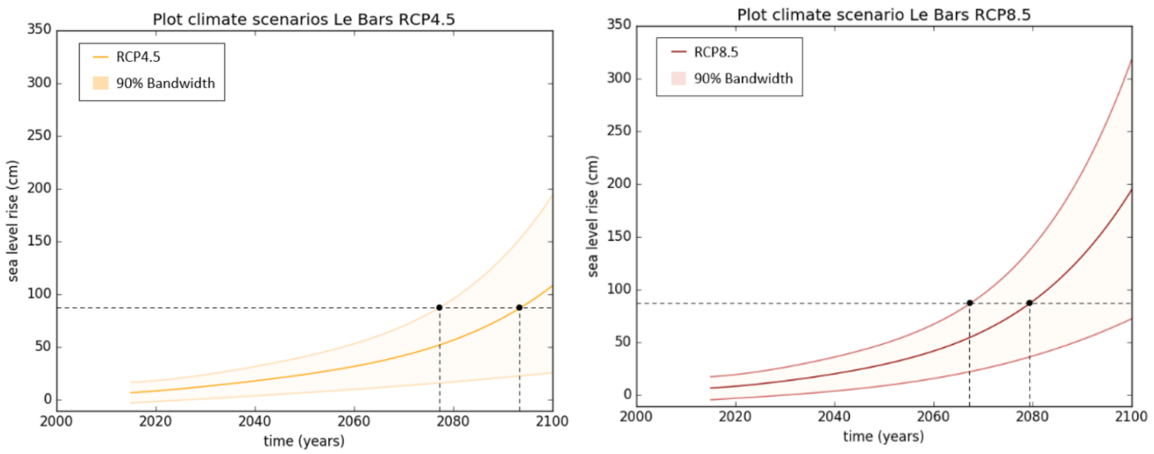

Figure 32 Climate plots based on the projections of Le Bars showing Tipping Points at 87 cm sea level rise.

Table 25 Expected year of Tipping Points for 87 cm sea level rise in all climate projections. Results for G_L and W_H from Ruessink (2019 *(* specific year not reported)*

	KNMI'14 scenarios		Projections Le Bars	
Confidence line	G_L	W_H	RCP4.5	RCP8.5
Lower bound	*	*	2175	2107
Middle	2185	2105	2093	2079
Upper bound	*	*	2077	2068

Since the projections used by Le Bars include scenarios on the more extreme side, it is chosen to only compare the results with the W_H scenario at the 50% confidence line (middle line). The use of more recent climate predictions (than the KNM 14 scenarios) leads to a reduction of the remaining life time by 12 - 26 years, which can be seen from Table 25.

7.3.3 Reassessment of the decision parameters used in existing models

From the previous section, it can be concluded that based on the criteria set on the functional requirement, the Tipping Point of the Haringvliet sluices could be reached as early as 2068, based on the upper bound of the most extreme scenario from Le Bars projections. Besides looking at what the consequences are on the end of life of different climate scenarios, it is also important to assess the impact of the decision for the criteria of failure. This is especially important in cases where the criteria are not based on a formal requirement. The criteria for the Tipping Point are now set in Ruessink as; 'The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter'. To show the impact of this decision on the life time, other decision parameters are explored in this research. In this analysis, the same dike sections are investigated and presented as in the work of Ruessink (dike sections are presented in Appendix J). The data set consists out of 18 calculation points, spread over the hinterland of the Haringvliet sluices. For each dike section Ruessink determined a ratio of how much increase of the hydraulic load is expected by 1 cm of sea level rise. This ratio will be used to compute the result of other decision criteria.

The first explored change in the decision on the end of life criteria is a higher allowed overflow of the dike sections. The allowed threshold assumed now is 1 L/s/m. It is investigated what the acceptance of 10 L/s/m would do to the amount of sea level rise the system can withstand before reaching end of life. The results per dike section can be found in Appendix I. The new calculated amount of sea level rise the system can handle, taking into account the initial criteria as set by Ruessink, but now accepting an overflow of 10 L/s/m for each dike section, is 137 cm. Figure 33 shows the initial (87 cm SLR) and the new Tipping Points (137 cm SLR) for the Le Bars climate projections.

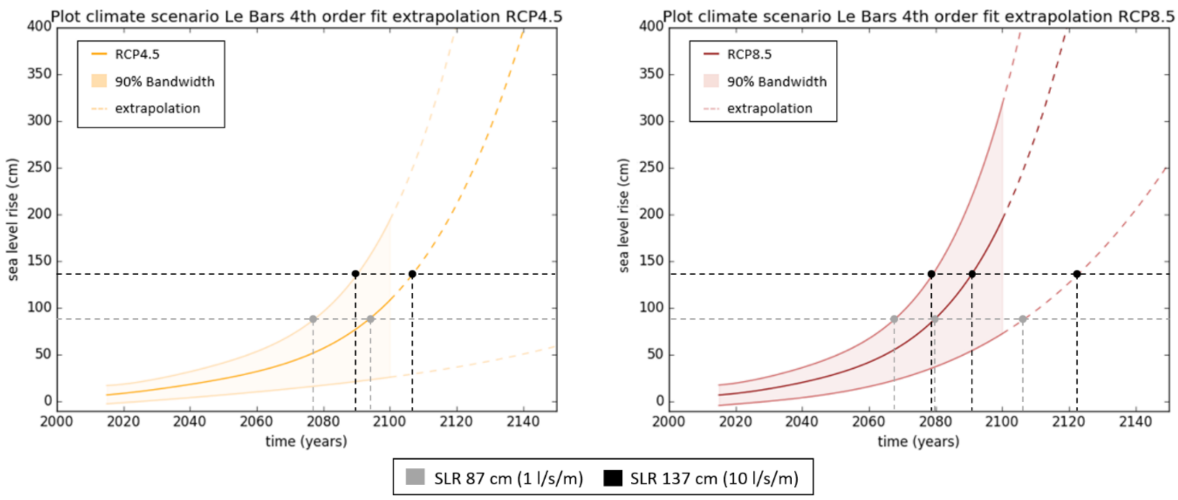

Figure 33 Tipping Point based on an overflow criterion of 1 L/s/m (87 cm) and 10 L/s/m (137 cm)

*Table 26 Tipping Points based on an overflow criterion of 1 L/s/m (87 cm) and 10 L/s/m (137 cm) (*occurs later then 2200)*

	Projections Le Bars (1 L/s/m case) 87 cm SLR		Projections Le Bars (10 L/s/m case) 137 cm SLR	
Confidence line	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Lower bound	2175	2107	*	2123
Middle	2093	2079	2107	2091
Upper bound	2077	2068	2090	2079

When comparing the new results of Table 26 to the initial results of Table 25, it can be seen that accepting a larger volume of overtopping elongates the expected lifetime in the order of 14 years (depending on which scenario is investigated). If a larger overtopping volume on the dike sections in the Haringvliet is accepted, then the dikes have to be modified in such way that the dike revetment can withstand the new loading conditions. Also, it has to be assessed what the consequences would be in regards to damage to buildings and infrastructure in the hinterland and if these would be acceptable.

The next explored change in the decision criteria is to change the values used for the minimum elevation height (initial: 20 cm) and the minimum number of dikes in need of elevation (initial: 2). The values from the initial criteria are based on costs, available space and safety of the hinterland, as stated in Ruessink (2019). It is chosen to explore new criteria based on values within a realistic window: 1 to 4 dike sections and 1 to 30 cm. The results are shown in Table 27.

Table 27 Tipping Points in cm sea level rise the system can take in future conditions based on different decision criteria for the 1 L/s/m and 10 L/s/m case.

Number of dikes that need to be elevated	Maximum allowed SLR if elevation criterion is: elevation needs to be at least 10 cm per section [1 L/s/m – 10 L/s/m]	Maximum allowed SLR if elevation criterion is: elevation needs to be at least 20 cm per section [1 L/s/m – 10 L/s/m]	Maximum allowed SLR if elevation criterion is: elevation needs to be at least 30 cm per section [1 L/s/m – 10 L/s/m]
1	60 - 123	68 - 133	78 - 142
2	79 - 125	87 - 137	96 - 149
3	85 - 143	95 - 154	101 - 163
4	88 - 147	91 - 155	110 - 164

It can be concluded that the amount of sea level rise that the system can withstand is dependent on the values used in the functional requirement criteria and can differ in orders of tens of cm. To show what actually happens to the dike system for each level of SLR, the available excess-height of the dikes sections is shown as a function of sea level rise in Figure 34, for the 1 L/s/m limit, and in Figure 35, for the 10 L/s/m limit. Excess-height of a dike implies that the height of the dike is higher than the hydraulic load calculated for that specific dike section. Figure 34 and Figure 35 also show the initial criteria points quite well at 87 and 137 cm SLR as discussed before. The supporting calculated data for these plots can be found in Appendix I.

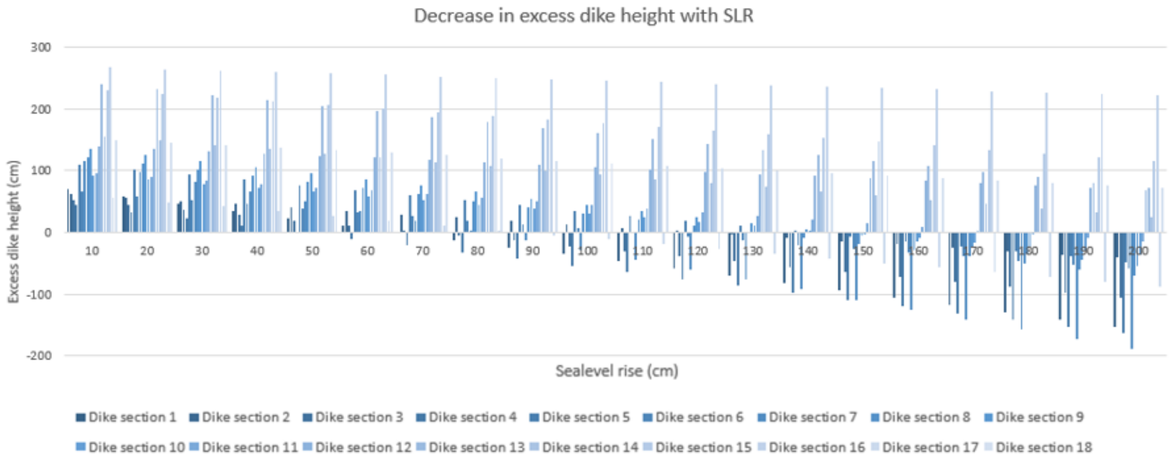

Figure 34 Decrease in excess dike height with SLR for the 1 l/s/m limit for each dike section (Excess-height of a dike implies that the height of the dike is higher than the hydraulic load calculated for that specific dike section).

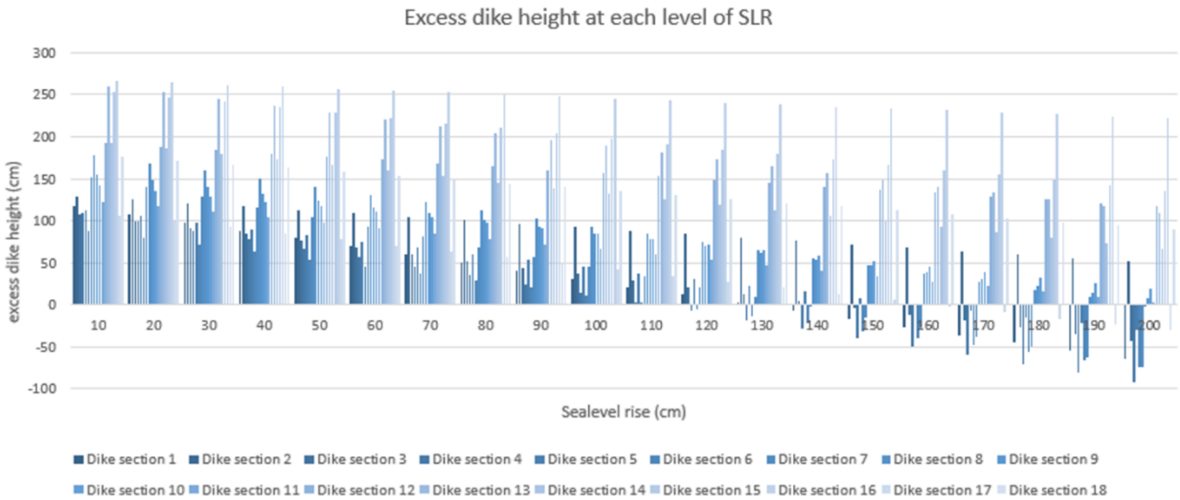

Figure 35 Decrease in excess dike height with SLR for the 10 l/s/m limit for each dike section (Excess-height of a dike implies that the height of the dike is higher than the hydraulic load calculated for that specific dike section)

To make the data more insightful for the actual case study area, two situations from Figure 34 are taken as an example and illustrated in Figure 36 and Figure 37. The evaluation points are at 100 cm sea level rise and 150 cm sea level rise. More of these illustrations at different amounts of sea level rise and the 10 L/s/m limit case can be found in Appendix K.

From both figures it can be concluded that there are four dike sections which are most vulnerable to the sea level rise (indicated with the orange heigh deficit label in Figure 36). Furthermore, it can be noted that the northernmost dike sections are the first to fail, indicating a weaker dike ring.

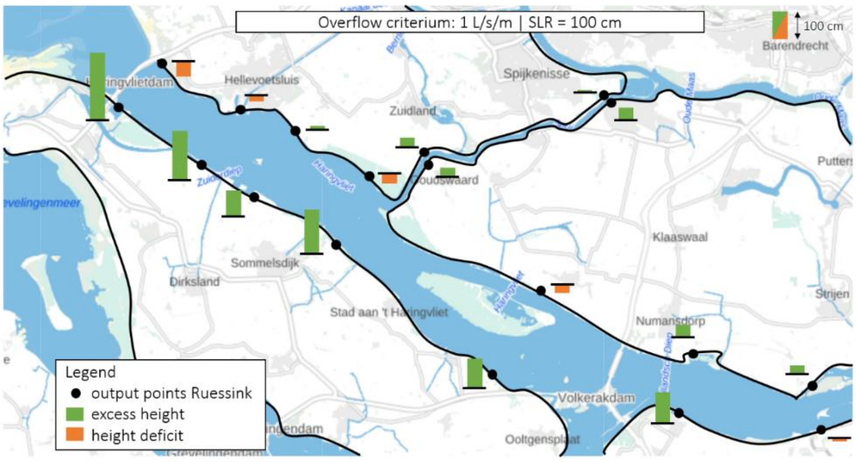

Figure 36 Excess dike height or height deficit in comparison to the actual dike per sea level rise for all the dike sections included in the Hydra-BS model (100 cm SLR, Overflow criterium 1 L/s/m). Scale in cm stated in top right corner.

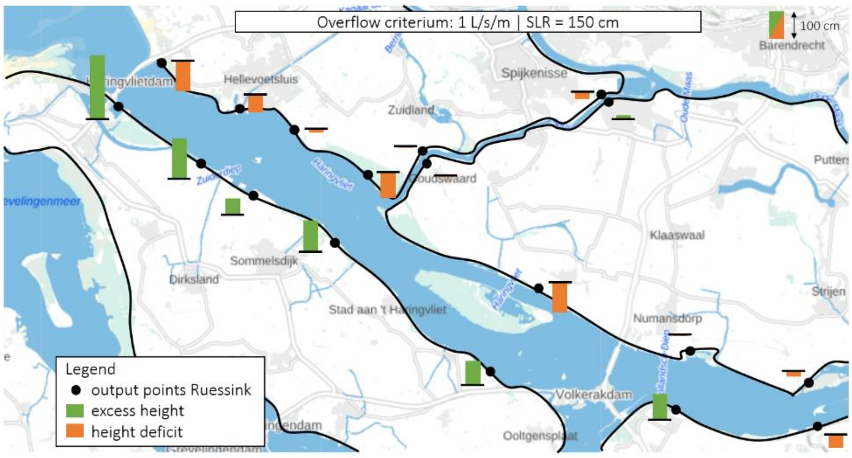

Figure 37 Excess dike height or height deficit in comparison to the actual dike height per sea level rise for all the dike sections included in the Hydra-BS model (150 cm SLR, Overflow criterium 1 L/s/m). Scale in cm stated in top right corner.

7.3.4 Insights on other functions and driver combinations for the Haringvliet sluices

As explained before, only Tipping Points regarding the flood safety function as a result of the driver sea level rise are investigated in this research in a quantitative way. The work of Ruessink also investigates other functions in quantitative estimations. The lifetime regarding strength and stability, fresh water supply and ecology are taken into account. To give more insight on these other functions and driver combinations, the conclusions of the work of Ruessink are summarized here.

The lifetime concerning strength and stability is based on expert judgement of an employee of Rijkswaterstaat who was involved in the design of the Eastern Scheldt barrier and the Haringvliet sluices. It is concluded that structural safety can be guaranteed up until a maximum sea level rise of 1 m. This maximum is based on expert judgement on an estimation of how much increase of load could be withstand by the NABLA beam. The increase in load is caused by the increase in static forcing resulting from the larger water level gradient over the sluice gates. This assumes that the average water level in the Haringvliet is kept at the current threshold levels.

For the lifetime considering fresh water availability two different types of salt water intrusion are investigated. The first mechanism is salt intrusion caused by the opening and closing of the Haringvliet sluices and the second mechanism is salt intrusion caused by backwards salt intrusion via the Spui. The expected end of life of the first mechanism is estimated to be at a sea level rise of 1 to 1,5 m in combination with a relatively long period of low river discharge (between 1500 and 2000 m^3/s). At this point the salt intrusion length is estimated to be too long and influencing fresh water boundaries significantly. For the second mechanism it is expected that at a sea level rise of already 0.5 meter the salt intrusion via the Spui could be a reoccurring problem during the summer months.

For the lifetime considering the ecology, it is focussed on the availability of migration possibilities for different species of fish. The available migration possibilities are based on how much the sluices are able to open according to the Kier Policy, i.e. the balance of available river discharge and keeping fresh water boundaries. It is concluded that the available migration possibilities drop significantly already in 2050 in the most extreme scenario and thus limiting the ecological benefits the current Kier Policy is meant to provide.

7.4 Conclusion on the Tipping Points in the timeline of the remaining life of the Haringvliet sluices

For the Tipping Point analysis of the Haringvliet sluices, existing models are evaluated and used to quantify Tipping Points due to the expected most dominant driver and function combination. The dominant combination, resulting from chapter 6, is the effect of sea level rise on the flood protection function. The result of the Tipping Point according to the model of Ruessink is at 87 cm of sea level rise. In the work of Ruessink, this amount of sea level rise is expected to occur in 2185 and 2105 for the two climate scenarios G_L and W_H respectively for the 50% confidence line. Using more recent climate projections the life time of the barrier is decreased by roughly 12 to 26 years, as the allowable sea level rise of 87 cm is already reached in 2093 and 2079 for the scenarios RCP4.5 and RCP8.5 respectively (50% confidence line). Other decision parameters for the functional requirement show that there is a large dependence of the Tipping Points on the decisions made. The consequences of choosing other values or limits for these decision criteria are presented. For example: altering the allowed overflow from 1 L/m/s to 10 L/m/s already makes a difference of 50 cm in the sea level rise the system could withstand. In the used climate scenarios this comes down to a difference of roughly 14 years extended life time (depending on which climate scenario is considered). Even though there is a large sensitivity of the Tipping Points on the decision parameters, making estimations for suitable criteria does provide valuable insights in the response of the system to sea level rise. Weaker points in the system can be defined, so that in the next step of the research these can be focussed on when considering suitable measures to elongate the life time of the Haringvliet sluices.

8. Elongating the remaining life of the Haringvliet sluices

After determining estimates for the possible Tipping Points of the Haringvliet sluices in the previous step, this chapter aims to prevent these Tipping Points by introducing life elongating measures. These measures are focussed at preventing Tipping Points following the analysed critical function and driver combination: Flood safety under the pressure of sea level rise. This chapter will elaborate on step 7, 8 and 9 of the research approach (chapter 3.3) and will conclude the analysis of the Haringvliet sluices.

In the first section of this chapter, life elongating measures for the Haringvliet sluices are proposed. In this, a distinction is made between life elongating measures following from more object or system-based measures and national strategies for the future of the Dutch Delta. The latter could either elongate the life time of the Haringvliet sluices, but could also shorten the life time. More on this in section 8.1. The effects of suitable life elongating measures are quantified and an Adaptation Pathway (as introduced in section 2.3) is used to visualize possible courses for the remaining life time of the Haringvliet sluices. The chapter is concluded by a conclusion concerning the elongation of the life time of the Haringvliet sluices.

8.1 Life elongating measures for the Haringvliet sluices

As described in this chapter's introduction, measures that can influence the life time of the Haringvliet sluices can be split into two different categories: Strategies for the bigger water system, i.e. future visions for the Dutch Delta, and measures focussed on the object or direct system itself. The difference between the two categories is not only the difference in scale of application, it is also about the uncertainty of application and the impact on the life time. Meaning that national strategies could have a large impact on the Haringvliet sluices, but the timing of the decision on those strategies and the exact implications are too uncertain to include as a concrete action in the Adaptation Pathways. For this part of the research, the focus lies on presenting mitigations to stretch out the life time of the Haringvliet sluices in such a way that it can continue to meet its requirements until the next big impact due to the decision-making process. In fact, these measures aim to prevent the system from reaching potential Tipping Points. Also, the national strategies could either have a negative or positive impact on the remaining life of the Haringvliet sluices, i.e. they could either elongate or shorten the life time. This is illustrated in Figure 38. The focus for this research and the Adaptation Pathway will be on the life time depicted by the black dotted line in Figure 38.

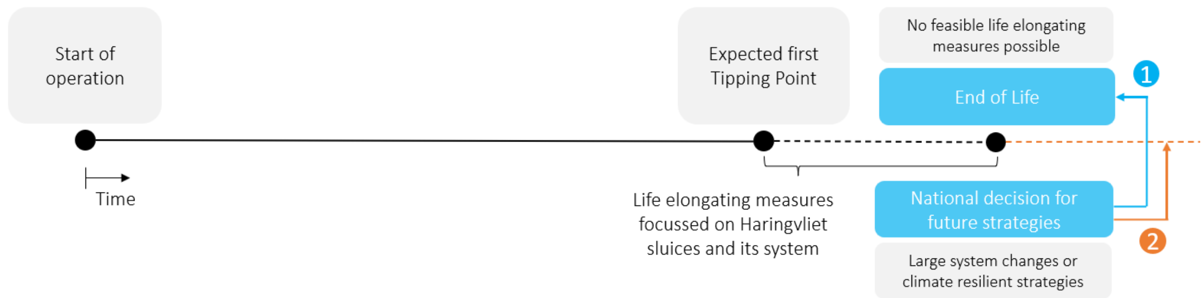

Figure 38 Possible positive or negative impact of national strategy decision making on the life time of the Haringvliet sluices. Focus for this thesis lies on the black dotted line, described as 'Life elongating measures focussed on the Haringvliet sluices and its system.

Elongating the life time of the Haringvliet sluices to a certain point in the future could be considered as providing a transitional period between the initial end of life (first expected Tipping point) and the implementation of new national strategies, providing needed time if decision making or resources are delayed.

Besides national strategies for the Dutch Delta or measures for the Haringvliet sluices themselves, other system alterations can impact the lifetime as discussed in chapter 6.4.3. The system alterations referred to here, are engineering changes, which could have an influence on the case study (replacement of other storm surge barriers, or realization of other hydraulic structures which influence the functions or boundary conditions of the Haringvliet sluices). Similar to the impact of the national strategies, these system changes could have either a positive or negative effect on the remaining life time. These system alterations are not taken further into account in the life elongating measures illustrated in the Adaptation Pathway in section 8.2, due to the uncertainty in their implementation (as reasoned in section 6.4.3).

8.1.1 Future strategies for the Dutch Delta affecting the Haringvliet sluices

End of life of hydraulic infrastructure can be considered dependent on the defence strategy or future vision of the Netherlands as a nation. The awareness of climate change and its consequence on sea level rise can alter this strategy. Research done by Deltares gives insight in what possible future strategies could be to deal with rising sea levels in the Netherlands (Simonovic et al., 2022). The report of Deltares presents four different long-term themed strategies: Protect-closed, protect-open, advance and accommodate (illustrated in Figure 39). The current strategy of the Netherlands could be considered leaning towards the category 'protect-closed'.

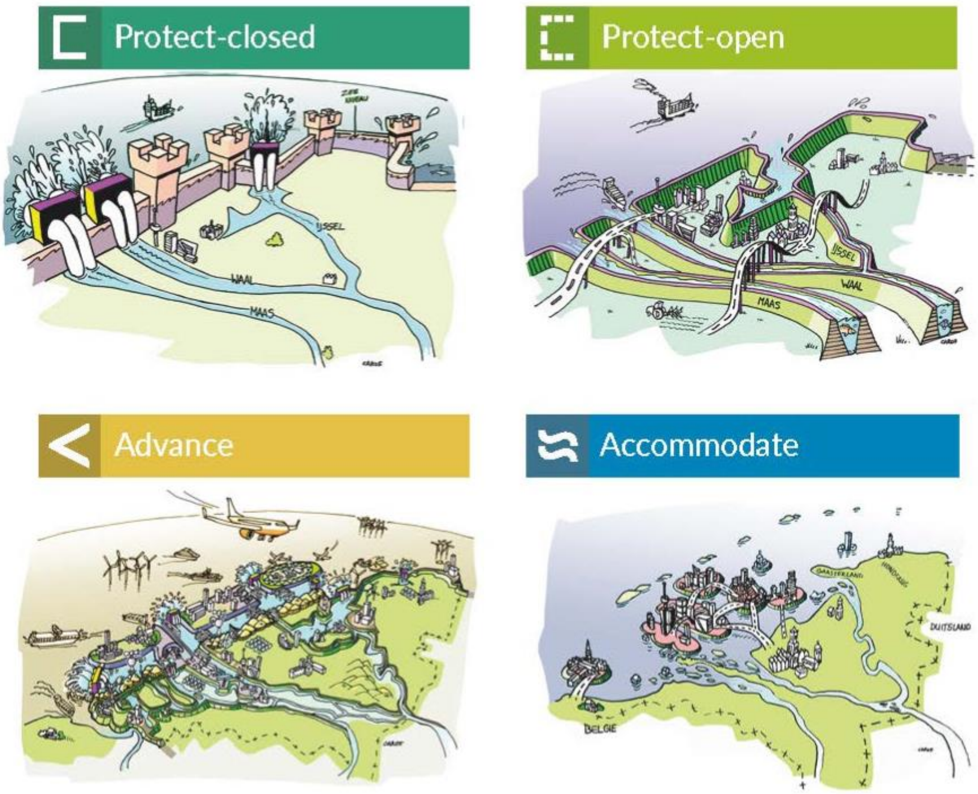

Figure 39 Four long term strategies to protect the Netherlands against rising sea water levels (Simonovic et al., 2022)

Each of these long-term strategies has its limitations regarding the maximum withstandable sea level rise, the technical feasibility, the social feasibility and the adaptivity it requires from the current system (Haasnoot & Diermanse, 2022). These strategies have different impacts on the functions or the demand on the Haringvliet sluices and could lead to end of life. In the work of Ruessink, the research used for the Tipping Point analysis in chapter 7, three different strategies for the Haringvliet sluices are proposed which could be categorized into the long-term strategies shown in Figure 39. The first strategy proposed by Ruessink is the removal of the Haringvliet sluices, letting the full North Sea tide back into the Haringvliet. The removal of the Haringvliet sluices as presented in the work of Ruessink could be considered 'protect open'. In line with the strategy of 'protect closed' are the other two plans proposed by Ruessink: Close off the Haringvliet with a dike or build a similar structure which is designed for newer hydraulic boundary conditions.

8.1.2 Description of life elongating measures for the Haringvliet sluices used in the Adaptation Pathway

As explained earlier, the life elongating measures for the Haringvliet sluices aim to stretch out the life time to allow time for new national strategies to be implemented for the Dutch Delta. The measures that will be applied follow from the Tipping Points analysis of chapter 7. The Tipping Point shows that as a result of rising sea levels, the water levels in the Haringvliet could rise to a critical level. The main consequence is that the dikes around the Haringvliet are not high enough at a sea level rise of 87 cm, if end of life is described as: The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter. The proposed measures aim to prevent the system from reaching the actual Tipping Points.

Possible life elongating measures can be categorized in physical changes made to the Haringvliet sluices, physical changes made to the system (e.g. the dikes), or changes in demands for either the sluice complex or the system. Physical changes to the Haringvliet sluices are not explored in this research, as the costs of potential measures could outweigh the impact due to the size of the structure. Decisions on these cost considerations are assumed to be out of the scope of this step of the analysis, as it would add a whole new dimension to the analysis. One of the considerations for exploring physical changes to the Haringvliet sluices would be if the costs could outweigh the benefits. Changing or increasing the retaining height of the gates could become costly due to the double gate system for all 17 openings. Another consideration in this is the available structural capacity when increasing the retaining height in other, non-replaceable elements. Besides the costs and structural capacity, an important consideration would be the feasibility of the construction challenges to replace or adapt the gates. Discharge capacity and flood safety must be guaranteed during these procedures. Longer storm seasons might impose a challenge.

Physical changes to the system that are explored more in depth are the elevation of the most vulnerable dike sections. Following the analysis in Chapter 7, the dike sections which are most vulnerable to rising sea levels are 1,4 and 7. If the sea level continues to rise the next set of critical dike sections is section 3 and 17. It is chosen to group these dike sections into two different mitigation actions in the adaptive pathway and make a distinction between reinforcing all the critical dike sections at once or dividing it into two steps. An investigated change in demand is the increase in the allowed overflow over the dike to 10 L/s/m (initially 1 L/s/m). This action would also include a physical change to the dikes to be able to withstand these new loading conditions (i.e. revetments need to be improved if necessary). A fourth action that is explored is the expansion of the water storage capacity outside the Haringvliet. Currently, water can already be stored in the Volkerak Zoomlake in high discharge conditions when the Haringvliet sluices are closed. The actions taken into account for the Adaptive Pathway are summarized in Table 28. The mentioned dike sections are illustrated in Figure 40. The effect of the actions on the life time of the Haringvliet sluices are quantified in the next section.

Table 28 Life elongating measures based on the flood protection function taken into account in the Adaptive Pathway analysis.

Action	Category	Additional information
Action A: Elevation of dike section 1, 4 and 7	Physical change to system	Dike elevation is 1 meter
Action B: Elevation of dike section 1, 3, 4, 7 and 17	Physical change to system	Dike elevation is 1 meter
Action C: Accept overflow of 10 L/s/m	Requirement change to system	Dike revetments will be upgraded where necessary
Action D: Expand water storage capacity	Functional change	-

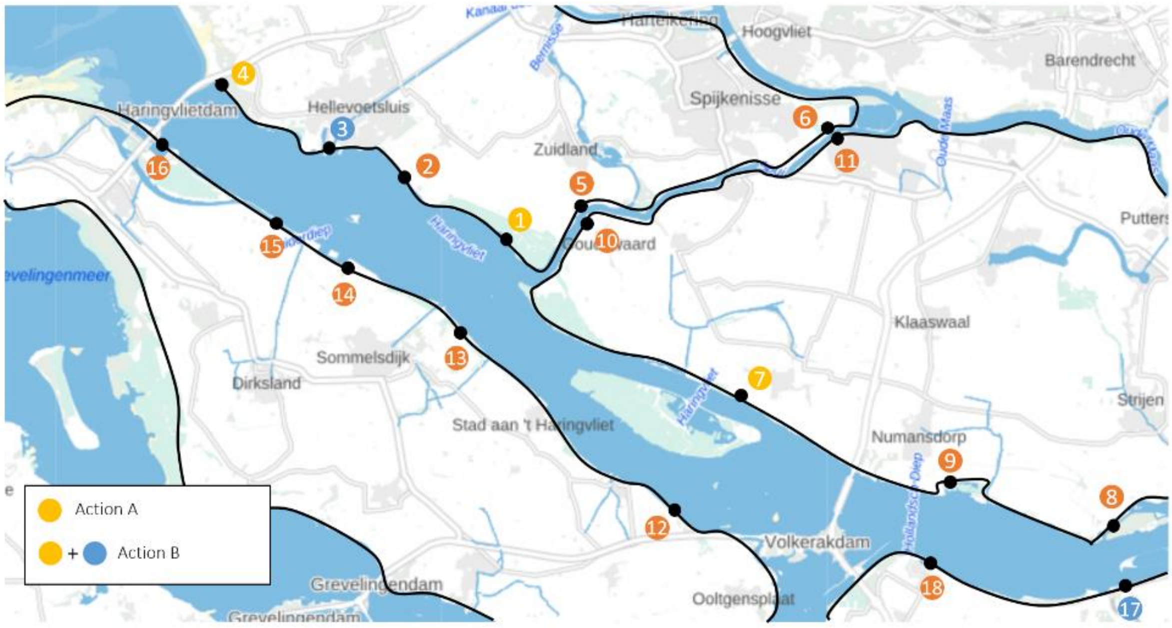

Figure 40 Relation of Action A and Action B to the specific dike sections in the Haringvliet system.

Other possible measures to elongate the life time of the Haringvliet sluices could be to focus on decreasing the impact of flooding. Examples of this are improving evacuation protocols or increase flooding awareness in vulnerable areas to decrease damages. Improving these more informal actions, could lead to a higher accepted probability of exceedance for critical dike sections. This is not further taken into account in the quantification of the measures for the Haringvliet sluices.

8.2 Adaptation Pathways for the remaining life of the Haringvliet sluices

To find the possible Tipping Points of each of the measures (A-C) the same calculation method is used as in chapter 7. The criteria for end of life is again set at: The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter. For the representation of the Adaptation Pathway, only measure A to C is taken into account.

Since all the four actions could be implemented in almost all possible combinations relative to each other, including option D would give unreadable results. To show the impact of including more actions into the adaptation pathway, it is referred to Appendix L in which an example of an added branch of option D is shown. The goal of adaptation pathways, as described in chapter 2, is to give decision makers a clear overview of the mitigations and their effects in the long term. Therefore, including too much mitigations would be counterproductive in reaching this goal. The fourth action (action D), is assumed to be an extra mitigation which could be deployed at any time, but is most likely to be the last action due to the implications it has on the rest of the Dutch Delta. These implications will be discussed in more detail in the next paragraphs. In Figure 41 the Adaptation pathway for action A to C is presented, including the timeline for climate scenarios RCP4.5 and RCP8.5. Only the middle bounds of the climate projections are used to provide a first estimate. The Adaptive Pathways of the full bandwidth of the climate scenarios (lower, middle and upper bound) can be found in Appendix L.

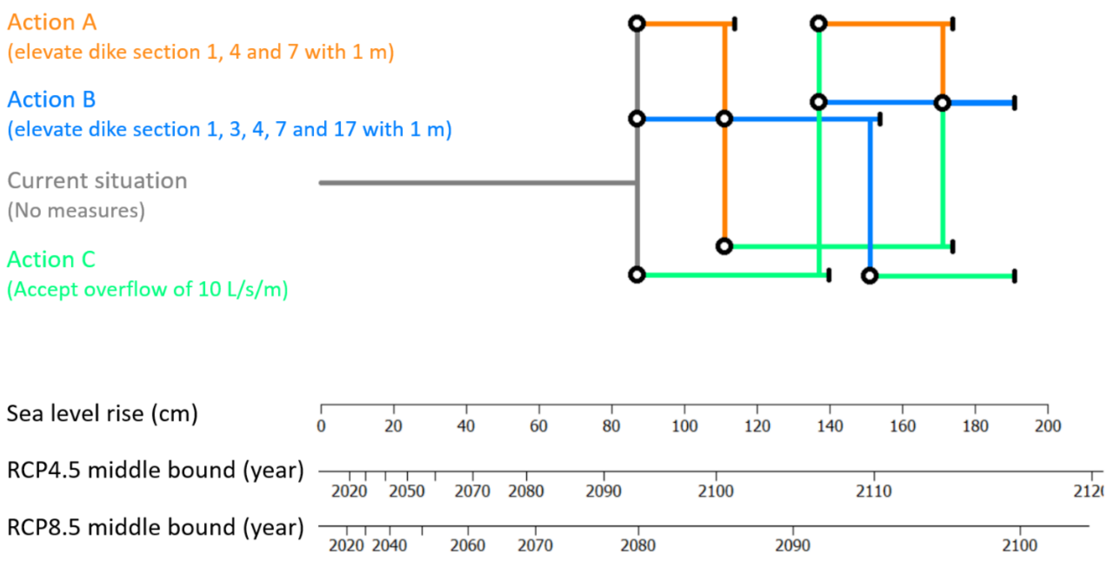

Figure 41 Adaptive pathway for the Haringvliet sluices based on sea level rise and the flood protection function.

From the adaptation pathway in Figure 41 can be concluded that the maximum elongation of the Haringvliet sluices based on mitigation action A to C is to 188 cm sea level rise. By comparing this with the initial Tipping Point resulting from chapter 7 (87 cm) it can be concluded that these measures could postpone the potential Tipping Point by roughly 1 m additional sea level rise. For the climate scenarios considered this results in an elongation of the remaining life time of 2117 or 2100 year, for RCP4.5 and RCP8.5 respectively (middle bound values).

The most remarkable observation based on the results is that by switching to action C (accept overflow 10 L/s/m) different dike sections become critical. This is due to the separate computation of the hydraulic load ratio as a response to 1 cm sea level rise for the 1 L/s/m and the 10 L/s/m case. For dike section 6 specifically, the response to rising sea levels in the 10 L/s/m case is higher than in the 1 L/s/m case. Therefore, dike section 6 should be included in the elevation actions A and B in the Adaptation Pathways when considering switching to action C.

The Adaptation Pathway in Figure 41 gives a clear overview on the different future courses for the Haringvliet sluices according to the three proposed mitigation actions. In Figure 42 the contribution of each action in the different paths is shown. From Figure 42, can be seen that the absolute effectiveness in terms of sea level rise in cm is dependent on the sequence of the implementation of the actions. However, the total effect of combining all the actions remains the same.

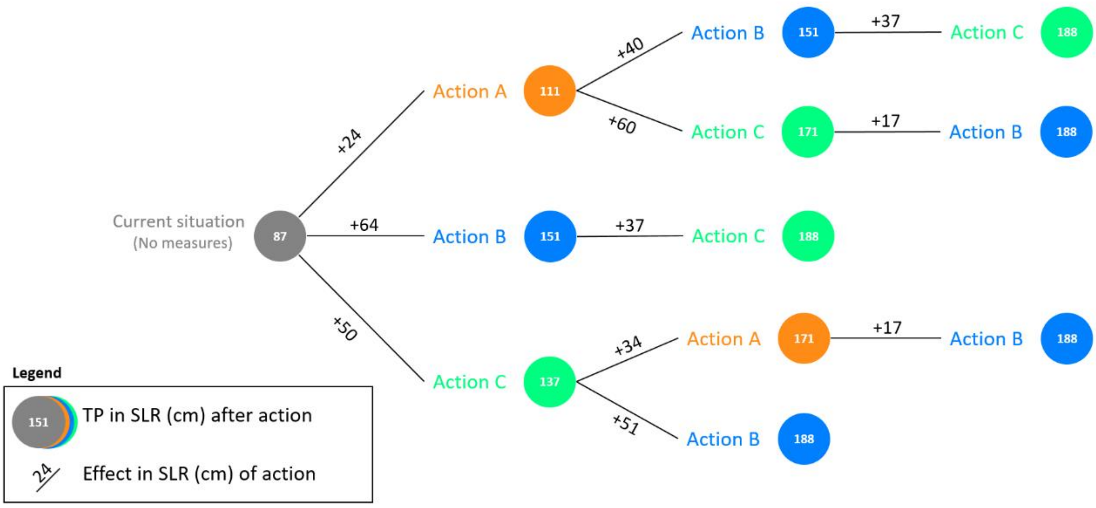

Figure 42 Different possible paths from the adaptation pathways to elongate the life time of the Haringvliet sluices including the numerical values for the additional sea level rise the system can take for action A, B and C.

For quantifying the effect of the expansion of the water storage capacity (action D), the current water storage on the Volkerak Zoomlake is investigated first. It is estimated that the current storage capacity in the Volkerak Zoomlake has the ability of lowering the water level in the Haringvliet by about 0,5 m (Rijkswaterstaat, 2012). To realise this water storage in the Volkerak Zoomlake, different dike sections have been reinforced to be able to withstand higher water levels in the lake. The normal water level in the lake is kept roughly around NAP + 0 m. It is assumed that it is not possible to increase the water storage inside the Volkerak Zoomlake, but that more storage needs to be realised elsewhere. The current storage surface area and other possible water storage options are illustrated in Figure 43. Extra water storage could be realised by storing water from the Volkerak Zoomlake into the Grevelingen lake and Eastern Scheldt, or by discharging more excess water into the Western Scheldt. Since the system is currently still begin adapted to accommodate the water storage in the Volkerak Zoomlake it is chosen to only apply this extra mitigation action as a final action in the Adaptation Pathway. This implies that sea level rise already has risen to a certain level and thereby it can be assumed that other water systems in the delta could have problems or higher water level as a result of dealing with this. Even more so, higher levels in other water systems or at sea in general could affect the capacity of the discharge sluices used in increasing the storage capacity. Taken this all into account it is estimated that expanding the water storage capacity could only lead to a maximum of 20 cm reduction in the water levels of the Haringvliet. It has to be noted that this action would have the same effect for each moment of employment and could be chosen to implement at any time.

Figure 43 Possible extra water storage areas, dashed area illustrates current water storage in the Volkerak Zoomlake (Edited from (Rijkswaterstaat, 2012))

In the computation for the new Tipping point a one-on-one reduction of 20 cm is taken into account to include the effect of the water storage expansion (the one-on-one reduction relates to the hydraulic load and the sea level rise the system can take). This results in an elongation of the lifetime as illustrated in Figure 44. The system is now able to take up to 214 cm of sea level rise before reaching an estimated Tipping Point. For the climate scenarios considered this results in an elongation of the remaining life time. The end of life is moved to 2120 or 2102, for RCP4.5 and RCP8.5 respectively (middle bound values).

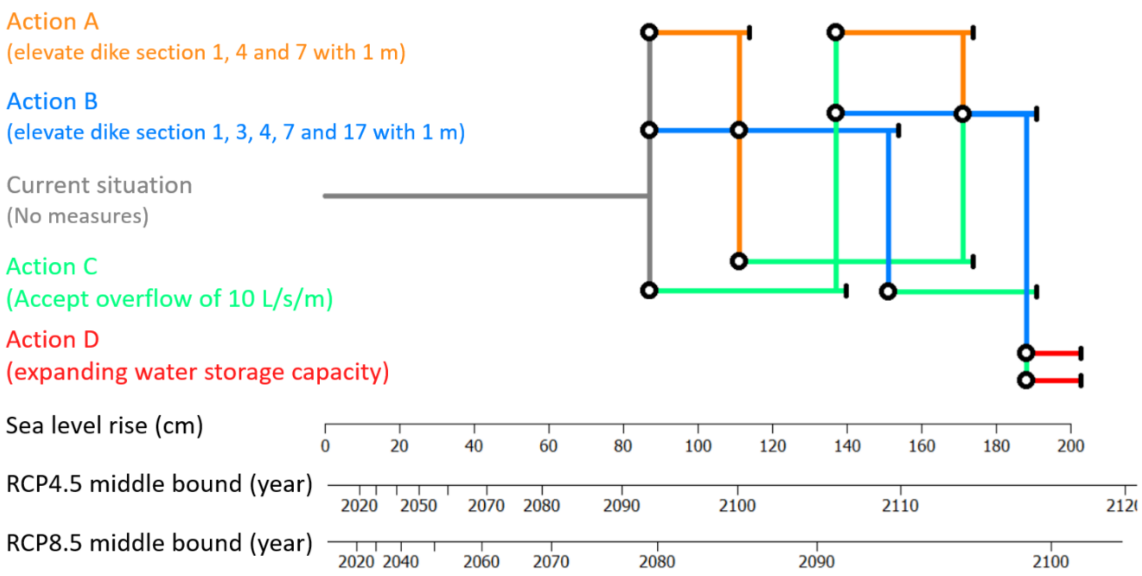

Figure 44 Adaptive pathway for the Haringvliet sluices including expanding water storage in the last stage.

The implications and applicability of realising this extra water storage have to be further investigated. It has to be taken into account that all mitigation actions are part of a larger system, and consequences of applications have to be investigated further.

8.3 Conclusion on the possible courses for the remaining life time of the Haringvliet sluices

Measures that influence the remaining lifetime of the Haringvliet sluices can be split into two different categories: Strategies for the bigger water system, i.e. future visions for the Dutch Delta, and life elongating measures focussed on the object or direct system. These future strategies for the Dutch Delta could impact the remaining life of the Haringvliet sluices either in a positive or negative way. As these strategies and their implementation are very uncertain and dependent on decision makers, it is chosen to only investigate mitigation measures focused on the Haringvliet sluices and its system. The actions proposed in the Adaptation Pathways map follow from the Tipping Points defined in Chapter 7. It is chosen to present the possible combinations of only three out of four actions. This to keep the pathway diagrams simpler and more structured. The four actions consist out of two different sets of dike section elevations, allowing more overflow and creating more external water storage. Using the first three actions the estimation for the end of life of the Haringvliet sluices can be elongated to withstand 188 cm sea level rise. By comparing this with the initial tipping point result in chapter 7 (87 cm), it can be concluded that these measures could postpone the Tipping Point by roughly 1 m additional sea level rise. For both the initial as the adaptative pathway tipping points the criteria for end of life is set at: The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter. It is chosen to present the possible combinations of only three out of four actions. This to keep the pathway diagrams simpler and more structured. Including the fourth action, expanding water storage possibilities, would lead to an additional 20 cm acceptable sea level rise, but the implications to surrounding areas of this fourth action need to be investigated further.

9. Discussion

The discussion is subdivided into a discussion on the methodology, i.e. the more overarching topics, and a discussion on the assumptions and limitations of the results per step in the analysis on the Haringvliet sluices.

9.1 Discussion of the results

The research approach consists out of multiple steps and each step can be seen as its own analysis, contributing to the main research goal. Each sub-analysis has its individual results and therefore its individual assumptions, limitations and critical remarks. The assumptions and limitations of previous steps could have a significant impact on other steps in the analysis. The discussion of the results is therefore subdivided in sections corresponding to the steps in the analysis. The scope definition and the impact of it is a reoccurring theme in these discussions. The scope definition of each analysis step is dependent on the total scope of the research and on how the sub-analysis fits into this, i.e., the level of detail has to be appropriate to fit the research goal. The core of the analysis of the Haringvliet sluices is described in chapter 5 to chapter 8, hence these will be the topics of the discussion.

Functional and structural analysis of the Haringvliet sluices (chapter 5)

In the functional and structural analysis, the functions of the Haringvliet were defined and potential weak structural elements were identified. The first critical point on this sub-analysis is that not all functional requirements follow from formal laws or guidelines. When a formal functional requirement is not available, an assumption on a suitable requirement has to be made or it can be left undescribed. If these functions will become critical in further steps of the analysis, it could be investigated on how to quantitatively specify the requirement. It is important to realise that although some functions are harder to describe in parameters and threshold values, leaving them undescribed could lead to a false view on their importance. For example, it is decided in this research that only a few parameters regarding the ecology function are taken into account, due to the scope limitations of this research. This does not mean that other ecology parameters, beside fish passage and salt intrusion, are not important for the system. As for the functions which are described formally, it has to be kept in mind that these functions descriptions, requirements and their importance could change over time. This would affect all later steps in the analysis.

In the structural decomposition, the Haringvliet sluices and the bridge deck on top are analysed. The assumption to not include the Goeree navigation lock or the dike sections of the Haringvliet dam in this analysis is made to tailor the analysis to the scope. The Goeree navigation lock could fit into the analysis without needing large additions, as the main construction materials of the navigation lock are similar to the ones of the Haringvliet sluices. Adding the dike sections to the analysis would lead to the addition of other deterioration mechanisms. This would expand the driver analysis in the next step as a result. From the case study description, it was concluded that the dikes of the Haringvliet dam were in good condition and were not expected to be governing in the end of life of the Haringvliet sluices. The other dikes in the system, the dikes around the Haringvliet, were also not taken into account. As the dikes are a focus point in the determination of the Tipping points and in the Adaptation Pathway, it is advised to add a technical decomposition of those dike sections into further analyses and consider more failure mechanisms then only overtopping.

Functional requirements in general or consequences are referred to as belonging to the Haringvliet sluices and its system throughout the analysis steps. In the function descriptions, but also in later steps, there is no clear difference in requirements for the Haringvliet sluices themselves or for the entire water systems. For a more formal application of this analysis step, an improvement on this could be made to differentiate between functional requirements for either the Haringvliet sluices themselves (the object) or functional requirements for the system.

External drivers which influence the remaining lifetime of the Haringvliet sluices (chapter 6)

An important result of the external driver analysis, is the overview matrices showing the expected impact of the driver and function combinations, but also for the combinations of the drivers and technical components (Table 18 and Table 19). The impacts are distinguished by their importance or dominance compared to others. From this is concluded which combinations could be valuable to analyse in follow up steps of the research and define quantitatively. The colour coding used for the overview in the matrices (to highlight the importance or the threat) is dependent and influenced by the following; Firstly, it is dependent on the level of detail of the analysis performed on the expected future changes of the drivers and their impact on the case study. A quick scan of the drivers fits the scope of the research goals, but could be too simplistic for other applications of this method. Secondly, the importance of each function is assumed to be related to the initial goals set for when the Haringvliet sluices were constructed. This could potentially lead to an overestimation in the dominance of the impacts of flood safety related functions and drivers. It is recommended to have an additional expert assessment outside the field of hydraulic engineering to decrease any uncertainty on this. Thirdly, the colour coding of the matrices is not static, as functions, technical state and driver impact could change over time. The impact description is expected to be the same, but the assigned colour, and thus severity, could be revised. Besides these critical notes on the colour coding of the impacts, it can be noted that the matrices provide an important overview of the system for future reference. It is not achievable in most projects or analysis of hydraulic structures to look at all the relations and implications simultaneously, confirming the need for assumptions. The matrices allow to check the severance of possible implications of the assumptions made in the results in further analysis steps.

The analysis on the external drivers focusses on the importance of larger system changes and socio-economic drivers. It is argued why in further steps in the analysis these drivers where not taken into account directly, but that it is key to be aware of possible plans and the consequences on the Haringvliet sluices regarding these drivers. The main argument for excluding these drivers from further analysis is based on their large uncertainty. From this can be concluded that it is important to develop methods similar to the framework of Vader et al. (2023) and the approach of Haasnoot (2013), because these could be the tools that could help in dealing with these larger system changes and their uncertainty. At the moment a large change occurs in the future, a structured approach can be applied to assess the specific impact on the remaining life time of the structure. This does not only apply when changes influence the case study negatively, therefore reaching its end of life earlier, but also when changes influence the system positively, possibly making other external drivers and function combinations more governing. The analysis can be used to show if planned mitigation actions or large maintenance operations could be postponed, due to the positive affect of system changes. This would then allow resources to be redirected to other critical projects.

In this research it is mentioned that mobility availability regarding navigation and traffic are not part of the scope. Even though it is outside of the scope of the analysis, it could become a critical aspect of the performance of some of the functions of the Haringvliet sluices. Various physical drivers and socio-economic drivers could affect the functioning of the navigation lock and the traffic connection provided by the Haringvliet sluices. Examples of this are; rising sea level effecting the available draft under the bridge deck, causing the traffic to be stopped more often, which in turn could become more problematic if the traffic flow would increase in the future. It could be investigated to optimize the interaction between the use of the navigation lock and the bridge by limiting the navigation passages during rush hours. In extreme impact situations, the usage of the outer and inner port could be re-evaluated. Quantifications of the effect of these combinations of drivers and functions can be achieved by using the methodology presented in this thesis.

Tipping Point analysis of the Haringvliet sluices (chapter 7)

For the Tipping Point analysis in chapter 7 it is chosen to investigate only one of the possible governing combinations of drivers and functions. This could falsely imply that the flood safety functions and rising sea level driver causes the first Tipping Point in the remaining life of the Haringvliet sluices. All other expected governing combinations should be quantified by further analysis, to be able to make any final conclusions on which Tipping Point has to be tackled first. From the work of Ruessink (2019) is concluded that the functions and drivers analysis in that research results in Tipping Points in a similar timespan, i.e. it is stated that the functions and driver combinations would have Tipping Points not further apart than 20 years. From this can be concluded that the sense of urgency to make adaptations to the Haringvliet sluices could be quantified by only addressing one of the critical combinations, but to elaborate on which Tipping Point to expect first, all the critical combinations need to be analysed.

For determining the Tipping Points in the analysis, existing models are used to quantify the Tipping Points. Using existing models results in uncertainties in the quantification of the expected Tipping Points. This research tries to decrease the uncertainties by validating or discussing assumptions and limitations of the used model. Open access to the model would improve the reliability in using the results and would create more flexibility in tailoring the results to a specific analysis.

One of the expected most impactful assumptions made in the used model is the choice to schematize the Haringvliet as a basin when determining the critical water levels in the case of extreme storms and overflow over the Haringvliet sluices. This underestimates the impact on the water levels in the hinterland, which could become critical at an earlier moment. It has to be noted here that the SOBEK calculations were performed taking into account the real geometry of the system and only the assumption of the basin was made when translating the overtopping volumes to the effect on the water level in the Haringvliet. An assessment has to be done on the implications on the hinterland regarding the flood safety function. Another important underestimated impact of the analysis, caused by the scope definition, is the increasing flow velocities in the Spui when there is a large water level difference between the Haringvliet and the Nieuwe Waterweg, which has not been taken into account. How the Spui is located in the discharging system of the Dutch Delta is shown in Figure 8. The direction of the flow of the water is dependent on the water level difference between the Haringvliet and the Nieuwe Waterweg, and could quickly change directions. The coupling of the system of the Maeslant barrier and the system of the Haringvliet sluices via the Spui could be investigated further.

A technical assumption is made in the calculations of the Tipping Points by assuming the overflow conditions over the Haringvliet sluices. The resistance of the structure against these extreme conditions of full overflow has to be reassessed. Other technical or structural implications could lead to the technical end of life of the Haringvliet sluices caused by the assumed allowed overflow. For example; the overflow could cause turbulence and thus scour of critical places in the bed protection of the Haringvliet sluices, or could increase the forcing in the gates. The implications of such an overflow scenario should be further investigated.

Adaptation Pathways analysis on the Haringvliet sluices (chapter 8)

The goal of the Adaptation Pathway is to provide a clear overview on the possible paths for the remaining life time of the structure, created by suitable life elongating actions. From the analysis it is concluded that a maximum of three actions could be visualized to prevent the Pathways from becoming too complicated. The fourth proposed action is therefore seen as a last resort in elongating the life time. It can be questioned here, how realistic it is to apply action four as the final action to elongate the lifetime (action four proposes to expand the water storage capacity), as in future conditions where sea levels have risen already, other water systems will have their own individual response to it. Expanding the water storage to reduce the water level in the Haringvliet to other water systems, could be shifting the problem elsewhere. Therefor it is reasoned in chapter 7 that taking this into account the action can only provide a limited amount of extra water storage (a reduction of 20 cm in the Haringvliet. It should be investigated how to optimise the activation of this fourth action in the time line of the Adaptation Pathways.

In the analysis of the Adaptation Pathways, it is chosen to only provide an overview of the possible pathways for the Haringvliet sluices. A preferred pathway could be identified by using different scoring criteria, like costs, as concluded from the literature study in section 2.4. This could be an additional step in the research approach, but for the scope of this research it is chosen to not make any assumptions on the preferred path and leave the result more advisory. Another additional step could be the addition of decision points. Proposed mitigations measures in the Adaptation Pathway are assumed to be activated before the Tipping Point arrived, this to make sure the structure can comply to its demands continuously. It could be interesting to look into the added value of adding decision points to the Adaptive Pathways, with the intension of marking the moment in which decisions need to be made on the mitigation measure to allow for sufficient time for its implementation.

The result and the impact of the Adaptation Pathways is dependent on the use of climate change projections. To make the Adaptation Pathways more generally applicable, it is chosen to link the Tipping Points to the amount of sea level rise first, before coupling them to time stamps using climate change projects. For this research it is chosen to use a mild and a more extreme climate projection to define estimates for the end of life of the Haringvliet sluices. The choice on these scenarios could impact the conclusion of the results significantly. Reporting an objective sense of urgency on the end of life of an important hydraulic structure like the Haringvliet sluices, is a difficult task when choosing and using different climate scenarios. One could argue if the analysis would then benefit from not including a choice in climate scenarios, but only link the tipping points to raising sea levels. In the next section the results for the Tipping Points in different climate projections are provided, to shown the sensitivity of the choice of climate scenario.

The use of sea level rise projections (chapter 7 and chapter 8)

The estimations for the remaining life of the Haringvliet sluices, when expressed in time, is dependent on sea level rise projections. In chapter 7 there is made a comparison between the climate projections used in Ruessink (2019) and the projections used by this thesis. Ruessink (2019) uses the G_L and W_H scenarios from the KNMI'14 report (Klein Tank et al., 2015), which can be seen in Figure 31. For this research the RCP4.5 and the RCP8.5 from the projections of Le bar are used, which can be seen in Figure 32. These projections could chronologically be placed in between the KNMI'14 report and the Climate Signal'21, as explained before. The data was available up to the year 2100, after which it is chosen to extrapolate the data using a 4^{th} order polynomial fit. For a further comparison to show the impact of which climate scenario to use when presenting results, climate scenarios from the new IPCC report (AR6) are used. Only the 50% confidence lines are compared.

First, the initial Tipping Point of 87 cm sea level rise is compared for the different climate scenarios (resulting from chapter 7). This is approximated by looking at the expected year the AR6 scenarios reach a sea level rise of 90 cm (results for increments of 10 cm are used in the data). The results are shown in Figure 45. From Figure 45 can be concluded that G_L and W_H scenarios from KNMI'14 are similar to the SSP1-2.6 and the SSP5-8.5 respectively. It can be seen that the RCP4.5 and the RCP8.5 from the projections of Le bar are situated on the left side of the predictions for the AR6 scenarios, confirming earlier statements that the used scenarios are on the more extreme side of sea level rise predictions. The RCP4.5 results are similar to the SSP5-8.5 Low Confidence results, in which the 'Low Confidence' refers to the uncertainties in behaviour and impact of ice sheet instabilities NASA (n.d.). The RCP8.5 results are similar to the upper boundary of the SSP5-8.5 Low Confidence scenario.

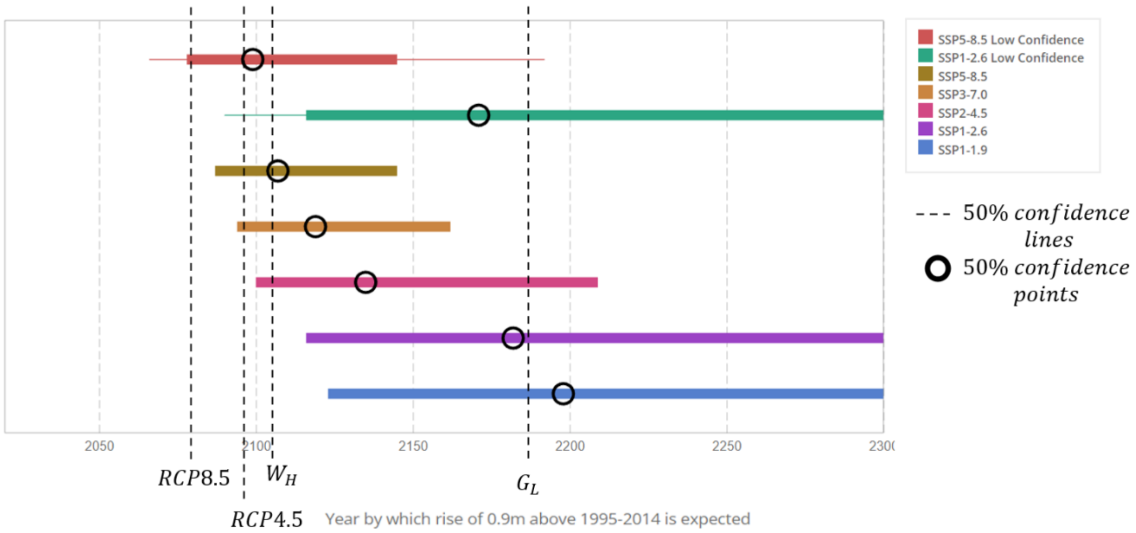

Figure 45 Comparison of the year in which 90 cm sea level rise is expected for climate scenarios from KNMI'14 , projections of Le bar and the IPCC AR6 scenarios. Adapted plot from Adapted plot from sea level projection tool NASA (n.d.).

Comparing the RCP4.5 scenario used in chapter 7 and chapter 8 with the SSP5-4.5 scenario, it can be concluded that there is roughly a difference of 40 years. When looking at the two lowest emission scenarios of the IPCC AR6 climate projections (SSP1-1.9 and SSP1-2.6), the Tipping Point of reaching 87 cm sea level rise, could be expected in the range of 2180 – 2195, which is roughly 100 years later then the predictions for the RCP4.5 (2093) and RCP8.5 (2079) scenarios. From this can be concluded that the ranges of climate projection can differ significantly and it is therefore important to place the used climate scenarios into a larger spectrum of scenarios to allow for interpretation of the results.

Second, the final result for the Tipping point of the Haringvliet sluices after applying the mitigations actions from chapter 8 can be compared with the IPCC climate projections. The sea level rise corresponding with this Tipping point is 188 cm and for easy data excess this is approximated by looking at the expected year the AR6 scenarios reach a sea level rise of 190 cm (results for increments of 10 cm are used in the data). The results are shown in Figure 46.

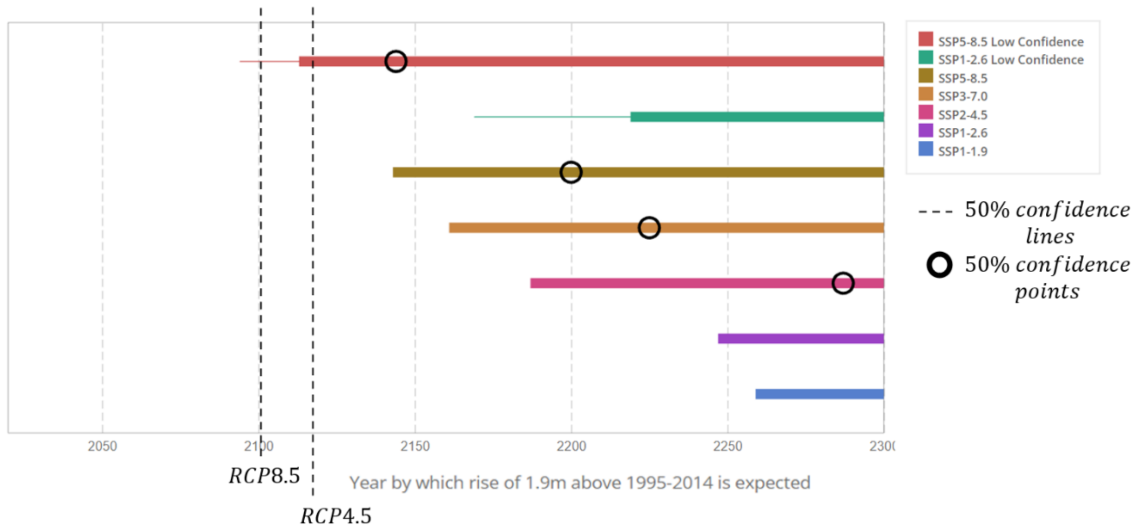

Figure 46 Comparison of the year in which 190 cm sea level rise is expected for climate scenarios from the projections of Le bar and the IPCC AR6 scenarios. Adapted plot from sea level projection tool NASA (n.d.).

From Figure 46, it can be concluded that comparing the RCP4.5 and RCP8.5 to the most extreme projections of the IPCC AR6 scenarios (SSP5.8.5 Low Confidence), there is already a difference of roughly 30 to 40 years in the expectancy of when 190 cm sea level rise is reached.

From this can be concluded that the estimations for the life time of the Haringvliet sluices are significantly dependent on the chosen climate scenarios and it should be carefully considered which scenarios to use when presenting the results. Showing a comparison with other scenarios creates a better representation of the results.

9.2 Discussion of the methodology

For the methodology of this thesis two existing method are combined to create a full system analysis of critical hydraulic structures and provide insight into the estimated remaining life time, as well as how to create adaptivity within the life elongation measures.

The target hydraulic structures for this methodology are complex, making the proposed analysis a significant task. The case study of the Haringvliet sluices proves to be suitable to test the performance of the methodology on a complex system. For the analysis to stay within scope, decisions on the level of detail of the investigation need to be made. This requires a balance between describing aspects of the analysis quantitatively and qualitatively. The level of detail and the ratio between quantitative and qualitative analysis in the methodology differs per step, the level of detail and thereby the scope description is the largest in the analysis of chapter 5 and chapter 6 in which the functional and technical decompositions are performed and the influence of external drivers is investigated. This work highlights the necessity to weigh the quantitative versus the qualitative approach. Future research should carefully evaluate which type of analysis is the most applicable per step in the analysis. The validity to choose either approach highly depends on the investigated function or system and the required accuracy of the produced results.

The model by Ruessink (2019) introduced in chapter 7, describes a similar analysis on the end of life of the same case study as this research. By Ruessink the same dominant and governing combinations of functions and drivers are found using a less extensive analysis. It could be argued if a more extensive analysis adds value and is necessary to come to the expected causes of the tipping points. Even though the work of Ruessink and this research arrive at the same conclusions on the governing parameters, it cannot be concluded that this is the case for other case studies. By applying a more detailed analysis the most dominant combinations can be found with more certainty, as all the other reasons to end of life are investigated. This decreases the chance that some mechanisms are overlooked. Another benefit of a detailed analysis is the addition of the matrices of chapter 6. These provide a tool to directly check the implications of changes in the boundary conditions on all the elements in the system (in a qualitative way). This could also be helpful in decision making regarding technical repairs. It can be checked if there is added value in increasing the capacity or strength of the element, based on functional expected future impacts.

A similarity in results can also be found between the most important drivers in the analysis of the Hollandse IJsel barrier in the work of Vader and the analysis of the Haringvliet sluices in this thesis. Both structures are storm surge barriers and are used as a case study for the framework of Vader. As a result, the functional requirements of both structures are significantly affected by rising sea levels. One could argue that the same driver would be dominant for other storm surge barriers and as a result shorten the analysis. It would be advised to still apply the full framework for a new case study, as the target structures are multifunctional objects, and it cannot simply be assumed that sea level rise is the most impactful driver. It can be concluded that sea level is expected to be one of the important drivers, but other drivers should not be ignored.

By using Adaptive Pathways, future conditions are taken into account to allow for some adaptivity in the elongation of the remaining life time of the structure. The proposed adaptation measures are based on the most critical points in the system based on the current case description and conditions. In future conditions, other combinations of driver and functions could become more critical due to changes in demand or changes in boundary conditions. This would change the cause of the Tipping Points and the actions within the Adaptive Pathway. From this follows the importance of methods of the one applied in this research; by providing detailed in the first steps of the analysis, a 'base' is formed which can be used for future iterations of the analysis to explore other critical combinations. This is illustrated in Figure 47.

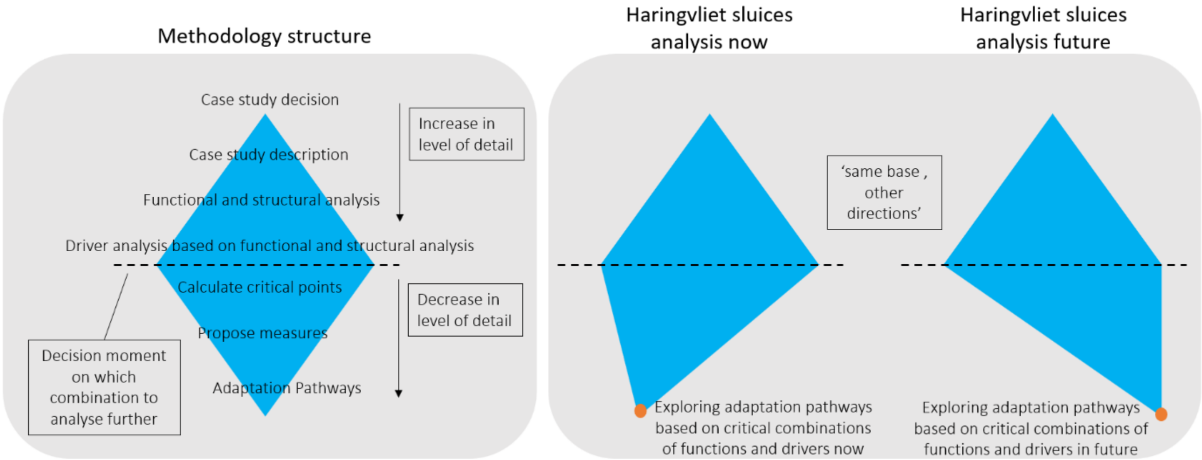

Figure 47 Illustration of the iterative usage of the methodology in changing future conditions

Besides the proposed iterative usage of the method as described in Figure 47, there is a second recommendation that can be made on the application on the method. It is recommended to add an extra feedback loop at the end of step 9, after the adaptation pathways are used to compose the final results, to the overview of all the functions and external drivers as a result of step 4. The final Tipping Point in this research is estimated to be at 188 cm sea level rise, based on the flood protection function. Mitigation actions are combined to reach this 188 cm as an elongated life time for the Haringvliet sluices. However, it has to be investigated if for these values of sea level rise other combinations of functions and drivers might become more dominant over time and are in need of adaptations themselves then the initial investigated combinations. For both the implications on the system caused by the mitigation actions as well as the magnitude of sea level rise considered in the life elongation, it is advised to look back at the full overview of all the functions and external drivers as a result of step 4. This is visualized in Figure 48 by using the research design presented in chapter 3.

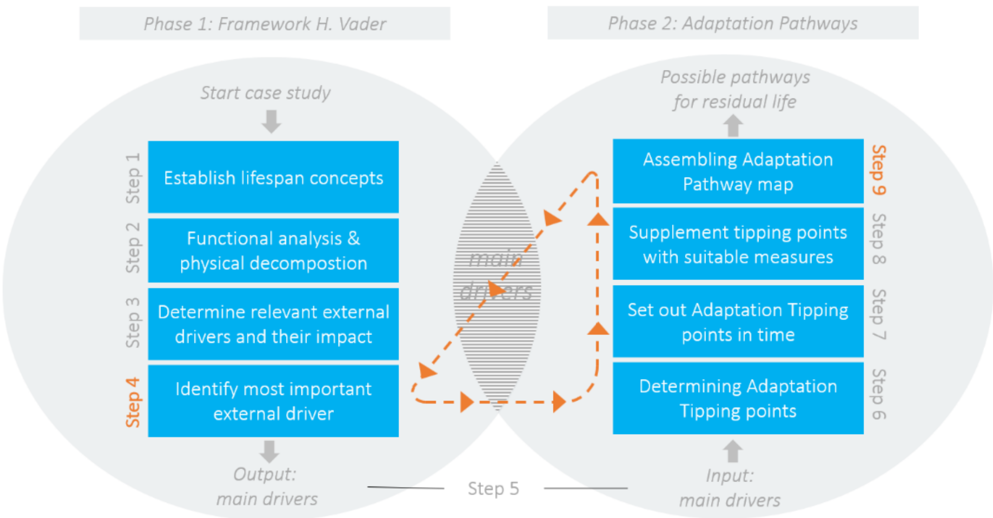

Figure 48 The two different phases within the research approach from chapter 3, including the recommended extra feedback loop from step 9 to step 4 (indicated in orange).

10. Conclusion and recommendations

The final chapter of this research sums up the main conclusions by giving key insights and answers to the research questions. Recommendations on future research are also provided.

10.1 Conclusions

The conclusions are presented by summarizing the key insights on the remaining lifetime of the Haringvliet sluices and by providing the answers to the research questions.

10.1.1 Key insights on the remaining lifetime of the Haringvliet sluices

The results for key insights are based on simplifications or assumptions made within the research, which are stated in the discussion of chapter 9 as well as discussed in the corresponding analysis steps (chapter 5 to 8). The following key insights on the Haringvliet sluices can be concluded from this research:

(1) The functional end of life is more dominant than the technical end of life for the Haringvliet sluices.

From the functional and structural analysis in chapter 5 is concluded that in future conditions achieving the functional performance requirements is expected to be more challenging than material deterioration leading to structural failure. The current quality of the materials, like the concrete, is assumed to be in sufficient condition, based on research on the concrete quality of storm surge barriers in the Netherlands (TNO, 2022). It is expected that for the Haringvliet sluices material deterioration can be reduced or repaired by increasing the number of inspections and maintenance moments.

(2) The most critical external drivers effecting the end of life of the Haringvliet sluices are sea level rise and changing river discharges.

From the external driver analysis in chapter 6 can be concluded that the most critical divers are expected to be rising sea levels and changing river discharges. These drivers are expected to change the most in comparison to other drivers. Also, the magnitude of their impact and the variety of consequences on the functional requirements or demands is expected to be the most significant. The Haringvliet sluices are impacted by these drivers simultaneously, as rising sea levels impact the 'front side' of the barrier and changing river discharges impact the 'back side' of the barrier. This change in boundary conditions from both sides of the system increases the stress on the system caused by the external drivers.

(3) The most critical combinations of drivers and functions for the Haringvliet sluices are the combinations of; the flood safety and water management function with the driver sea level rise and the driver extreme river discharge situations.

By combining the results of chapter 5 and chapter 6 it can be concluded that the impact of rising sea levels and extreme discharges is expected to result in a significant impact on the flood safety and water management function of the Haringvliet sluices. The water management function consists out of water level management (i.e., keeping the water level in the Haringvliet at required levels during normal operational conditions) and water quality management (i.e., ensuring fresh water at intake points or formal fresh water boundaries from the Kier Policy). For the flood protection function it is expected that rising sea levels cause more frequent closure of the barrier and cause more overtopping or overflow over the barrier. High extreme river discharges are also expected to test the limits of the discharge capacity of the Haringvliet sluices. It is expected that the current Kier Policy will be under pressure of rising sea levels and extreme low or high river discharges. Long periods of drought could impact the ecological benefits of the Kier Policy and could make it harder to maintain fresh water boundaries continuously. These combinations of functions and drivers should be investigated further to quantify their impact and to estimate their influence on the end of life on the Haringvliet sluices.

(4) The Tipping Point in the analysis on the combination of the flood safety function and the rising sea levels is highly dependent on the evaluation criteria.

In the analysis of the Tipping Point in chapter 7 it is chosen to investigate the effect of rising sea levels on the flood protection function. The consequence of extreme storm conditions and rising sea levels on the water level in the Haringvliet is investigated. There are no formal thresholds for when the system would reach end of life under these conditions. In previous research these criteria are stated as: 'The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter'. The choice on the value of the parameters is based on costs, available space and safety of the hinterland. Changing the values of the parameters or allow the overflow threshold to be larger than the initial 1 L/s/m results in an estimated increase of acceptable sea level rise up to 70 centimetres (shown in Table 27). This results in a high dependence of the end of life of the Haringvliet sluices, based in the evaluated combination of driver and function, to be highly dependent on the decision of these criteria. The criteria can be summarized as: (1) the combination of how many dike sections need to be elevated and the minimum of elevation height necessary (initial criteria set at 2 sections and 20 cm respectively), and (2) the critical overtopping discharge (initially set at 1L/s/m).

(5) The end of life of the Haringvliet sluices could be expected in roughly 50 to 70 years based on more extreme climate scenarios, if no mitigation actions would be implemented.

If no mitigations would be implemented, it is estimated that the Haringvliet sluices could withstand up to 87 cm of sea level rise. This is based in the combination of the driver sea level rise and the function flood protection. The function flood protection is directly related to the water levels in the Haringvliet. Using projections of the RCP4.5 and RCP8.5 scenarios the end of life of the Haringvliet sluices is estimated to be in the range 2079 -2093, for the 50% confidence interval of the two climate scenarios reaching the 87 cm of sea level rise.

(6) The four explored mitigation actions to elongate the life time of the Haringvliet sluices could make the system resilient up to 1 m extra sea level rise, in comparison to making no adaptations.

In chapter 8 possible mitigation actions to elongate the life time of the Haringvliet sluices are investigated. Their combined impact on the life time is to allow for roughly a resilience up to 1 m extra sea level rise in comparison to the initial estimate of 87 cm. The mitigations explored consist out of dike elevations, changes in the allowed overtopping of the dikes and the expansion of water storage during extreme conditions. This elongation of the life time only holds for the investigated critical combination of driver and function (sea level rise and flood protection function).

10.1.2 Answers to the research questions

The central research question and the sub questions are stated below and the results of the research are used to provide answers to these questions.

Central research question (1): How can the remaining life time of critical hydraulic structures be assessed and what methods can be used to elongate its remaining life?

The remaining life time of critical hydraulic structures can be assessed by creating an overview of all the possible ways the structure could reach its end if life using the framework of Vader et al. (2023). For this, all three types of end of life need to be considered (functional, technical and economic end of life). By decomposing all the functions and technical elements of the structure the impact of external drivers on each component can be assessed. From this can be seen which combinations of drivers and functions or drivers and technical elements are expected to be governing for the end of life of a structure. This makes for a considered decision on the choice of combinations to further investigate and quantify when determining the remaining life of the structure. The most likely dominant drivers for critical hydraulic structures are climate change related and therefore contain a lot of uncertainty. To deal with the uncertainty of the influence of external drivers on the systems, a method for elongating the remaining lifetime has to accommodate for this uncertainty. The method of illustrating plausible pathways based on mitigation action for the remaining life time of a system as presented by Haasnoot et al. (2013) is suitable to deal with this uncertainty. The method allows for presenting estimated Tipping points based on the amount of sea level rise, including an overview of which mitigations actions would be possible before reaching that Tipping Point. The method allows for a continuation of functioning under changing external conditions by investigating the effect of mitigation actions that elongating the lifetime of the structure.

Sub question (a): What and when are expected Tipping Points in the life time of the Haringvliet sluices which could lead to end of life decision?

By combining the results of the functional, technical and driver analysis (chapter 5 and chapter 6) the cause of the expected Tipping Points can be defined and it is concluded that the effects of rising sea levels and extreme discharges is expected to result in a significant impact on the flood safety and water management function of the Haringvliet sluices. For the analysis of the Tipping Points in chapter 7 it is chosen to investigate the effect of rising sea levels on only the flood protection function. This Tipping point is expected to be at 87 cm of sea level rise under the assumption that the end of life criteria is set as: ‘The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter’. Using projections for the RCP4.5 and RCP8.5 scenarios the end of life of the Haringvliet sluices is estimated to be in the range 2079 -2093, for the 50% confidence interval of the two climate scenarios.

Sub question (b): Can the framework of Vader also be applied to other critical hydraulic structures?

By applying the framework of Vader to the Haringvliet sluices successfully in this research on the Haringvliet sluices, it can be concluded that the framework is suitable for other critical hydraulic structures. Even in the case of a complicated system, like the one of the Haringvliet sluices, the framework is able to provide an overview to allocate the expected dominant causes for reaching the end of life of the hydraulic structure. When comparing the application on the Haringvliet sluices to the application on the Hollandse IJselbarrier, it can be seen that one of the most dominant drivers in both case studies is rising sea levels, which in both case influences among others the flood protection function.

Sub question (c): How can adaptive pathways support in maximizing the remaining life of critical hydraulic structures?

Adaptive Pathways can support in maximizing the remaining life of critical hydraulic structures by providing an overview of all the possible paths for the remaining life of the structure. The pathways provide insights in at which moments which mitigation measure has a certain effect. It allows for decision makers to manage the structure adaptively to deal with climate drivers which influence the performance or demand of the structure at that time when it is most critical. To achieve this goal, the adaptive pathways need to stay understandable and this could limit the number of mitigation measures shown in the adaptation pathways. The adaptivity provided by adaptive pathways allows for the structure to respond to expected climate resilient strategies of the Netherlands in the long term.

Sub question (d): Can a combination of the framework of Vader and adaptive pathways of Haasnoot lead to a full system analysis of critical hydraulic structures to determine plausible courses for the remaining life time?

The framework of Vader and adaptive pathways of Haasnoot can be combined seamlessly, because the output of the first method provides the starting input for the second method. Therefore, combining the two methods leads to a full system analysis which starts by decomposing the case study and identifying critical impacts of external drivers, to allow for derivation of the bottlenecks and suitable life elongating measures. From which plausible courses for the remaining lifetime of the structure are determined, using the adaptive pathways. The full analysis allows for an iterative component to explore all critical points that could lead to end of life, starting every iteration from the basis of the decomposition of the case study and the impact of external drivers. The full analysis must be run through several times to create a more complete overview of the most critical ways a structure could reach its end of life and to indicate which measures could be applied at what time. The analysis would benefit from an extra feedback loop to check possible implications on other functions, when assessing the effectivity of certain mitigations measures within the adaptive pathways.

10.2 Recommendations

This research aims to provide tools to tackle the renovation and replacement challenge and to give more insight on determining possible courses for the remaining life time of hydraulic structures. More research needs to be done to further address this challenge and to provide insights in how to manage our critical hydraulic infrastructure in an adaptive way. Recommendations on potential research topics are described below.

(i) Investigate other combinations of critical drivers and for the Haringvliet sluices

From the analysis in chapter 6 can be concluded that there are multiple critical functions and driver combinations which are expected to be dominant in the end of life of the Haringvliet sluices. In this research, only the flood safety function under pressure of rising sea levels is investigated. A different critical combination which should be assessed is the discharge capacity of the sluices in cases of extreme river discharge. This could become increasingly critical over the years due to the increase of extreme discharge volumes, as stated by climate change scenarios. Even more so, if the discharge capacity is decreased by rising sea levels.

(ii) Investigate the implications on the hinterland of the Haringvliet sluices

One the most impactful simplifications in this research is that in the computations of the extreme water levels, the Haringvliet is modelled as a basin. In real conditions, the water level of the hinterland will also rise. It could be interesting to expand the model for the Haringvliet, but also models for other Storm surge barriers, to investigate the implications on the hinterland. This impact to the hinterland could also be investigated regarding the consequences of mitigations proposed in the adaptation pathways, i.e. do other locations or aspects become more critical due to mitigation actions proposed to elongate the life time of the Haringvliet sluices.

(iii) Applying this methodology to other critical hydraulic structures

Applying this methodology (the combination of the Framework of Vader and the Adaptation Pathways of Haasnoot) to other critical hydraulic structures could give insights on the applicability of the methodology or could lead to more insights on possible similarities on dominant external drivers.

(iv) The addition of decision points to the Adaptation Pathways

In this research Tipping Points are used in the Adaptation Pathways to indicate the moments of when the Haringvliet sluices do not meet its requirements anymore. Proposed mitigations measures in the Adaptation Pathway are assumed to be activated before the Tipping Point arrived, this to make sure the structure can comply to its demands continuously. It could be interesting to look into the added value of adding decision points to the Adaptive Pathways, with the intension of marking the moment in which decisions need to be made on the mitigation measure to allow for sufficient time for its implementation. It can be investigated if there is a generalised time needed between a Tipping Point and a decision point, or if every mitigation measure requires a different decision point.

(v) Investigate how to keep Adaptive Pathways clear when including more mitigation measures

From this research it was concluded that adding a fourth mitigation measure created an unclear adaptation pathway. This was partly due to the fact that each of the mitigation actions for the Haringvliet sluices could be all sequentially combined, which is not generally the case. It could be investigated if there are ways to add measures to the Adaptation Pathways, while keeping a clear overview of the different paths. Adaptation Pathways are a great tool to set out all the different plausible courses for the life time of a structure, but its applicability would be limited if there is a maximum of actions which can be illustrated clearly.

(vi) Validation or review of existing models

For the scope of the analysis step on quantifying the tipping points in this work, using existing models on the Haringvliet sluices fit best. From this research can be concluded that there is added value in using existing models to get the detailed information needed while staying within the scope of the research. The recommendation in this is to promote that existing models have to be reviewed and validated to be used in other case studies. This also implies that the model data and the model itself must be opensource. Hereby knowledge on a specific topic and on reviewing models can be increased.

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Appendix A

The Delta works

The Delta Works in the Netherlands were built to protect the country against high water from the North Sea. After all, a significant part of the Netherlands is situated below sea level. The water finds its way to the sea via the many rivers through the country. This makes the Netherlands a typical delta region (Rijkswaterstaat, n.d.-a). The Delta works consist out of the following assets: 5 storm surge barriers, 2 sluices and 6 dams (all shown in Figure 49). In these definitions the Haringvliet sluices are integrated in the Haringvliet dam.

Figure 49 Assets of the Delta Works and their year of start of operation

The primary purpose of the Delta Works is to prevent The Netherlands from flooding, but the Delta Works provide also other benefits. The most important are listed below:

- The dams and weirs allow the water to be manipulated to assure navigable water depths and to control water quality.
- The Delta Works guaranties sufficient supply of fresh water for the population, but also for agriculture.
- Accessibility to the province of Zeeland for inland shipping is improved by reducing the impact of tidal movements.
- The Delta Works create recreational areas and at the same time create new beneficial ecological system

Appendix B

Practical approach to the literature study on prior research on using Adaptation Pathways for hydraulic structures

This appendix is complementary to the literature study described in section 2.4 and will address three topics which are not or not included in the main text:

(1)	(2)	(3)
Set up of the literature study (practical steps)	Limitations of the used approach on the set up of the literature study	Recap of the main findings and also additional findings

(1) Set up of the literature study

For the literature study of this research, it is chosen to limit the search to master theses done at the TU Delft. This has the side effect that a useful overview will be created on which students has worked with Adaptation Pathways on hydraulic infrastructure in their thesis at the section of hydraulic engineering. This overview can be used to guide futures theses to define their research in tune with previous research. The following steps are performed to make sure the literature study is as complete as possible.

Step 1 For the studies used in the literature review it is looked only at the TU Delft repository (https://repository.tudelft.nl/). This is assumed to be sufficient since each student is obliged to upload their work to this database.

Step 2 For the filtering 'master thesis' is used. Also, the key words use in the search bar are 'Adaptive' and 'Adaptation Pathways'. This gives 595 results.

Step 3 All the results with the above-mentioned filter and key words are then scanned on their title. If it is expected that the thesis might include the use of Adaptation Pathways it is saved for the next step.

Step 4 After scanning the titles and creating a list of potential studies, the scanning of the abstracts is use to determine of the thesis will be valuable for the literature study. This shortens the list from step 3.

Step 5 The list studies from step 4 are then analysed on their abstract, summary and conclusion after which is determined in which way, they are valuable to the literature study, i.e. categorize them in two categories: (1) fitting the search statement perfectly (using Adaptation Pathways as well as focussed on hydraulic structures); (2) using Adaptation Pathways on different system but could be valuable in a different manner to the total literature study.

Step 6 Reading and analysing all important sections in the selected studies and summarize the findings.

Step 7 Compare all the findings and look for key differences, conclusions and other remarks.

(2) Limitations of the literature study

By only considering master theses at the TU Delft the literature study has some limitations which are worth mentioning. (1) The first limitation is that these kinds of studies are not pear reviewed in any way, which make it questioning of results are reliable. However, this is assumed to not pose a problem for this literature study necessarily since no direct quantified results are used to make any conclusions, only main take aways or statements are considered here on the use of the method of Adaptation Pathways. (2) The second limitation is that the analyses or results presented in these theses are not applied in real life. These theses do use real life case studies, but are never applied.

(3) Recap of the main findings within the literature study and including additional findings

In summary, Adaptation Pathways can be used as a tool to investigate different design options and can test the performance when looking at renovating or (re)designing hydraulic structures. It can give a lot of useful insights, but the outcome is dependent on the evaluation criteria. Although often costs are considered, other relevant criteria are helpful to make a better choice for the preferred pathway. Also, a generalised pathway for similar structure cannot be achieve due to the dependence on local conditions. Lastly, it can be concluded that as far as the studies concerned, some hydraulic structures are not yet analysed using Adaptation Pathways. Examples of this are storm surge barriers or weirs. In the research done by Vader a storm surge barrier, the Hollandse IJsel barrier, is analysed for its remaining life time and life elongating measures are proposed (Vader, 2021). However, Vader does not make use of the Adaptive Pathway approach.

In the list below, other findings which were left out of the main text are listed.

Remark 1 Another difference in the implementation of Adaptation Pathways, besides the use of evaluation criteria, is the representation on the x-axis. While all theses present on the y-axis the different measures, the x-axis is variable. The two options for the x-axis used mostly are either the time in years or sea level rise in metres. A combination of this is having multiple x-axis represented by different climate change scenarios with different scales in x-direction.

Remark 2 Alongside all these theses, based on either hydraulic structures or other engineering works including in their approach the method of adaptation pathways, there are also other works that include adaptability without the formally using any method from literature. An example of this is the thesis of Dorrepaal (2016) in which is looked at a navigation lock, similar to the main object of Huijsman (2021) which is also a navigation lock. Dorrepaal (2016) does not use Adaptation Pathways in the approach of designing a new navigation lock, but does include a design variant in which a modular lock design is proposed to include adaptivity of the structure. Notable is that both authors conclude the same about the cost feasibility of adaptive measures on the design of a navigation lock. Both compare a conservative engineering design, taking into account worst case scenarios, to an adaptive design in which is started with smaller dimensions and leave room for expansion in the future. Including a more conservative design and comparing it to more adaptable options, can also be seen in the work of Hadders (2021) in which also a middle option is presented. Dorrepaal (2016) as well as Huijsman (2021) discuss the consideration that initially an adaptive lock design is more cost efficient, but when going in to the more extreme climate scenarios an adaptive lock design is hardly feasible in comparison to a conservative design from the beginning. In this Huijsman (2021) comments justly that in order to compare alternatives and their paths in relation to costs in a correct manner, it has to be discussed whether spreading of initial costs suits the project better than high initial costs.

Remark 3 Most of the studies look at defining Tipping Points for their case study, whereas Trommelen (2022) also describes the use of ‘trigger values. These trigger values are defined as values to provide enough time to prepare subsequent actions. This can be compared to the definition of ‘decision points’ used in this study.

Appendix C

Dike trajectories in the Netherlands

The first figure (Figure 50), shows an overview of all the dike trajectories in the Netherlands with their corresponding number indication and required signal value. In the second figure (X), the required signal values as well as the absolute lower limits are presented.

Figure 50 Overview all dike trajectories in The Netherlands and their required safety (signal values) ((Rijkswaterstaat, 2016))

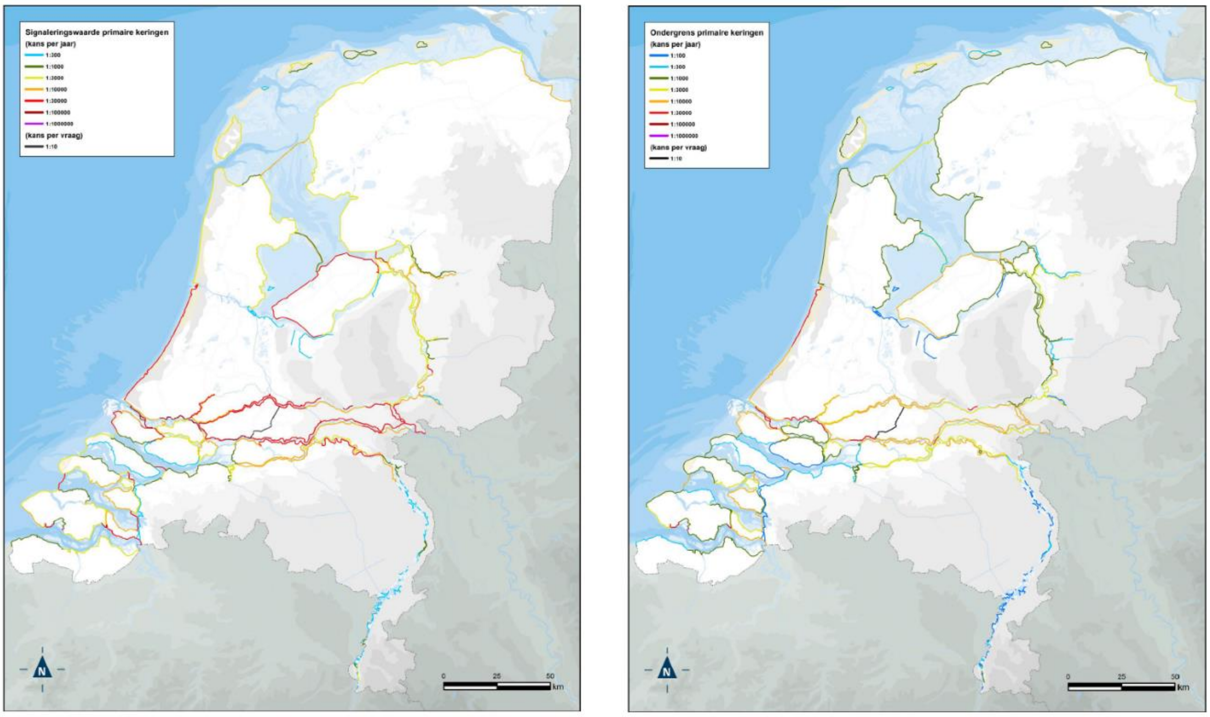

Figure 51 Dike trajectories of the Netherlands showing signal values (left) en lower limits (right) (Ministerie van Infrastructuur en Millieu, 2016)

Appendix D

Additional information on decomposed elements of the Haringvliet sluices

In this appendix the three different categories used for the decomposition are defined in more detail. The decomposition is repeated and shown in Figure 52.

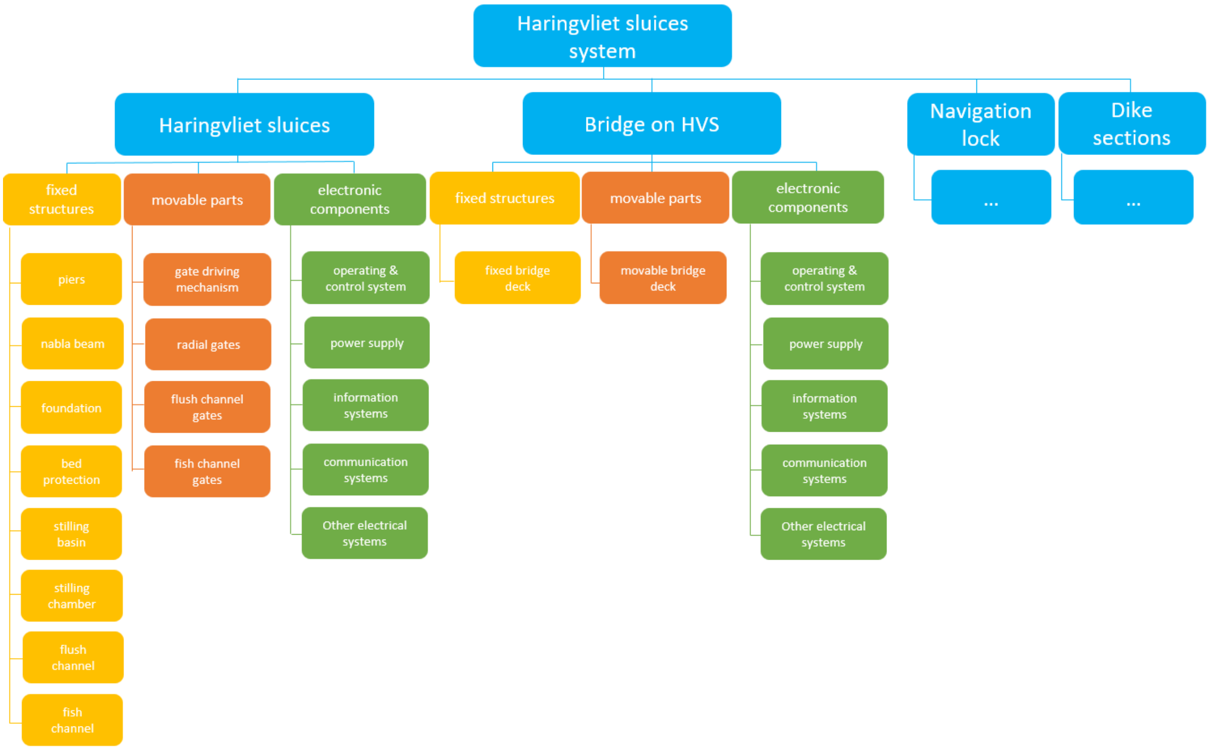

Figure 52 Breakdown of structural elements Haringvliet sluices complex

Fixed structures

The fixed structures resulting from the decomposition, Figure 52 , are further discussed below. The primary fixed structures of the Haringvliet sluices consist of the piers, NABLA beam[6], bed protection, foundation, stilling basin and stilling chamber. Where the stilling basin serves as energy dissipator for flow and the stilling chamber as energy dissipator for waves. Secondary fixed structures are the flushing channels and the fish passages. The fixed structures for the bridge deck on top of the Haringvliet sluices consist only of the fixed bridge deck.

Piers – The concrete piers house the driving mechanisms of the sluice gates and provide the support points for the NABLA beam resting on top of the piers. The piers redirect the forces to the foundation of the structure. In total there are 16 concrete piers and 2 abutments on each side of the barrier. The ToS is located at NAP +18.2 meters and the BoS, defined here as the location of the work floor level, is located at NAP -8.5 meters. Because these piers form the basis of the total structure in regards to

[6] The term 'nabla beam' refers to the shape of the beam, which resembles the mathematical sign called nabla. This sign looks like the inverted version of the Greek letter delta.

the sluices gates, but also the bridge on top, reaching end of life of these piers implies reaching the end of life of the Haringvliet sluices, since the whole barrier would need to be replaced.

NABLA beam – The NABLA beam spans the total width of the Haringvliet barrier and consist out of many connected smaller concrete elements. It is possible to walk through the NABLA beam to the piers and therefore provides a passage for operation and maintenance for everything located inside the NABLA beam and piers. The NABLA beam also houses the main hinges of the sluice's gates and functions as the base for the bridge deck on top.

Bed protection – The soil on either side of the Haringvliet sluices mainly consist out of fine sand. Fine sand is easily eroded by waves or flow. Therefor a bed protection is applied on both sides of the Haringvliet sluices. A cross section of the bed protection can be seen in Figure 53. The bed protection consists out of a concrete slab for the first part. The concrete slab has a pile foundation and has a length of 33 and 64 meters respectively for the river- and seaside. The second part is a bed protection consisting out of a horizontal loose rock layer. The length of the rock protection is similar on both sides and roughly equal to 125 meters. At the end of the rock bed protection are several obstacles in the form of tetrahedrons. This influence (reduce) the turbulence of the water and thereby reduce scour. Since the Kier Policy the bed protection is thoroughly checked on its current condition. Next to this, the bed protection is checked four times a year using multibeam measurements. Over the years two significant observations have been made regarding changes in the bed protection. Firstly, on the riverside of the Haringvliet sluices, a scour pit of 18 meters deep is observed. However, comparing measurement maps over the years, there are no significant differences found on the river side. Secondly looking at the seaside, it is noticeable that sedimentation is changing the local delta landscape. Currently, the direct cause in still investigated and this could lead to a change in hydraulic boundary conditions for the sea side of the Haringvliet sluices. This change will have a positive effect, since the sedimentation will cause the waves to lose more energy when traveling towards the barrier.

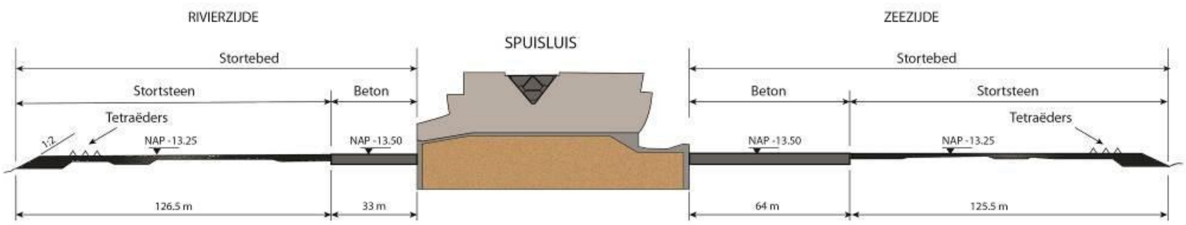

Figure 53 Cross section of the bed protection of the Haringvliet sluices (Left = riverside, Right = seaside)

Foundation – The piers as well as the bed protection and the concrete sills under the sluice gates are based on a pile foundation. For the total complex, 21843 piles are used. The piles used are prefab concrete piles.

Stilling basin – At the sea side there is a stilling basin to reduce the energy in the flow when discharging water from the Haringvliet. The stilling basin is only located at the sea side, since the original design only included the flow direction to the Sea. Since the Kier Policy there is also flow to the riverside. The stilling basin is made out of reinforced concrete. The stilling basin also has a wave breaking purpose.

Stilling chamber – The stilling chambers are located in the abutments on either side of the Haringvliet sluices, only at the sea side. The function of these stilling chamber is to reduce the energy of the waves at the gates located close to the abutment. Otherwise, phenomena like wave reflection could increase the wave attack on these specific gates. The stilling chambers can be described as a gallery of pillars as obstacles.

Flushing channel – The flushing channels are designed to flush away accumulated salt behind the Haringvliet sluices from the riverside to the sea side. There are in total two flushing channels located in the abutment structures. The flushing channels are square concrete channels which can be closed off by a steel gate.

Fish channel – Before the Kier Policy, the way that the fish could pass the barriers where the fish channels. There are a total of 6 fish passage located in 6 of the concrete piers. The fish channels are square concrete channels which can be closed off by steel gates. An attraction current is provided in these channels so the fish can find the passage. The channels are currently still operation, despite the Kier Policy which also allows for fish passage.

Fixed bridge deck – The bridge deck on top of the Haringvliet sluices consist out of a 2x2 regional road, supplemented with a separate lane meant for pedestrians, cyclers and operational and maintenance traffic for the Haringvliet sluices. The bridge deck is located at NAP + 19 meters.

Movable parts

The movable parts for the Haringvliet sluices consist of the gate drive mechanism as well as the radial gates themselves. Smaller gates to consider are the gates of the flushing channel and the gates of the fish passage channels. Movable parts to consider for the bridge on top of the Haringvliet sluices is the movable bridge deck.

Gate driving mechanism – In each of the piers in total four hydraulic gate driving mechanisms are located. Two for the river side gate and two for the sea side gates. The working of the gate driving mechanism can best be explained by showing the cross section. It consists out of a hydraulic system using oil pressure to retract or extent the cylinder moving along a track. This can be found in Figure 54. The driving mechanism is equal on both sides of the Haringvliet sluices, even though their dimensions differ. Each individual gate is set in motion by the driving mechanisms in two separate piers.

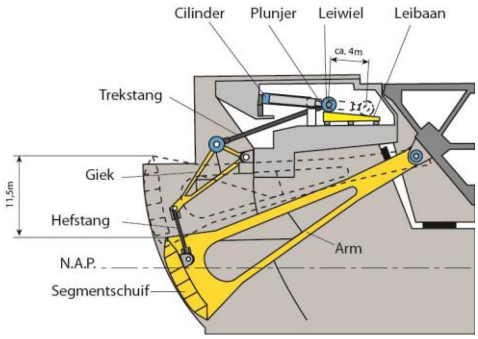

Figure 54 Driving mechanism of the sluice gate of the Haringvliet sluices

Radial sluice gates – There are a total of 34 radial sluices gates, each having a span of 56.5 meters. The height of the gates is different for the sea- and river side. The height of the gates of the seaward side is NAP +3.0 m and the height of the river side is NAP + 5.0 meters. Both sides close in storm conditions and the sea gate side will act as a wave breaker for the river side gate. The gates are made out of steal and the connections are mainly consisting out of rivets. The radial shape of the gates caused the hydraulic water to press the gates downwards when closed. Also, the gates are filled and empties with water when either lowered or lifted. The steel gates are influenced by the salt water on a daily basis. Each gate is set to move every 24 or 48 hours. The number of gates as well as the size of the gates makes for a challenging maintenance strategy. Currently, the sluices gates are planned to have a renewed preservation coating.

Flushing channel gates – The salt flushing channel gates consist out of single steel plate gates with a lifting and lowering mechanism. These gates can be operated in the dry since they are located in the abutments.

Fish channel gates – The fish channel gates consist out of single steel plate gates with a lifting and lowering mechanism. These gates can be operated in the dry since they are located in the piers.

Movable bridge deck – The movable part of the bridge deck spans the Goeree navigation lock and makes sure vessels with a high draft can pass the lock. The movable bridge deck is about 22 meters long and spans the full lane width of the 2 x 2 lanes. A separate drawbridge is located at the river side of the lock for the local road.

Electronic components

Several electric components of the Haringvliet sluices can be considered. The electronic components of the bridge deck on top of the Haringvliet sluices are included in the systems of the sluices themselves. The components considered are the operating and control system, power supply, information and communicating systems and finally, remaining other electronic systems.

Operating and control systems – The Haringvliet sluices as well as the Goeree navigation lock are controlled from the same control room. In total there are three identical control and operating desks. One for regular use and two back up set ups in case the first one fails, one of which is in a separate building. All control and operational set up are identical for easy use in critical times.

Power supply – The main and primary power supply comes from the North side of the barrier and allows for all of the sluices to be operated at the same time. In case this power supply fails, a secondary power grid is activated from the South side. This power supply is not large enough to be able to operate all the sluices at the same time, but only two gates can be operated simultaneously. The third and last power option is a emergency diesel generator which can provide enough power to operate 2 sluices at the same time. In case every power supply fails, the gates can be lowered manually. When lowering the gates manually, one has to keep in mind that raising them again can only be done using electricity. River discharge can thus pile of behind the barrier.

Information and communication system – These information and communication systems include a wide variety of types. For the communication systems one can distinguish systems like marine radio, telephones in the building, fire alarms and camera systems. These communication systems are necessary to have communication with the users of the Goeree navigation lock and these systems can also provide coordination when normal operation fails. For the information one can distinguish local and national information systems. Local systems are referring to local water level, tide level and chloride content measurements, which are performed by measurement buoys. National systems refer to systems which measure operational threshold values for the Haringvliet sluices like the discharge at Lobith a water levels at Hoek van Holland.

Other electronic systems – This last category is introduced for completeness and include systems which are aimed at the comfort of the employees and visitors at the complex. Systems like climate control and ventilation systems are included in this final category.

Appendix E

Additional information on the deterioration mechanisms per element of the Haringvliet sluices

This appendix aims to indicate the different possible deterioration mechanism for each of the element of the decomposition of the Haringvliet sluices. Also, it is estimating wat the consequences would be of the component would deteriorate.

Fixed structures

The common construction material of the fixed structures is reinforced concrete. Even though the material is the same, the deterioration mechanisms can differ due to the type of exposure it has in the system. There are multiple deterioration mechanisms related to concrete and according to the analyse of Vader the most important processes of concrete deterioration are the ones related to the reinforcement corrosion (Vader, 2021). These processes are carbonation and chloride-ingress. For each of the fixed elements of the Haringvliet sluices the possible deterioration mechanisms and the plausible consequences are listed below.

Piers – The piers are made out of reinforced concrete and are situation under water as well as above water. They are mostly vulnerable for concrete deterioration processes. The piers are inspectable above water as well as the part underwater. Frequent inspection of these concrete piers can prevent their end of life and repairs can be scheduled a head of team. If the deterioration has gone to far and the concrete of the pier is not repairable anymore, the whole structure will reach its technical end of life.

NABLA beam – The NABLA beam is an important element in transferring the forces on the gates to the structure and is fully made out of reinforce concrete. It also holds the road on top. The NABLA beam is completely above water, but is still influences by salt water conditions due to winds and splashing water. Concrete deterioration is the main deterioration mechanism here. Since the NABLA beam is fully above water it is easy to inspect it frequently and observe deteriorated parts in need of repairs. Same as for the pier holds that when the deterioration process has passed an irreversible stage, the barrier will have reached its technical end of life.

Bed protection – The bed protection is mostly influenced by the flow of water, especially by the flow velocity and the turbulence level. The bed protection is partly a concrete slab as well as a layer of rocks. The layer of rocks can be filled up again of there are any instable scour holes. The concrete slab could be filled up using underwater concrete if it would be damaged by any debris. Scour holes can easily be measures and development over time can be monitored. Since the Haringvliet sluices were originally not designed to let water back in, which is the case since the Kier Policy, the bed protection might not be sufficiently strong in the long run. Again, monitoring this could prevent scoure holes from reaching the foundation of the structure.

Foundation – The foundation consists out of a great number of piles. The foundation is not inspectable, but an individual pile failure will not lead to a total failure of the foundation. The foundation is not repairable or replaceable in case of failure and this would directly lead to technical end of life. It is highly unlikely that this type and size of foundation would fail in its entirety.

Stilling basin – The stilling basin is constructed out of a concrete slab and is fully immersed in salt water. Inspection of potential damages is possible as well as repairs using underwater concrete. It is not expected that the stilling basin can be damages by flow velocities and turbulence only, but if there would be larger parts of debris present, these could damage the concrete. This could occur when gates are fully open and debris can easily flow through. In regular conditions, there is only underflow and possible debris would be stuck behind the gates.

Stilling chamber – The stilling chambers are made out of concrete and are situated above as well as under water. High wave energy could potentially damage the concrete and concrete deterioration could be accelerated. The concrete has to be inspected in regular intervals to indicate any damages patches of concrete.

Flushing channel – The flushing channel consist out of a concrete and yet again concrete deterioration is the main mechanism here. High flow velocities through the channel could also be damaging the concrete, even more so if the water carries any larger particles like sand. The channels can be closed offed and empties, making inspection and repair possible.

Fish channel – The fish channel consist out of a concrete and concrete deterioration is the main mechanism here. High flow velocities through the channel could also be damaging the concrete, even more so if the water carries any larger debris. The channels can be closed offed and empties, making inspection and repair possible.

Fixed bridge deck – The fixed bridge deck is assumed to be repairable as well as fully replaceable when considering the road surface only.

The considerations per element are summarized in the table below.

Table 29 Main deterioration mechanisms and their consequence for the fixed structures category

Element	Deterioration mechanism	Consequence
Piers	Concrete deterioration	Repairing of deteriorated concrete
NABLA beam	Concrete deterioration	Repairing of deteriorated concrete
Bed protection	Erosion	Repair by placing new or additional bed protection (stones or concrete slab)
Foundation	Settlements	If pile foundation fails, implies technical end of life
Stilling basin	Erosion	Repairing of concrete under water slab
Stilling chamber	Concrete deterioration	Repairing of concrete under water and above water
Flushing channel	Concrete deterioration, erosion	Repairing of deteriorated and eroded concrete
Fish channel	Concrete deterioration, erosion	Repairing of deteriorated and eroded concrete
Fixed bridge deck	Road surface deterioration	Repairing or replacing road surface

Movable parts

For the movable parts, the common material is steel, which leads to a common deterioration mechanism of corrosion. The movable elements are also vulnerable to wear.

Gate driving mechanism – The driving mechanism is situated in an enclosed environment, which makes it less vulnerable to outside conditions. However, the driving mechanism is vulnerable to mechanical wear. The parts can be easily inspected and replaced.

Radial sluice gates – The sluice gates are made of steel and therefore the main deterioration mechanism is corrosion. The protective layer, preventing erosion, can be locally repaired or a full recoating can be done. Also, large debris could damage the gates. In the case of fully replacement of a single gate, technical end of life is not yet the case. Only when multiple gates are in need of full replacement.

Flushing channel gates – The flushing channel gates are made out of steel and are vulnerable to corrosion. The protective layer, preventing erosion, can be locally repaired or a full recoating can be done. The gates can also be replaced.

Fish channel gates – The fish channel gates are made out of steel and are vulnerable to corrosion. The protective layer, preventing erosion, can be locally repaired or a full recoating can be done. The gates can also be replaced.

Movable bridge deck – The movable bride deck is mostly made out of steel, which again makes the main deterioration mechanism corrosion. Frequent lifting and lowering of the bridge deck causes mechanical wear of the lifting system.

The considerations per element are summarized in the table below.

Table 30 Main deterioration mechanisms and their consequence for the movable parts category

Element	Deterioration mechanism	Consequence
Gate driving mechanism	Mechanical wear	Repairs or replacement of parts
Radial Sluice gates	Corrosion Debris damage	Repairs of coating Local repair of damage
Flushing channel gates	Corrosion	Repair of coating (locally or fully) or full gate replacement
Fish channel gates	Corrosion	Repair of coating (locally or fully) or full gate replacement
Movable bridge deck	Corrosion Mechanical wear	Repair of coating (locally or fully) or full bridge replacement Repairs or replacement of parts

Electronic components

The electronic components can be grouped together. Their deterioration mechanism is general ageing of electronic components, hardware or software. These are all considered to be replaceable as long as operational ability is not compromised. The general life time of electronic components can be short due to developments in the technological industry, i.e. components can become outdated and need to be replaced.

The considerations per element are summarized in the table below

Table 31 Main deterioration mechanisms and their consequence for the electronic components category

Element	Deterioration mechanism	Consequence
Electronic components	General ageing	Repairs are replacement of electronic components, hardware and software

Appendix F

System Alternations

This appendix aims to shown the locations and the influenced areas of the system alternation discussed in section 6.4.3. The discussed plans are: Replacement of current storm surge barriers (not illustrated), The Haakse Zeedijk (DHZ) (Figure 55), Northern Europe Enclosure Dam (NEED) (Figure 56) and Delta21 (Figure 57)

Figure 55 Location of The Haakse Zeedijk (DHZ)

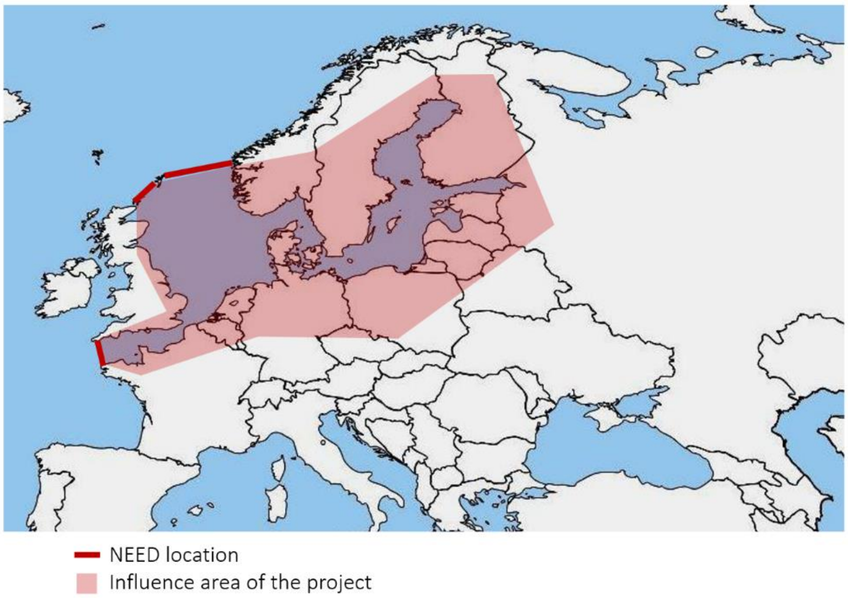

Figure 56 Location of North Europeans Enclosure Dam (NEED)

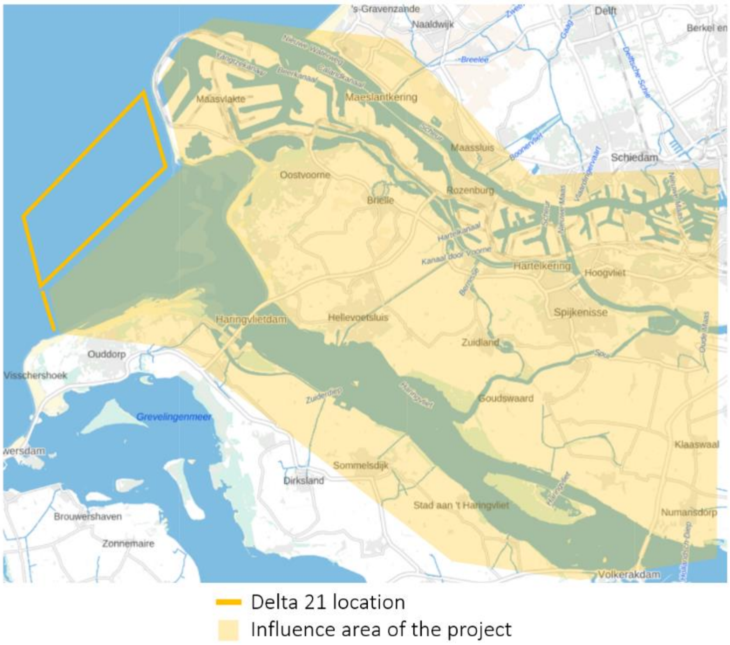

Figure 57 Location of Delta21

Appendix G

Description of existing models on the Haringvliet sluices

The three models used for estimating the Tipping Points will be elaborated on their goal, methods, type of results and their main take aways. The existing models on the Haringvliet sluices that are used in this thesis are shown in Table 32.

Table 32 Existing models for the Haringvliet sluices and their assigned abbreviations

Model / Report tittle	Reference	Abbreviation
The future of the Haringvliet sluices (MSc thesis)	(Ruessink, 2019)	-
Performance level model Haringvliet sluices	(Kuijper et al., 2022)	PLM-HV
Wave overtopping model	(Kortlever et al., 2008)	WOM-HV

(1) MSc Thesis: 'Future of the Haringvliet sluices' (Ruessink, 2019)

The goal of the work of Ruessink is in line with the first phase of this thesis: Determining the life time of the Haringvliet sluices based on the effect of climate change scenarios. For this, climate change scenarios of KNMI'14 are used. For the assessment of the life time of the Haringvliet sluices, programs like Hydra-BS, Hydra-NL and SOBEK are used. This is supplemented with literature and information from interviews with experts.

The following life times are investigated in the research:

- Life time concerning: strength and stability
- Life time concerning: Flood protection
- Life time concerning: fresh water availability
- Life time concerning: ecology

After determining estimations for these life times, the research continues in proposing strategies for the life time of the Haringvliet sluices.

(2) Performance level model Haringvliet sluices (Kuijper et al., 2022)

The aim of this model is to determine performance levels for the Haringvliet sluices in a probabilistic way, taking into account the relevant failure modes. This does not concern the absolute water levels that are calculated, but the influence of the failure of the Haringvliet locks on these water levels.

A probabilistic calculation tool has been developed to determine the performance levels, which is an adaptation/extension of the existing probabilistic set of instruments for the Rhine-Meuse estuary (Hydra-NL). To be able to do calculations with this tool, SOBEK3 calculations for different combinations of storms and river discharges were made. The probabilistic calculation tool uses the effect of storms and river discharges (maximum local water levels) in combination with the probability of occurrence of such events to calculate the exceedance frequency line of water levels.

The model produces three types of output figures:

- Matrix with water level differences due to failure
- Water level paths with and without failure

- Behaviour of barriers with and without failure

One of the main conclusions of this study is that the behaviour of the storm surge barriers is in line with expectations, which was also assessed in the discussion with experts from Rijkswaterstaat. Next to this, the failure mode of ‘do not open' has a water level raising effect in particular in combinations with high river discharge and low sea water levels. If the water level does rise behind a closed front of the barrier during a severe storm (high sea water level), the contribution of not being able to discharge is limited. If the river discharge is not extreme, the effect of being able to discharge is also limited. The failure mode of 'not closing' has a water level-increasing effect, in particular, in combinations with high river discharge and high seawater levels. If the water level rises behind a closed front of the barrier during a severe storm (high sea water level), the inability to withstand this sea water level at the Haringvliet sluices results in an additional increase. For a significant effect, a large number of doors has to be not available (more than half). Also, the failure of 'not closing' is partly compensated by more frequent use of the water storage on the Volkerak-Zoomlake. It is concluded that the effect of failure practically disappears in probabilistic calculation. This can easily be explained from the small failure probabilities (particularly for 'all sluice gates fail'). As a validation, a sensitivity analysis was performed with the probabilistic calculation tool, the sensitivity to the probability of failure appears plausible in this.

(3) Wave overtopping model (Kortlever et al., 2008)

The Haringvliet sluices consist of two gates per opening, the seaward gate has a height of NAP + 3 m and the river side gate has a height of NAP + 5 m. In large storms, the waves and the high-water level could cause wave overtopping and in extreme cases also complete overflow of the gates. This report gives formulas for the wave transmission over the lower sea side gates and wave overtopping and overflow formulas for over the river side gate. In this the system is schematized as a broad crested weir and the shape of the gates is also taken into account in the parameters. When looking at extreme high-water levels, it is assumed that waves can quite easily pas the NABLA beam with out to much reduction in energy. The same formulas and schematizations are used in the model of Ruessink.

Appendix H

Climate scenario plots RCP4.5 and RCP8.5

This appendix provides background information on the climate data plots used in chapter 7.

The initial starting point was to use climate data from the report ‘climate signal ’21 ‘, the newly released climate report of the KNMI (KNMI, 2021). The report itself only presented sea level rise data for 3 specific points for each climate scenario (Table 33). This would lead to highly simplified plots, using linear extrapolation, presented in Figure 58.

Table 33 Key figures for SLR from Climate Signal '21 KNMI

Jaar	2050	2050	2050	2100	2100	2100
Scenario	SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
SLR (absolute water level)	14-38 cm	15-41 cm	16-47 cm	30-81 cm	39-94 cm	54-121 cm
SLR (speed)	2,8-8,7 mm/year	5,2-10,6 mm/ year	5,8-12,1 mm/ year	2,9-9,1 mm/ year	4,4-10,5 mm/ year	7,2-16,9 mm/ year

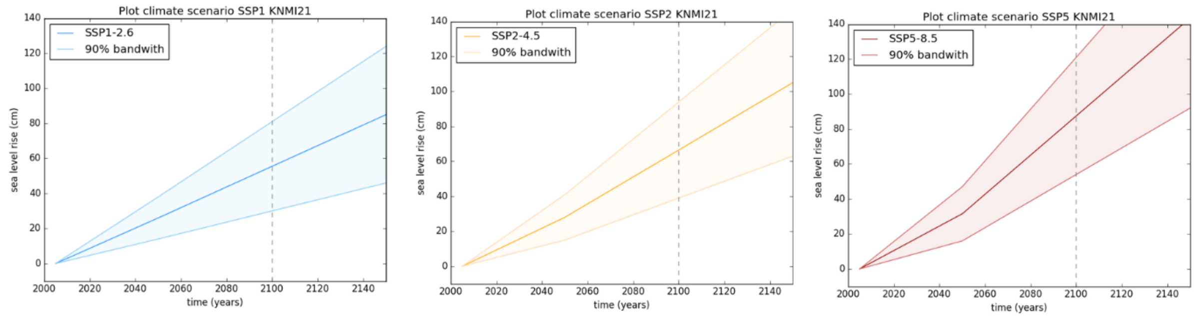

Figure 58 plots based on limited data points from Climate Signal '21 , including linear extrapolation from the year 2100 onwards

It was assumed to crude to use these plotted climate scenarios, but since the work of Ruessink already uses the climate scenarios from KNMI’14, a more recent data set was required. For this the projections of Le Bars are used, which are also used in (Haasnoot et al., 2018). These projections could be considered in the more extreme side, since they are based on the arctic collapse scenarios. The data is extrapolated after 2100 using linear, 3rd order polynomial and 4th order polynomial extrapolations. First the base plots are shown in Figure 59 for the two different climate scenarios. Then, the linear, 3rd order polynomial and 4th order polynomial extrapolations are shown in Figure 60, Figure 61 and Figure 62 respectively.

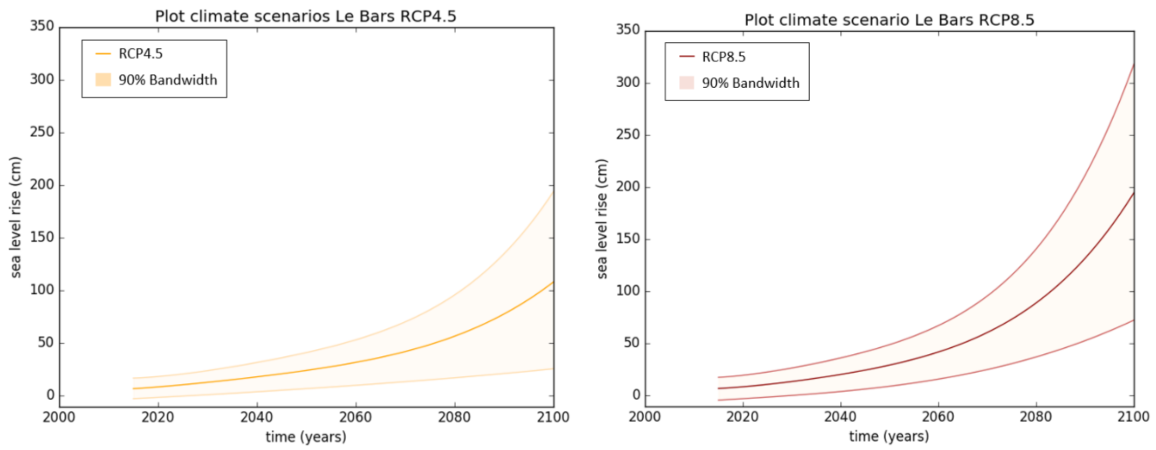

Figure 59 Plot climate scenarios Le Bars (RCP4.5 and RCP8.5)

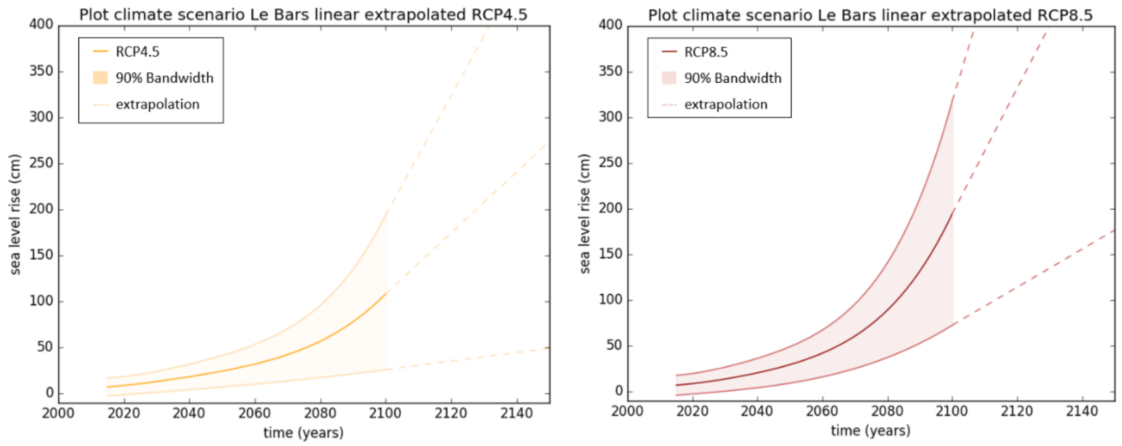

Figure 60 Plot climate scenarios Le Bars linearly extrapolated (RCP4.5 and RCP8.5)

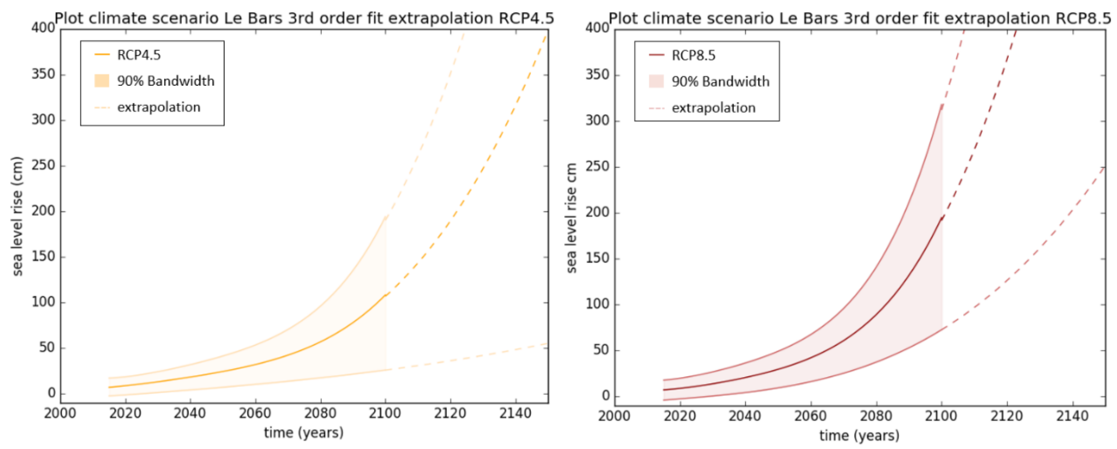

Figure 61 Plot climate scenarios Le Bars 3rd order polynomial extrapolated (RCP4.5 and RCP8.5)

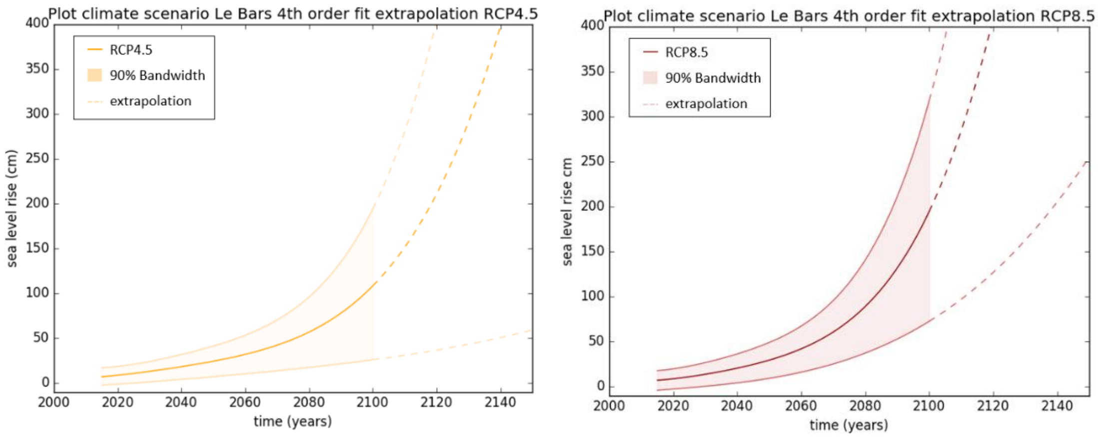

Figure 62 Plot climate scenarios Le Bars 4th order polynomial extrapolated (RCP4.5 and RCP8.5)

To show the effect on the level of estimated sea level rise of the type of extrapolation, Figure 63 shows the difference between the 3rd and 4th order polynomial extrapolation for the upper band. From this can be seen that for the sea level rise of interest the difference in sea level rise is minimal, but looking at zoomed out expectations, the difference can be quite fundamental. For the analysis in chapter 7 the 4th order polynomial extrapolation is used since it fits the data best.

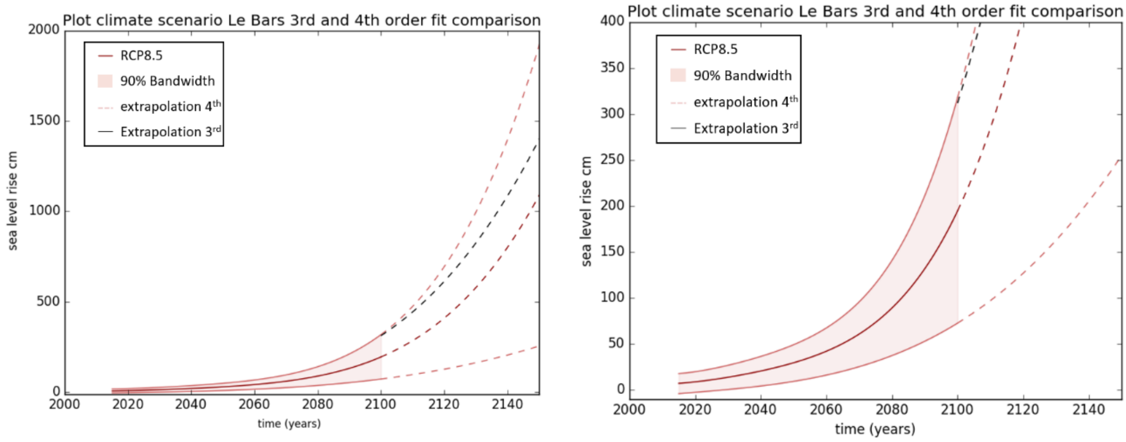

Figure 63 Comparison between 3rd order fit and 4th order fit on the most extreme scenario (left figure showing full results, right showing results in sea level rise of interest)

Appendix I

Full results of Tipping Point analysis

This appendix shows the different results discussed in chapter 7 for the Tipping Point analysis

Results for decision criteria: accepting 10 L/s/m

The Tipping Point determined here, is a result of allowing 10 L/s/m over the dike and calculating the hydraulic load accordingly. The ratios between SLR and hydraulic load per dike section is resulting from the work of Ruessink (Ruessink, 2019). The results shown in Table 34 is based on the sea level rise of 137 cm which is the Tipping Point based on the criteria; 'The life time of the Haringvliet sluices is reached if 2 dike segments need to be reinforced by at least 0.2 meter'.

Table 34 Results of the Tipping Point of 137 cm sea level rise

Dike sections	HBN R2015	Ratio between SLR and hydraulic load	Actual dike height	Model uncertainty	New calculated hydraulic load	Dike height – new hydraulic load
1	2,707	0,956	4,330	0,431	4,371	-0,041
2	3,168	0,411	4,900	0,431	4,129	0,771
3	2,825	0,793	4,350	0,431	4,279	0,071
4	2,758	1,063	4,310	0,431	4,560	-0,250
5	2,356	0,748	3,930	0,431	3,752	0,178
6	2,929	0,852	4,260	0,431	4,459	-0,199
7	2,605	1,189	4,550	0,400	4,539	0,011
8	2,432	0,941	4,650	0,417	4,063	0,587
9	2,391	0,781	4,380	0,417	3,815	0,565
10	2,868	0,652	4,600	0,292	4,001	0,599
11	2,854	0,633	4,420	0,323	3,994	0,426
12	3,115	0,393	5,500	0,457	4,079	1,421
13	2,469	0,796	5,550	0,461	3,957	1,593
14	2,674	0,659	5,070	0,461	3,985	1,085
15	2,463	0,619	5,470	0,461	3,723	1,747
16	2,357	0,237	5,490	0,461	3,124	2,366
17	3,179	0,722	4,720	0,459	4,569	0,151
18	2,768	0,459	5,000	0,459	3,819	1,181

The new hydraulic load is calculated following equation (EQ1):

$$HBN_{new} = (SLR - SLR_{R2015}) * Ratio + HBN_{R2015} + Model\ uncertainty \qquad \text{(EQ1)}$$

With:
$SLR = sea\ level\ rise\ of\ interest$
$SLR_{R2015} = Sea\ level\ rise\ used\ in\ the\ reference\ scenario\ (7cm)$
$Ratio = Ratio\ between\ hydraulic\ load\ and\ sea\ lever\ rise$
$HBN_{R2015} = hydraulic\ load\ in\ the\ reference\ scenario$

$$Modeluncertainty = following\ from\ the\ research\ of\ ruessink$$

The ratio used in the work of Ruessink is computed per dike section using the result for the hydraulic load of two climate scenarios, calculate the difference and then divide that results by the difference in SLR between the two scenarios. These ratios could be improved by using more climate scenarios to compare them with.

Results for the course of the over height as a functions of sea level rise.

Table 35 Results for th decrease in excess dike height with SLR for the 1 l/s/m limit for each dike section (in cm)

	Sea level rise (cm)																			
Dike section	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
1	70,252	58,512	46,772	35,032	23,292	11,552	-0,188	-11,928	-23,668	-35,408	-47,148	-58,888	-70,628	-82,368	-94,108	-105,848	-117,588	-129,328	-141,068	-152,808
2	61,818	56,408	50,998	45,588	40,178	34,768	29,358	23,948	18,538	13,128	7,718	2,308	-3,102	-8,512	-13,922	-19,332	-24,742	-30,152	-35,562	-40,972
3	52,934	44,604	36,274	27,944	19,614	11,284	2,954	-5,376	-13,706	-22,036	-30,366	-38,696	-47,026	-55,356	-63,686	-72,016	-80,346	-88,676	-97,006	-105,336
4	44,022	33,132	22,242	11,352	0,462	-10,428	-21,318	-32,208	-43,098	-53,988	-64,878	-75,768	-86,658	-97,548	-108,438	-119,328	-130,218	-141,108	-151,998	-162,888
5	110,14	101,84	93,54	85,24	76,94	68,64	60,34	52,04	43,74	35,44	27,14	18,84	10,54	2,24	-6,06	-14,36	-22,66	-30,96	-39,26	-47,56
6	65,588	59,028	52,468	45,908	39,348	32,788	26,228	19,668	13,108	6,548	-0,012	-6,572	-13,132	-19,692	-26,252	-32,812	-39,372	-45,932	-52,492	-59,052
7	114,514	98,584	82,654	66,724	50,794	34,864	18,934	3,004	-12,926	-28,856	-44,786	-60,716	-76,646	-92,576	-108,506	-124,436	-140,366	-156,296	-172,226	-188,156
8	121,786	111,716	101,646	91,576	81,506	71,436	61,366	51,296	41,226	31,156	21,086	11,016	0,946	-9,124	-19,194	-29,264	-39,334	-49,404	-59,474	-69,544
9	135,2	125,2	115,2	105,2	95,2	85,2	75,2	65,2	55,2	45,2	35,2	25,2	15,2	5,2	-4,8	-14,8	-24,8	-34,8	-44,8	-54,8

10	11	12	13	14	15	16	17	18
92,438	96,238	138,766	240,122	155,33	230,792	266,726	56,782	148,4
85,628	90,428	135,096	231,232	148,48	224,752	264,356	49,192	144,4
78,818	84,618	131,426	222,342	141,63	218,712	261,986	41,602	140,4
72,008	78,808	127,756	213,452	134,78	212,672	259,616	34,012	136,4
65,198	72,998	124,086	204,562	127,93	206,632	257,246	26,422	132,4
58,388	67,188	120,416	195,672	121,08	200,592	254,876	18,832	128,4
51,578	61,378	116,746	186,782	114,23	194,552	252,506	11,242	124,4
44,768	55,568	113,076	177,892	107,38	188,512	250,136	3,652	120,4
37,958	49,758	109,406	169,002	100,53	182,472	247,766	-3,938	116,4
31,148	43,948	105,736	160,112	93,68	176,432	245,396	-11,528	112,4
24,338	38,138	102,066	151,222	86,83	170,392	243,026	-19,118	108,4
17,528	32,328	98,396	142,332	79,98	164,352	240,656	-26,708	104,4
10,718	26,518	94,726	133,442	73,13	158,312	238,286	-34,298	100,4
3,908	20,708	91,056	124,552	66,28	152,272	235,916	-41,888	96,4
-2,902	14,898	87,386	115,662	59,43	146,232	233,546	-49,478	92,4
-9,712	9,088	83,716	106,772	52,58	140,192	231,176	-57,068	88,4
-16,522	3,278	80,046	97,882	45,73	134,152	228,806	-64,658	84,4
-23,332	-2,532	76,376	88,992	38,88	128,112	226,436	-72,248	80,4
-30,142	-8,342	72,706	80,102	32,03	122,072	224,066	-79,838	76,4
-36,952	-14,152	69,036	71,212	25,18	116,032	221,696	-87,428	72,4

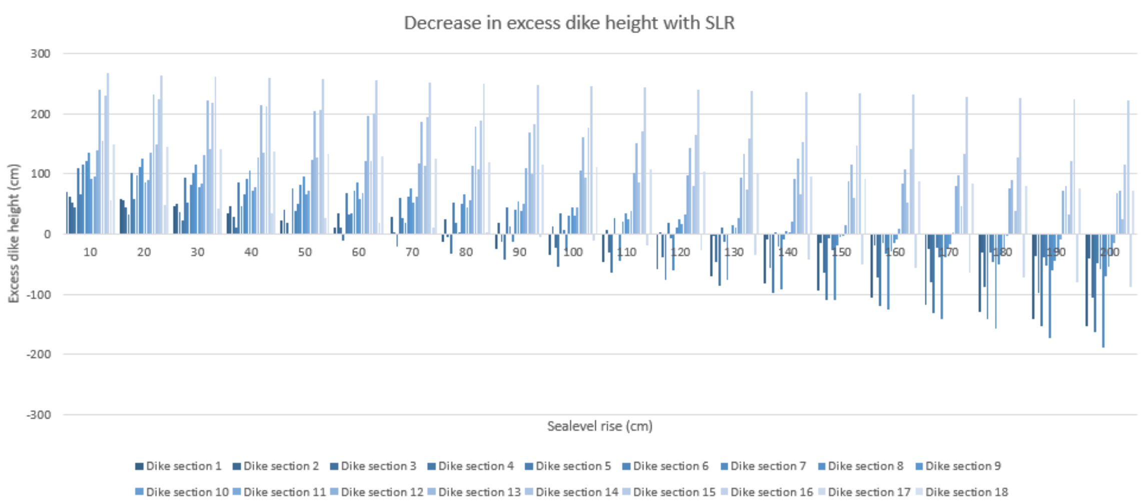

Figure 64 Decrease in excess dike height with SLR for the 1 l/s/m limit for each dike section

Table 36 Results for the decrease in excess dike height with SLR for the 10 l/s/m limit for each dike section (in cm)

Dike section	Sea level rise (cm)																			
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
1	117,288	107,728	98,168	88,608	79,048	69,488	59,928	50,368	40,808	31,248	21,688	12,128	2,568	-6,992	-16,552	-26,112	-35,672	-45,232	-54,792	-64,352
2	129,278	125,168	121,058	116,948	112,838	108,728	104,618	100,508	96,398	92,288	88,178	84,068	79,958	75,848	71,738	67,628	63,518	59,408	55,298	51,188
3	107,814	99,884	91,954	84,024	76,094	68,164	60,234	52,304	44,374	36,444	28,514	20,584	12,654	4,724	-3,206	-11,136	-19,066	-26,996	-34,926	-42,856
4	109,974	99,344	88,714	78,084	67,454	56,824	46,194	35,564	24,934	14,304	3,674	-6,956	-17,586	-28,216	-38,846	-49,476	-60,106	-70,736	-81,366	-91,996
5	112,804	105,324	97,844	90,364	82,884	75,404	67,924	60,444	52,964	45,484	38,004	30,524	23,044	15,564	8,084	0,604	-6,876	-14,356	-21,836	-29,316
6	88,296	79,776	71,256	62,736	54,216	45,696	37,176	28,656	20,136	11,616	3,096	-5,424	-13,944	-22,464	-30,984	-39,504	-48,024	-56,544	-65,064	-73,584
7	152,122	140,232	128,342	116,452	104,562	92,672	80,782	68,892	57,002	45,112	33,222	21,332	9,442	-2,448	-14,338	-26,228	-38,118	-50,008	-61,898	-73,788
8	178,218	168,808	159,398	149,988	140,578	131,168	121,758	112,348	102,938	93,528	84,118	74,708	65,298	55,888	46,478	37,068	27,658	18,248	8,838	-0,572
9	155,638	147,828	140,018	132,208	124,398	116,588	108,778	100,968	93,158	85,348	77,538	69,728	61,918	54,108	46,298	38,488	30,678	22,868	15,058	7,248
10	142,696	136,176	129,656	123,136	116,616	110,096	103,576	97,056	90,536	84,016	77,496	70,976	64,456	57,936	51,416	44,896	38,376	31,856	25,336	18,816

18	17	16	15	14	13	12	11
176,382	106,756	266,726	253,362	192,182	260,408	192,014	123,034
171,792	99,536	264,356	247,172	185,592	252,448	188,084	116,704
167,202	92,316	261,986	240,982	179,002	244,488	184,154	110,374
162,612	85,096	259,616	234,792	172,412	236,528	180,224	104,044
158,022	77,876	257,246	228,602	165,822	228,568	176,294	97,714
153,432	70,656	254,876	222,412	159,232	220,608	172,364	91,384
148,842	63,436	252,506	216,222	152,642	212,648	168,434	85,054
144,252	56,216	250,136	210,032	146,052	204,688	164,504	78,724
139,662	48,996	247,766	203,842	139,462	196,728	160,574	72,394
135,072	41,776	245,396	197,652	132,872	188,768	156,644	66,064
130,482	34,556	243,026	191,462	126,282	180,808	152,714	59,734
125,892	27,336	240,656	185,272	119,692	172,848	148,784	53,404
121,302	20,116	238,286	179,082	113,102	164,888	144,854	47,074
116,712	12,896	235,916	172,892	106,512	156,928	140,924	40,744
112,122	5,676	233,546	166,702	99,922	148,968	136,994	34,414
107,532	-1,544	231,176	160,512	93,332	141,008	133,064	28,084
102,942	-8,764	228,806	154,322	86,742	133,048	129,134	21,754
98,352	-15,984	226,436	148,132	80,152	125,088	125,204	15,424
93,762	-23,204	224,066	141,942	73,562	117,128	121,274	9,094
89,172	-30,424	221,696	135,752	66,972	109,168	117,344	2,764

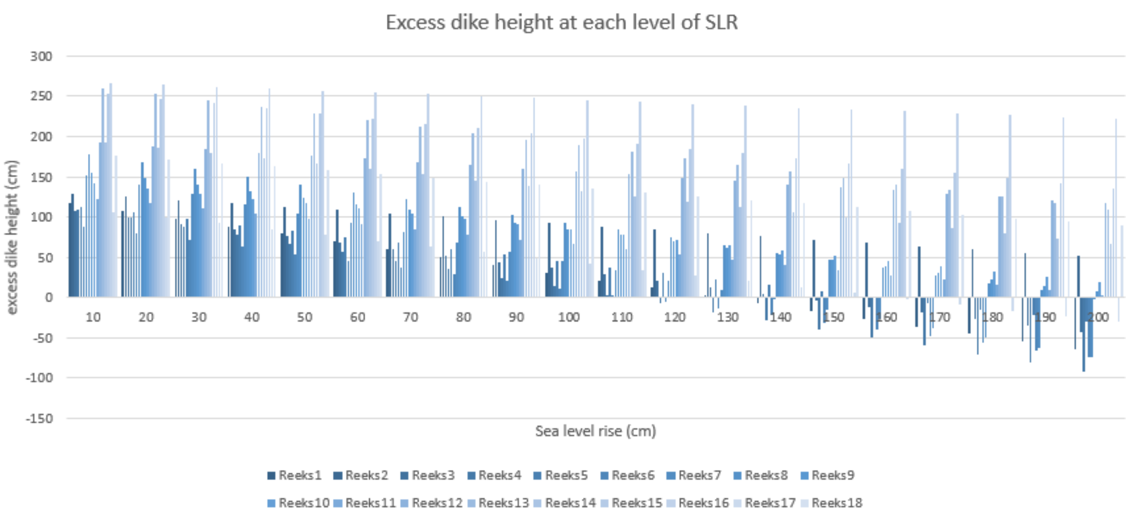

Figure 65 Decrease in excess dike height with SLR for the 10 l/s/m limit for each dike section

Appendix J

Linking Hydra – BS output to location of the dike sections

This appendix provides critical insights on how to link the data of Ruessink to the actual dike sections (Ruessink, 2019). Figure 66 shows the points for which the water levels are calculated using Hydra-NL and subsequent Figure 67 shows to points which are taken into account in the final assessment. Only these points are used for this research, since only data of these points are provided. It is assumed that the effect that the Haringvliet sluices have on the other points is small and are therefore not taken into account further.

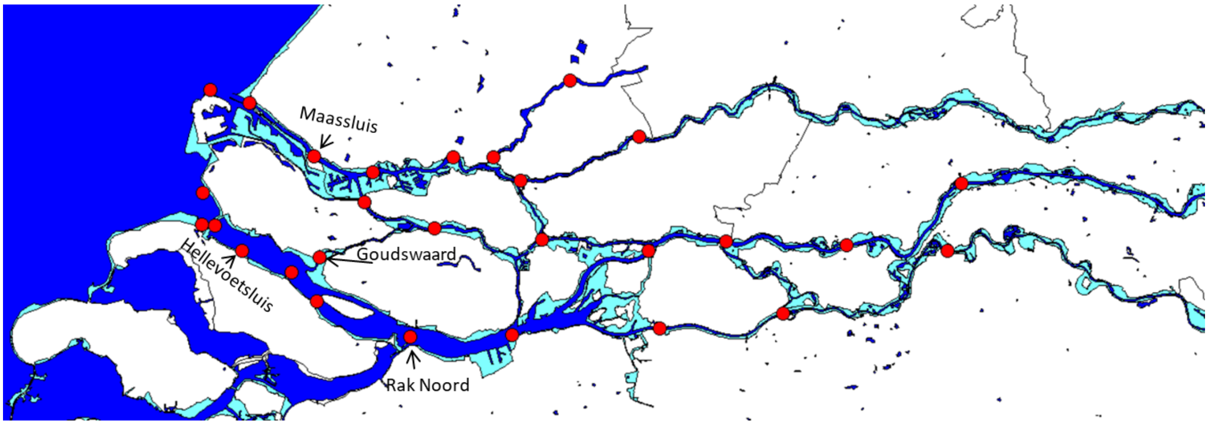

Figure 66 Illustration from Ruessink to show the location of the Hydra-BS output points.

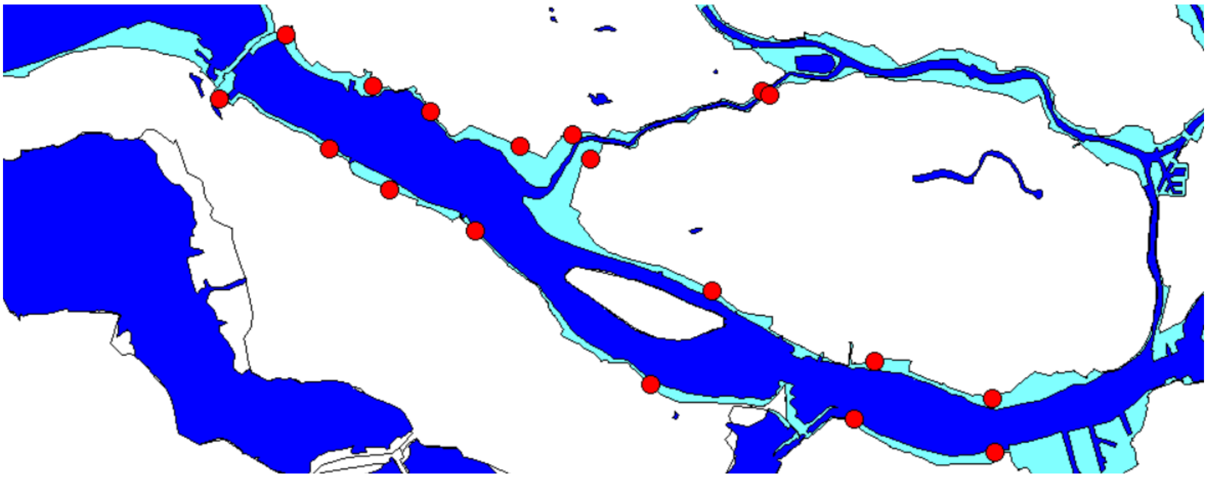

Figure 67 Illustration from Ruessink to show the location of the Hydra-BS output points used in the final dike assessment.

The output data of Ruessink consists out of 18 locations, which in total below to four different official dike sections (dike section 20, 21, 25 and 34). The datapoints and their assigned name and number are presented in Table 37, after which in Figure 68 they are linked to an actual location. This linking process is based on the horizontal and vertical axes reference system Hydra-BS uses in combination with the last sets of digits in their data name.

Table 37 Assigned name and number for the data points from Hydra-BS

Assigned number	Assigned name by data series Ruessink
1	Dkr 20 Haringvliet km 1017-1018 Loc 5_ 74959_424216
2	Dkr 20 Haringvliet km 1021-1021 Loc 4_ 71101_425758
3	Dkr 20 Haringvliet km 1023-1023 Loc 13_68571_426826
4	Dkr 20 Haringvliet km 1028-1029 Loc 13_64807_429054
5	Dkr 20 Spui km1008-1009 Loc 8_ 77233_424713
6	Dkr 20 Spui km999-1000 Loc 6_ 85508_426651
7	Dkr 21 Haringvliet km 1004-1005 Loc 5_ 83303_417928
8	Dkr 21 Hollandsch Diep km991-992 Loc 3_ 95531_413289
9	Dkr 21 Hollandsch Diep km997-998 Loc 5_ 90408_414873
10	Dkr 21 Spui km1008-1009 Loc 3_ 78022_423673
11	Dkr 21 Spui km999-1000 Loc 4_ 85838_426483
12	Dkr 25 Haringvliet km 1006-1007 Loc 8_ 80624_413901
13	Dkr 25 Haringvliet km 1015-1016 Loc 11_73022_420553
14	Dkr 25 Haringvliet km 1021-1022 Loc 5_ 69289_422366
15	Dkr 25 Haringvliet km 1024-1025 Loc 6_ 66663_424108
16	Dkr 25 Haringvliet km 1028-1029 Loc 20_61896_426286
17	Dkr 34 Hollandsch Diep km991-992 Loc 2_ 95620_410958
18	Dkr 34 Hollandsch Diep km996-997 Loc 13_89525_412391

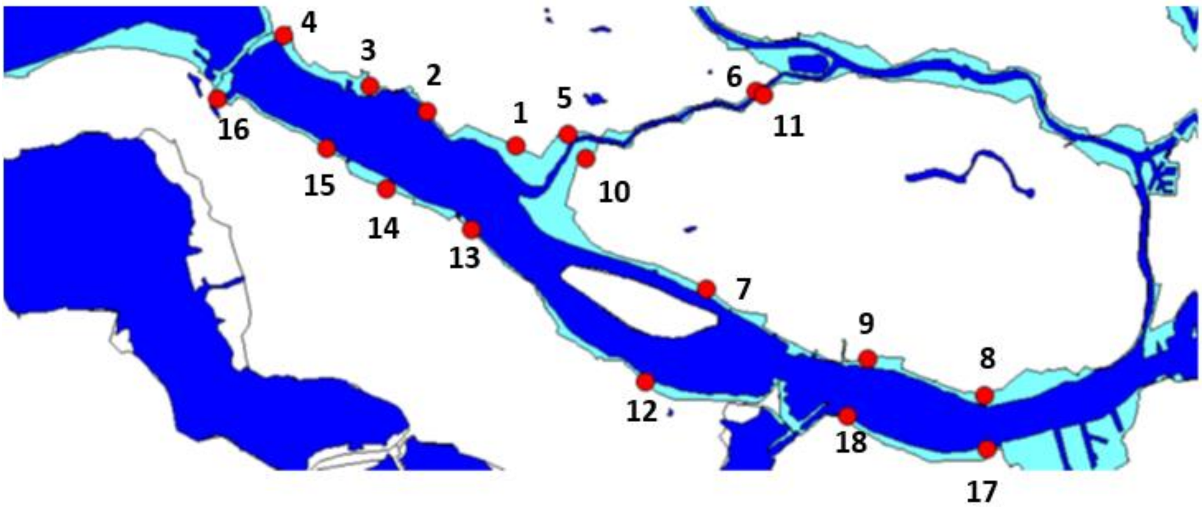

Figure 68 Illustration from Ruessink to show the location of the Hydra-BS output points used in the final dike assessment and linking them to the data set.

Appendix K

Excess dike height reduction as a response on sea level rise

This appendix shows the reduction in excess dike height as a response on rising sea levels. The excess dike height is determined by subtracting the calculated hydraulic load for that specific sea level from the actual dike height. This calculation is done for all the 18 measurement points for up to 2 meter of sea level rise at increments of 10 cm. The results are presented in Table 38 and Table 39 and are calculated using the ratio between the increase in hydraulic load and sea level rise as presented in Ruessink (2019). In the subsections illustration are provided to relate the excess dike height or shortage to a location in the hinterland of the Haringvliet sluices. These illustrations only show the sea level rise at a 50 cm increment. Figure 69 to Figure 72 show the situation for the 1 L/s/m overflow criteria and Figure 73 to Figure 76 show the situation for the 10 L/s/m criteria. Al the figures in this appendix show which dike sections are most vulnerable and therefor fail first in case of rising water levels at the North Sea, all according to the model of Ruessink (2019).

Table 38 Excess dike height (in cm) per dike section per sea level rise (cm) for the case that the overflow criteria of all dike sections is set at 1 L/s/m. Location of each dike section can be found in Figure 68. The light red colour indicates when a dike height is not sufficient anymore.

	Sea level rise (cm)																			
Dike #	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
1	70	59	47	35	23	12	0	-12	-24	-35	-47	-59	-71	-82	-94	-106	-118	-129	-141	-153
2	62	56	51	46	40	35	29	24	19	13	8	2	-3	-9	-14	-19	-25	-30	-36	-41
3	53	45	36	28	20	11	3	-5	-14	-22	-30	-39	-47	-55	-64	-72	-80	-89	-97	-105
4	44	33	22	11	0	-10	-21	-32	-43	-54	-65	-76	-87	-98	-108	-119	-130	-141	-152	-163
5	110	102	94	85	77	69	60	52	44	35	27	19	11	2	-6	-14	-23	-31	-39	-48
6	66	59	52	46	39	33	26	20	13	7	0	-7	-13	-20	-26	-33	-39	-46	-52	-59
7	115	99	83	67	51	35	19	3	-13	-29	-45	-61	-77	-93	-109	-124	-140	-156	-172	-188
8	122	112	102	92	82	71	61	51	41	31	21	11	1	-9	-19	-29	-39	-49	-59	-70
9	135	125	115	105	95	85	75	65	55	45	35	25	15	5	-5	-15	-25	-35	-45	-55
10	92	86	79	72	65	58	52	45	38	31	24	18	11	4	-3	-10	-17	-23	-30	-37
11	96	90	85	79	73	67	61	56	50	44	38	32	27	21	15	9	3	-3	-8	-14
12	139	135	131	128	124	120	117	113	109	106	102	98	95	91	87	84	80	76	73	69
13	240	231	222	213	205	196	187	178	169	160	151	142	133	125	116	107	98	89	80	71
14	155	148	142	135	128	121	114	107	101	94	87	80	73	66	59	53	46	39	32	25
15	231	225	219	213	207	201	195	189	182	176	170	164	158	152	146	140	134	128	122	116
16	267	264	262	260	257	255	253	250	248	245	243	241	238	236	234	231	229	226	224	222
17	57	49	42	34	26	19	11	4	-4	-12	-19	-27	-34	-42	-49	-57	-65	-72	-80	-87
18	148	144	140	136	132	128	124	120	116	112	108	104	100	96	92	88	84	80	76	72

Table 39 Excess dike height (cm) per dike section per sea level rise (cm) for the case that the overflow criteria of all dike sections is set at 10 L/s/m. Location of each dike section can be found in Figure 68.

	Sea level rise (cm)																			
Dike #	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
1	117	108	98	89	79	69	60	50	41	31	22	12	3	-7	-17	-26	-36	-45	-55	-64
2	129	125	121	117	113	109	105	101	96	92	88	84	80	76	72	68	64	59	55	51
3	108	100	92	84	76	68	60	52	44	36	29	21	13	5	-3	-11	-19	-27	-35	-43
4	110	99	89	78	67	57	46	36	25	14	4	-7	-18	-28	-39	-49	-60	-71	-81	-92
5	113	105	98	90	83	75	68	60	53	45	38	31	23	16	8	1	-7	-14	-22	-29
6	88	80	71	63	54	46	37	29	20	12	3	-5	-14	-22	-31	-40	-48	-57	-65	-74
7	152	140	128	116	105	93	81	69	57	45	33	21	9	-2	-14	-26	-38	-50	-62	-74
8	178	169	159	150	141	131	122	112	103	94	84	75	65	56	46	37	28	18	9	-1
9	156	148	140	132	124	117	109	101	93	85	78	70	62	54	46	38	31	23	15	7
10	143	136	130	123	117	110	104	97	91	84	77	71	64	58	51	45	38	32	25	19
11	123	117	110	104	98	91	85	79	72	66	60	53	47	41	34	28	22	15	9	3
12	192	188	184	180	176	172	168	165	161	157	153	149	145	141	137	133	129	125	121	117
13	260	252	244	237	229	221	213	205	197	189	181	173	165	157	149	141	133	125	117	109
14	192	186	179	172	166	159	153	146	139	133	126	120	113	107	100	93	87	80	74	67
15	253	247	241	235	229	222	216	210	204	198	191	185	179	173	167	161	154	148	142	136

16	267	264	262	260	257	255	253	250	248	245	243	241	238	236	234	231	229	226	224	222
17	107	100	92	85	78	71	63	56	49	42	35	27	20	13	6	-2	-9	-16	-23	-30
18	176	172	167	163	158	153	149	144	140	135	130	126	121	117	112	108	103	98	94	89

L.1 Excess dike height reduction as a response on sea level rise for the 1 L/s/m criteria

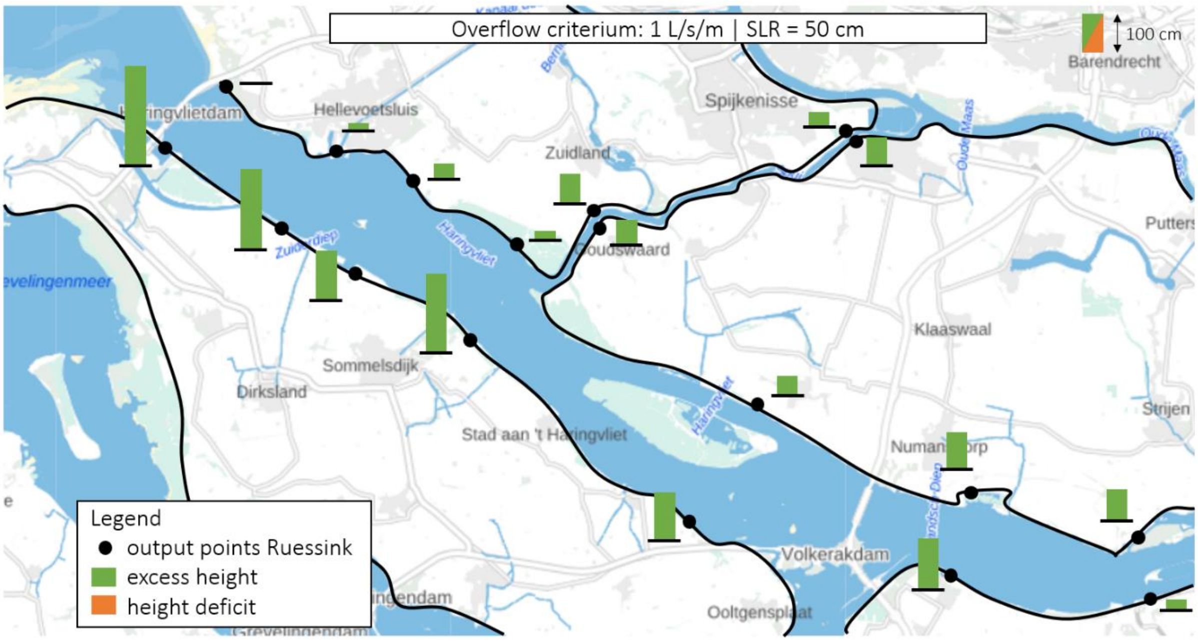

Figure 69 Excess dike height per sea level rise for all the dike sections included in the Hydra-BS model (50 cm SLR, Overflow criterium 1 L/s/m)

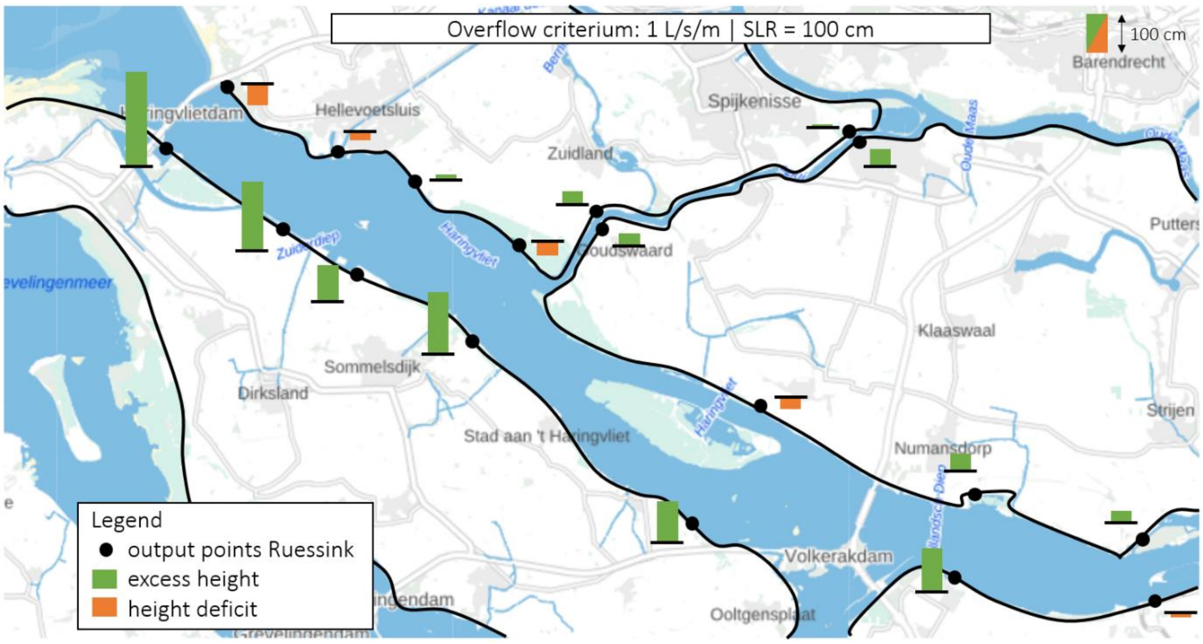

Figure 70 Excess dike height per sea level rise for all the dike sections included in the Hydra-BS model (100 cm SLR, Overflow criterium 1 L/s/m)

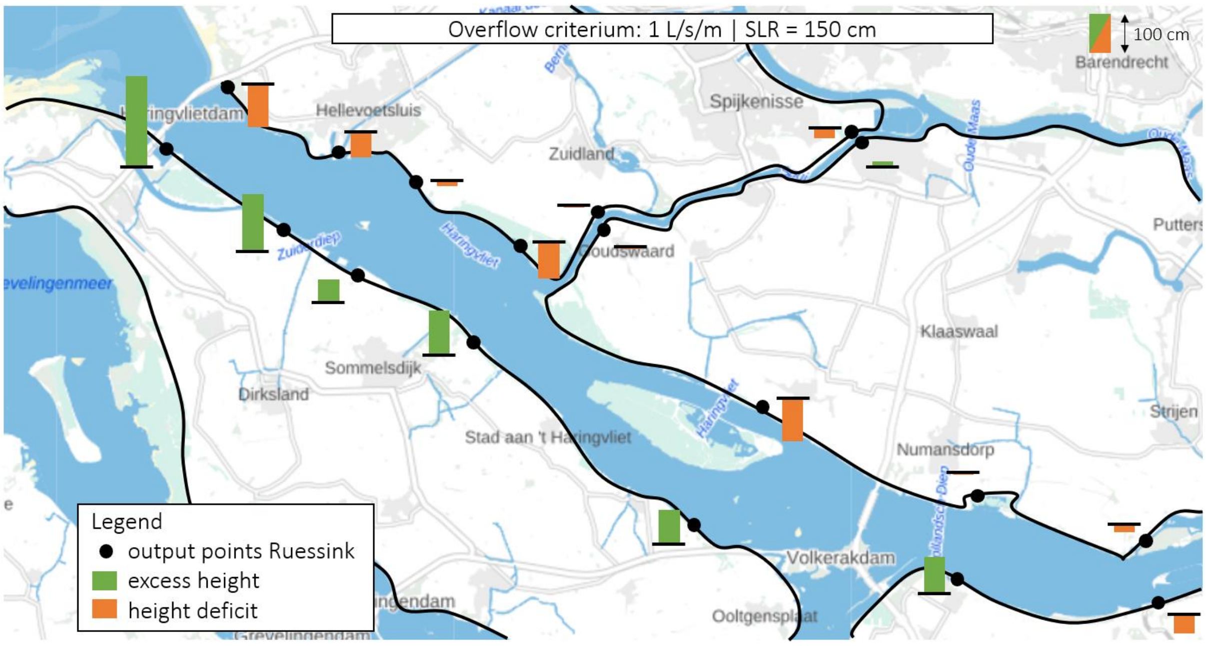

Figure 71 Excess dike height per sea level rise for all the dike sections included in the Hydra-BS model (150 cm SLR, Overflow criterium 1 L/s/m)

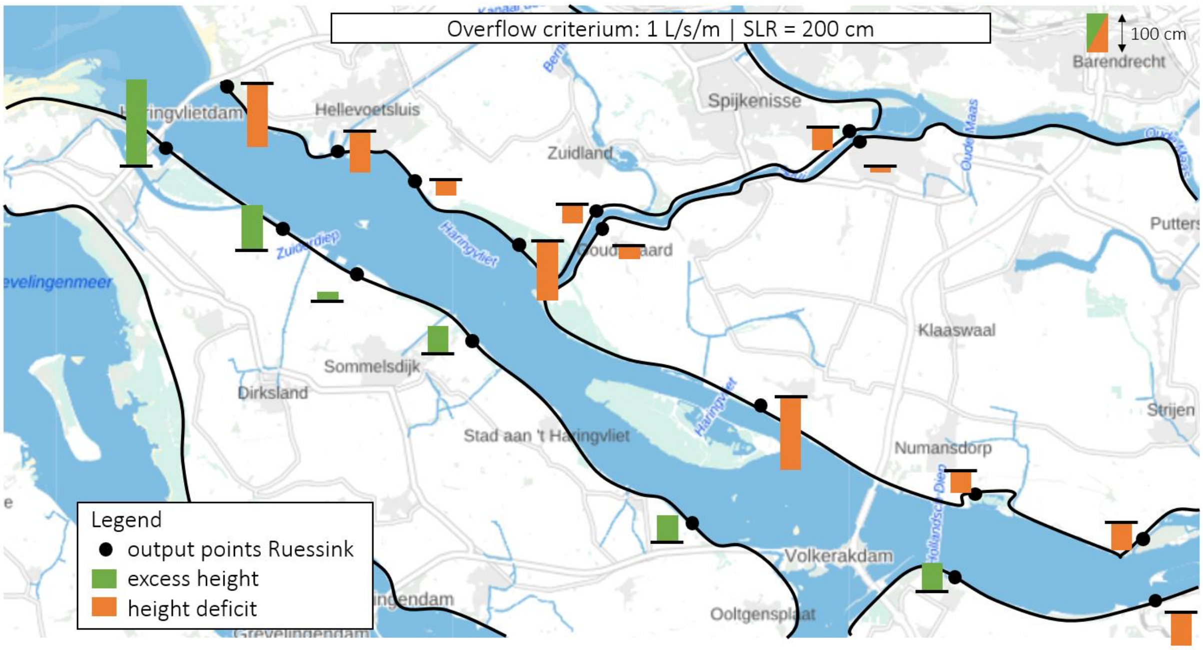

Figure 72 Excess dike height per sea level rise for all the dike sections included in the Hydra-BS model (200 cm SLR, Overflow criterium 1 L/s/m)

L.2 Excess dike height reduction as a response on sea level rise for the 10 L/s/m criteria

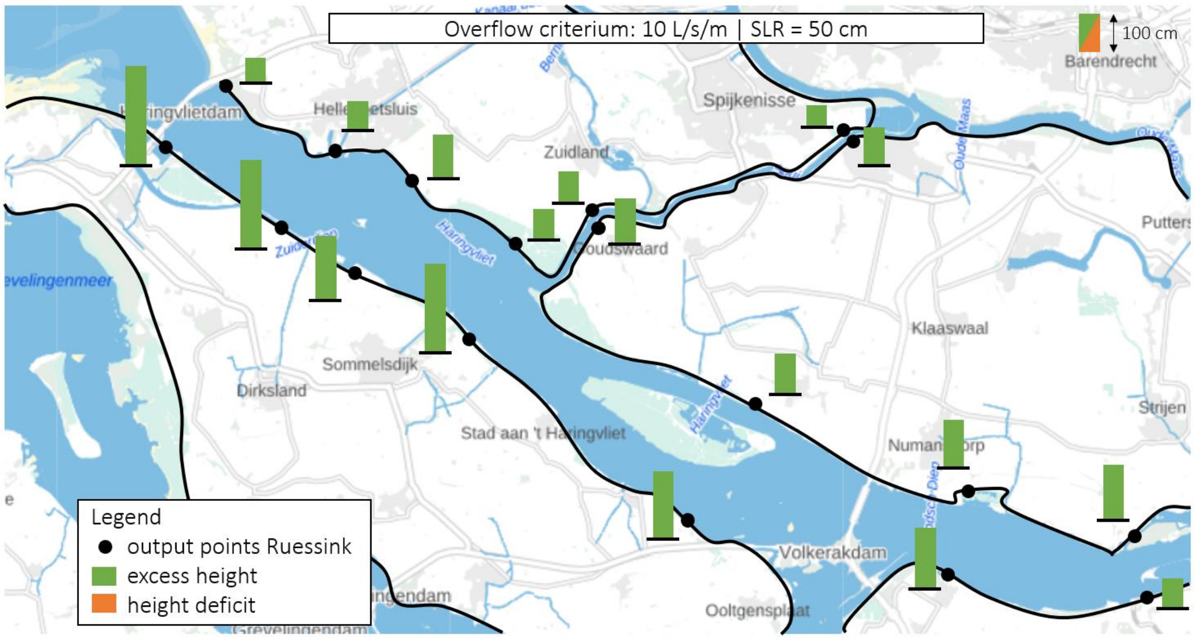

Figure 73 Excess dike height per sea level rise for all the dike sections included in the Hydra-BS model (50 cm SLR, Overflow criterium 10 L/s/m)

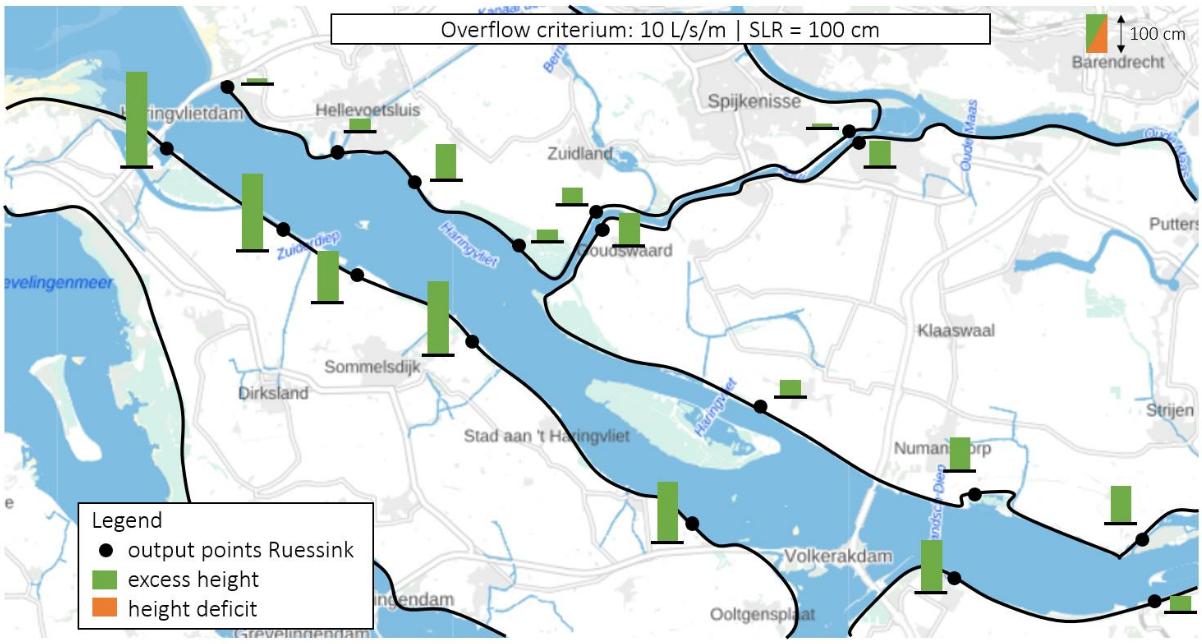

Figure 74 Excess dike height per sea level rise for all the dike sections included in the Hydra-BS model (100 cm SLR, Overflow criterium 10 L/s/m)

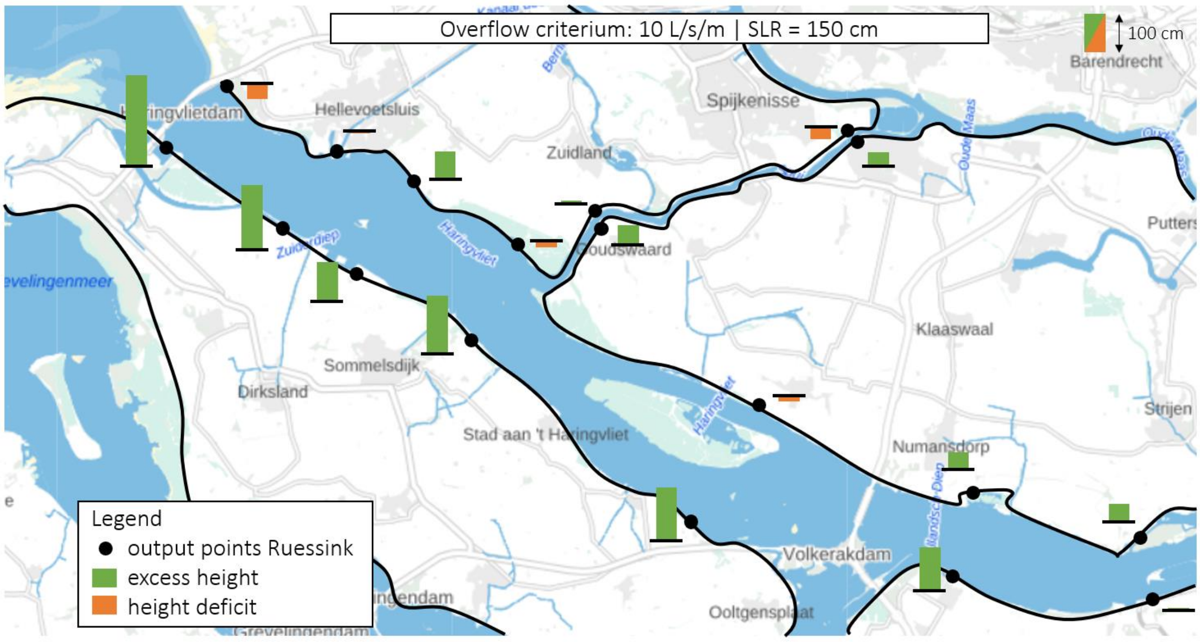

Figure 75 Excess dike height per sea level rise for all the dike sections included in the Hydra-BS model (150 cm SLR, Overflow criterium 10 L/s/m)

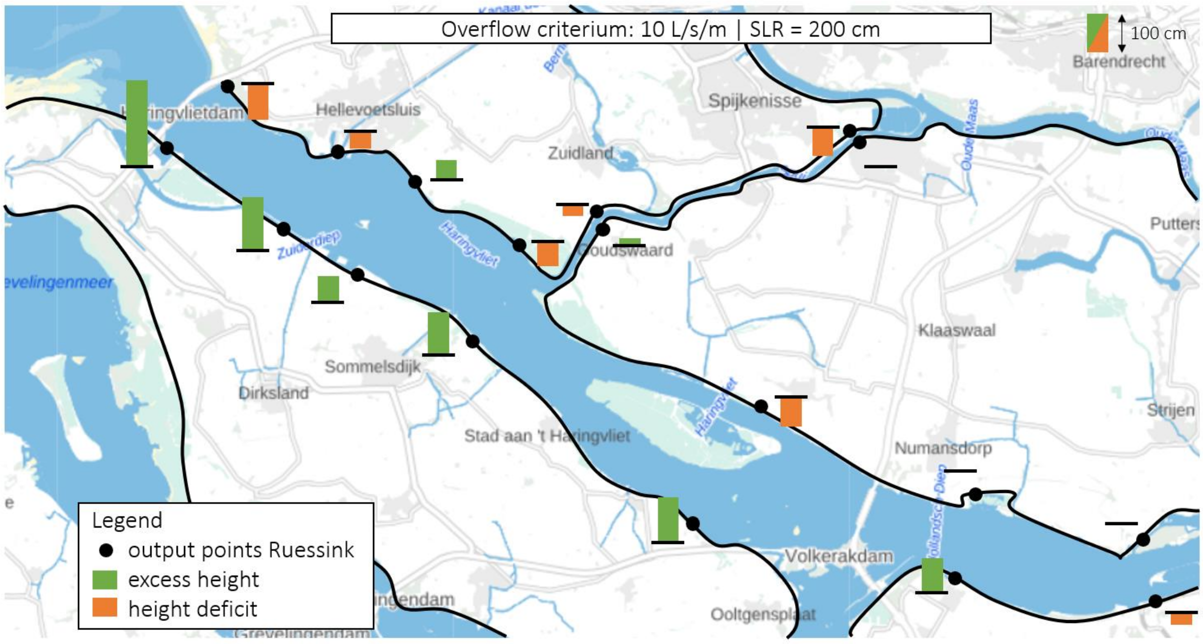

Figure 76 Excess dike height per sea level rise for all the dike sections included in the Hydra-BS model (200 cm SLR, Overflow criterium 10 L/s/m)

Appendix L

Addition representations of Adaptation Pathways

This appendix contains additions representations of the Adaptation Pathways of Chapter 8.

Unclear pathways: is four mitigation actions to much?

Figure 77 is showing how including all four mitigations actions makes the Pathways become unclear and unsuccessful in reaching the goal set for the use of Adaptation Pathways. In Figure 77 the base adaptation pathway of the first three mitigation is shown (orange, blue and red actions) and just a single branch of including a first action is added. The extra path shown is first action D, then action A, then action B and lastly action. Much more combinations are possible when including a fourth action. Figure 77 shows that already including a single branch makes it complicated. Therefor it is chosen to first elaborate on only three mitigation options.

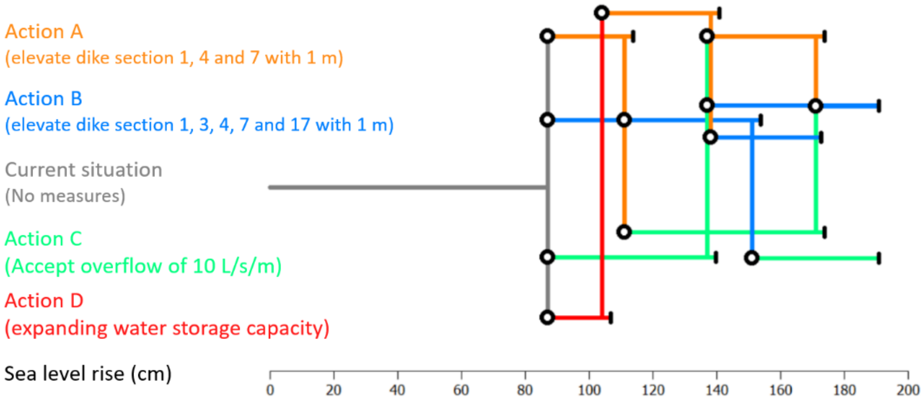

Figure 77 The result of including a fourth mitigation action in the Adaptative Pathway (Action A to D are found respectively from top to bottom on the left side of the illustration.

Full bandwidth of the climate scenarios on the x-axis (RCP4.5 and RCP8.5)

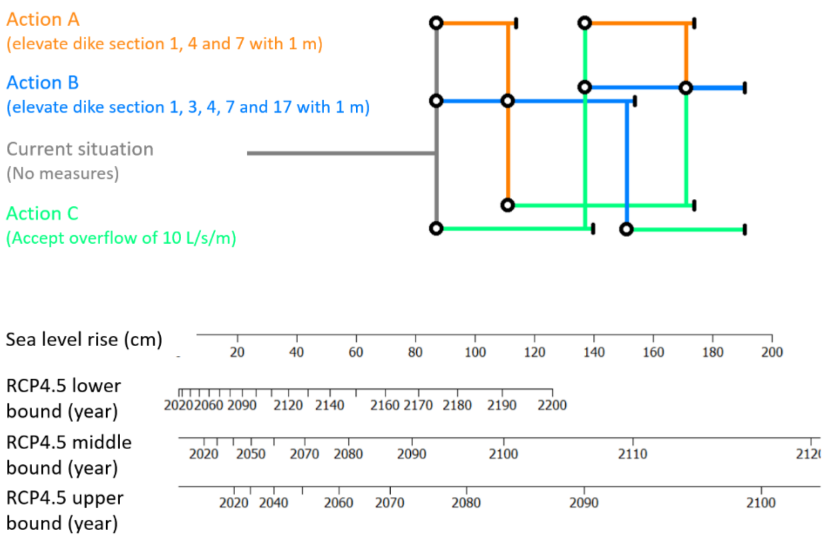

Figure 78 Full bandwidth of climate scenario RCP4.5 on the axis of the Adaptation Pathway

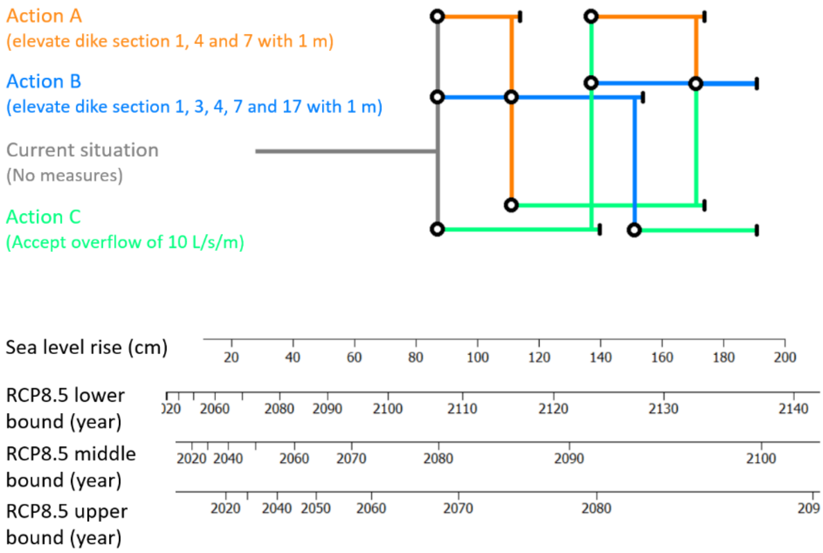

Figure 79 Full bandwidth of climate scenario RCP8.5 on the axis of the Adaptation Pathway