The missing link in adaptive delta management

Insights on the potential of pumps in reducing flood risk under sea level rise and adaptive social learning to improve decision-making in the Rhine-Meuse estuary

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Graduation project

MSc Hydraulic Engineering and
MSc Science Education and Communication

HKV LIJN IN WATER

TU Delft Delft University of Technology

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Insights on the potential of pumps in reducing flood risk under sea level rise and adaptive social learning to improve decision-making in the Rhine-Meuse estuary

by

Cees Oerlemans

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Cover: Map depicting land use (e.g. residential) in the Rhine-Meuse estuary (Based on data of European Environment Agency (2020))

Preface

With this thesis, I conclude my MSc studies in both Hydraulic Engineering and Communication Design for Innovation at Delft University of Technology. The combined effort in both studies explores climate adaptation in the Rhine-Meuse estuary from two perspectives: one is mainly physical and the other socio-political. The great pleasure with which I have been working on this project is largely due to the challenge of integrating both - at first sight - distinct subjects. In delta management, the engineering-oriented and communication-oriented perspectives can reinforce each other in many more areas than I could have imagined in advance.

I would not have been able to carry out this research without the guidance and support of my supervisors. It was a pleasure to conduct this research, and you definitely played a big role in that. I would like to express my sincere gratitude to all my supervisors for their constructive feedback and help to discover the most relevant direction for this research. Maarten for your sharp questions, enthusiasm to collectively learn and provide numerous valuable insights; Ton for your extensive knowledge about the water system and helping me to solve modelling issues; Mark for all your help regarding the research methodology, the countless times you read my manuscript and your active involvement in the Delta Futures Lab; Eva for your positivity and bringing abstract notions down to collaboration within teams and Matthijs for your scientific criticism which enhanced the progress meetings and providing interesting links between the physical and socio-political perspective from your daily experience. Also, thanks to the enjoyable working environment at HKV - Lijn in water, where I carried out part of this research.

Then I want to thank the interviewees, on behalf of the Ministry of Infrastructure and Water Management, Rijkswaterstaat, Waterschap Hollandse Delta, Port of Rotterdam, Municipality of Rotterdam, Province of South Holland and Delta Commissioner's staff. The interviews have enriched my view on delta management in general and specifically the Knowledge Program Sea Level Rise. I want to thank Martine Rutten and Jos Timmermans for setting up the Delta Futures Lab and uniting me with fellow graduating students in the fascinating field of delta management. Moreover, I want to express my gratitude towards the initiators of Delta21; Huub Lavooij and Leen Berke. Your everlasting motivation to keep the delta safe and your innovative solutions provided me with the opportunity to work on a unique case study. Thanks to Ties Rijcken for reviewing parts of this thesis and providing valuable feedback.

I would like to thank my parents and brother for their infinite support regardless of what I do. I am grateful to my 'old' friends - and all the new friends I made during my period of study - for all the great times we had. A last word of thanks is for Florence, for putting my feet back on the ground and supporting me in every possible way.

I wish you a pleasant read.

Cees Oerlemans
Delft, December 2020

Summary

Decision-makers in low-lying coastal zones are confronted with uncertain developments around flood risk. As the stakes are enormous, the consequences of wrong decisions can be tremendous. Many drivers influence flood risks and can be related to demographic trends, economic developments, technological developments, climate change and land subsidence. These drivers are surrounded by large uncertainties, which requires delta management to be adaptive. This research offers insights about adaptive delta management for the Rhine-Meuse estuary from three perspectives: a physical, a socio-political and a integrated perspective.

Part I - Physical perspective

In the physical perspective, the effect of pump capacity on the water system of the Rhine-Meuse estuary is quantified; one of the adaptation options against sea level rise. To assess the adaptation potential of pumps, the case study Delta21 is used; a plan to construct an artificial lake with an area of 35 km^2 next to the Maasvlakte 2 in combination with a pump capacity of 10 000 m^3/s. This leads to the main research question for the physical perspective:

> **What is the potential of Delta21 in reducing both the hydraulic loads and failure probabilities of flood defences in the Rhine-Meuse estuary under sea level rise?**

To answer this research question, a computationally efficient SOBEK-3 model of the Rhine-Meuse estuary is refined to make hydrodynamic computations for the Rhine-Meuse estuary with and without the intervention of Delta21. SOBEK-3, together with a number of python applications (MHWp5), allows to make hydrodynamic computations for different boundary conditions; storm surges, discharges and steps of sea level rise up to 2 meters. A comparison is made between the current water system and a system with Delta21 following three lines of reasoning: 1) influence on water flows - water levels, discharges and flow velocities - at different locations, 2) influence on the hydraulic loads described by water level frequency lines which include probabilistic information about the exceeding probability of boundary conditions and 3) effect on probabilities of the most important failure mechanisms piping and height using fragility curves. The Rhine-Meuse estuary is divided into four sub-areas depending on the dominant hydrodynamic process: storm surge dominant area, flood storage dominant area, discharge dominant area and transition area (Figure 1).

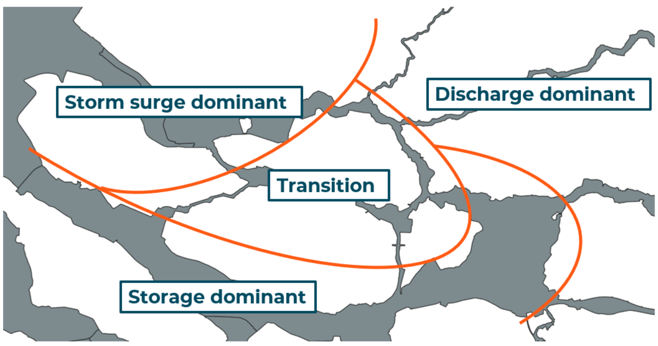


Figure 1: Sub-areas ot the Rhine-Meuse estuary based on dominant hydrodynamic processes.

For the water flows, the influence of Delta21 is largest when the Europoort barrier does not fail. In that case, along with a discharge of 10 000 m^3/s and a storm surge of 3.54 m, the maximum water level in storm surge area is reduced with 1.5 m, in flood storage dominant area with 1 m, in the discharge dominant area with 20 cm and in the transition area with 60 cm. These results are based on one realization and not on a probabilistic set of multiple realizations.

Delta21 succeeds in reducing the hydraulic loads throughout the entire Rhine-Meuse estuary. At the same time, these reductions differ depending on the dominant area. The reduction of governing water levels is based on water level frequency lines for various steps of sea level rise. For the storm surge dominant area, the reduction in governing water level is 10-20 cm, for the flood storage area 1-1.5 m, for the discharge dominant area 10-40 cm and for the transition area 30-60 cm.

The difference in failure probabilities follows a similar pattern as the reduction in hydraulic loads. For a sea level rise of 0 meters, 45 percent of the section fails on either piping or height in the current system (Figure 2). For Delta21, this percentage is equal to 30 percent. In case of 1 meter sea level rise, 77 percent and 42 percent do not meet the norm for the current system and Delta21 respectively. For 2 meters, 82 percent of the flood defences in the current system and 65 percent in a configuration with Delta21 do not have sufficient resistance. An improved Europoort barrier increases the number of sufficient section by 3 percent, but only in case of limited sea level rise (0 - 0.25 m).

To conclude, Delta21 succeeds in lowering the hydraulic loads and corresponding failure probabilities. At the same time, reductions are disproportionately over the Rhine-Meuse estuary leading to low reductions in some sub-areas. This can be attributed to the open connection between the Rhine-Meuse estuary and the sea among others. As the Rhine-Meuse estuary is a complex system with multiple lines of defence, research to the effects of a portfolio of interventions is recommendable.

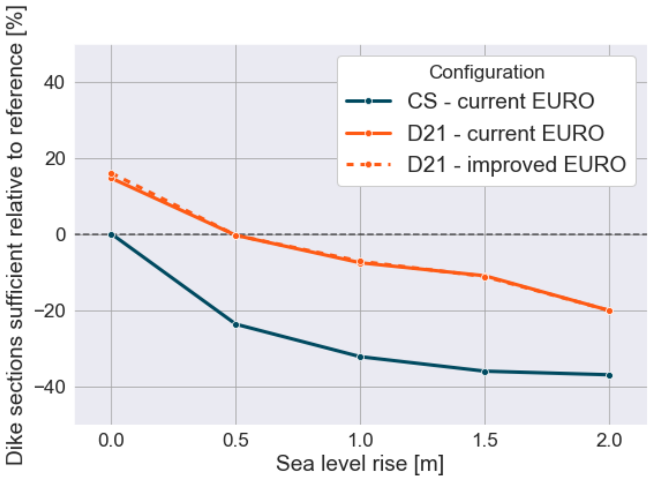


Figure 2: Percentage dike sections that meets the norm for three different configurations relative to the reference. For the reference scenario - current system without sea level rise - 45 percent of dike sections do not meet the norm for piping or height. The reference scenario is depicted with a horizontal dashed black line (0%), the current system is depicted in blue and Delta21 is depicted in orange. For Delta21, a distinction is made between the current failure probability (1/100 per closure) and an improved failure probability (1/1000 per closure) of the Europoort barrier. Due to sea level rise, the percentage of dike sections that meets the norm decreases, indicated by a negative percentage. In case of Delta21 and a sea level rise of 0.5 meters, the percentage of dike sections that does not meet the norm is equal to 45 percent, which is in turn equal to the percentage in the reference scenario. The total number of dikes sections in the domain is 526.

Part II - Socio-political perspective

Many actors are involved in delta management of the Rhine-Meuse estuary. Learning and decision-making takes place in a network structure, which means that knowledge and decisions do not belong to one single actor, but those decisions come about during interactions between various groups of actors. Not only the decisions need to be adaptive to cope with uncertain circumstances, but the learning process itself must also become adaptive. In the socio-political perspective, the relation between decision-making and learning is investigated to improve adaptive social learning. This answers the main research question:

> How can factors in decision-making and social learning be integrated into a conceptual model and support adaptive social learning in the Rhine-Meuse estuary?

A literature study identified relevant frameworks and theories which provided the basis for a conceptual model. In the conceptual model, theories are combined related to agenda-setting, decision-making under uncertainty, social-learning and framing. With this conceptual model, a process-tracing analysis is performed including semi-structured interviews, background document reviews and observations. A cross-case study analysis is applied to two cases: the Delta Program and the Knowledge Program Sea Level Rise.

A longitudinal analysis into the Delta programs showed that the frame and narrative changed over time which affected the interplay between learning and decision-making. The first phase - from 2007-2011 - concerned the initiation of the Delta Program and had a strong political character that succeeded in achieving three goals: 1) creating awareness and setting adaptation on the political agenda, 2) getting their political frame accepted by other actors and 3) already gained some progress in converging the frame of the problem and solution direction. The second phase - from 2011 to 2015 - worked towards the Delta Decisions in which the interaction was sought with other disciplines. In the last phase - from 2015 to 2020 - the shift was made from exploration to implementation. The preferential strategy includes incremental and adaptation actions are primarily aimed at maintaining the status quo.

Five different learning types can be distinguished in the Delta Program. A scientific learning frame mainly focused on sound science, building an evidence base and performing technical studies. The joint fact finding frame concerning development of knowledge with a diverse group of actors to create mutual understanding and broad support base for new knowledge. The cross-project learning frame is about sharing best practices between different projects. Learning by doing stresses that learning is achieved to practice, self-perfections and a series of minor innovations. The last frame - system learning - refers to reflection and focus directly on the learning potential of various activities. System learning is vital for adaptive social learning, as it allows us to evaluate and adjust learning practices depending on the changing circumstances.

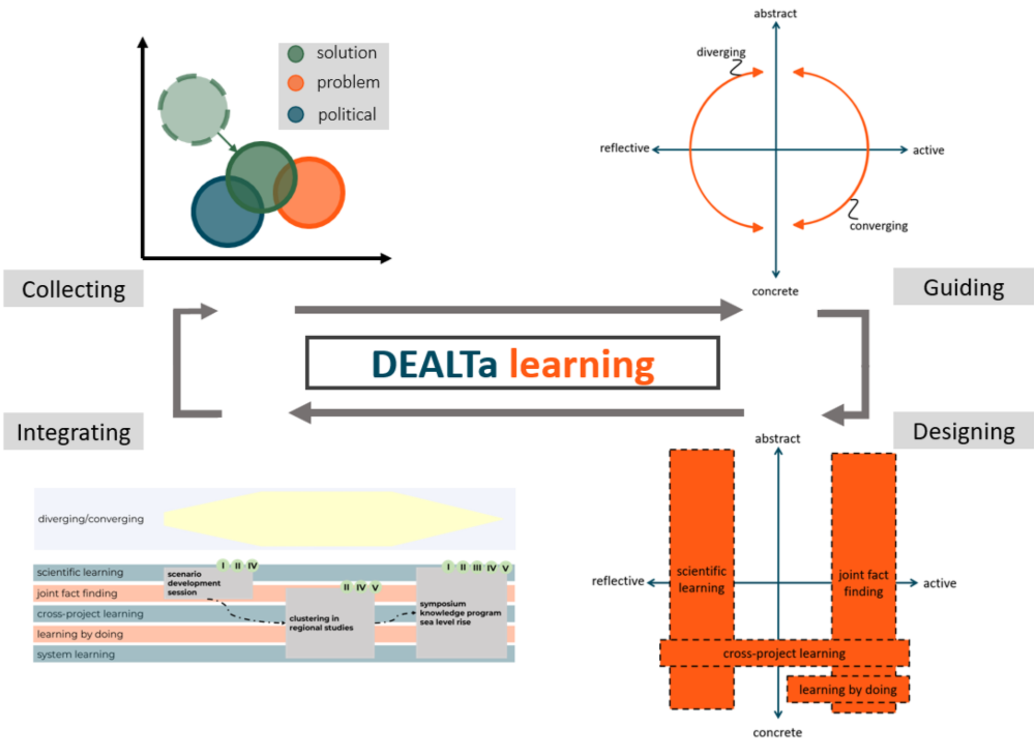


Figure 3: DEALTa learning handbook. The four steps of collecting, guiding, designing and integrating are depicted in the handbook. The collecting step is about analysing the different frames of the solution, problem and political stream. Subsequently, the choice can be made for diverging or converging. In the designing steps, learning types can be selected that form the basis for learning activities. In the last step, the learning activities can be integrated and aligned to other activities.

For the Knowledge Program Sea Level Rise, it is argued that the current focus is on convergent thinking within the five tracks of the Knowledge Program. Although this is beneficial in reaching consensus, it constrains the learning potential. More alternating between convergent and divergent design thinking and aligning learning activities to the circumstances can enhance adaptive social learning. The main challenges are to 1) communicate in a polarized world, 2) keep local parties involved, 3) unravel relations between parallel strategies, 4) provide guidance and formulate accountable goals, 5) explore shifts and 6) use both ”water level follows function” and ”function follows water level”. It is shown how roadmaps of various successive learning activities can be designed following the DEALTa learning handbook (Figure 3). In this way, learning is put at the heart of the Knowledge Program without compromising the efficiency of decision-making. The DEALta learning handbook delivers suggestions about how adaptive social learning can be applied by actors in the Rhine-Meuse estuary.

Part III - Integrated perspective

The integrated perspective is aimed to integrate the physical and socio-political perspective within technical studies. It provides an answer to the last research question:

> How can the socio-political and physical perspective be integrated to enhance adaptive social learning in technical studies?

Three steps have been taken to answer this research question; dissecting, rebuilding and assembling.

Dissecting is about identifying the components of technical studies that influence adaptivity; scenarios, scales and interventions. Scenarios, scales and interventions all influence the solution space. These might seem to be purely technical aspects, but determine to a large extent the room for adaptive social learning. Predictive scenarios - What will happen? - and exploratory scenarios - What could happen? are problem focused as these scenarios end up with projections or explorations. Normative scenarios - How can a specific future be realized? - make use of backcasting and are more solution-focused. This means that the type of scenario has a considerable impact on the kind of research and the connected learning features. Actors at different geographical and sectoral scales have different perceptions. As the policy sector winners and loses differ at scale, the system boundary of a technical study also interferes with how the outcomes are perceived. Hence, it is recommended to use a multi-scale approach whenever possible. There exists ambiguity about adaptivity of interventions.

Rebuilding refers to the connection of scenarios, scales and interventions to socio-political aspects within collaborations and communications. Methods are proposed on how to communicate the results of studies with a hybrid approach of both qualitative and quantitative elements. Among others, it is advised to make use of imaginaries. Imaginaries are not solely a normative construction, but a contested and politicized configuration at the same time. In other words, imaginary shape expectations which activate the socio-political network.

Assembling relates to gathering all the information of technical studies and connecting it to the socio-political surrounding. Frames about problems, solutions and politics compose together a solution space which contains solutions that are feasible and legitimate. It is shown how new knowledge affects the solution space within projects. The solution space stresses that non-decisions are also decisions, as waiting or delaying decisions affects the solution space.

The integrated perspective provides the link on how the physical and socio-political perspective can be integrated in practice and contributes to adaptive delta management.

Contents

Chapter 1

Introduction

1.1 Research motivation

Worldwide, decision-makers in low-lying coastal zones are confronted with uncertain developments around flood risk. As the stakes are enormous, the consequences of wrong decisions can be tremendous. Many drivers influence flood risks and involve demographic trends, economic developments, technological developments, climate change and land subsidence. This means that the criteria for assessment of flood risk management strategies are seldom solely technical but involve consideration of economics, environment and politics. Hence, flood risk management is shifting towards more integrated and adaptive modes of governance that accept uncertainties as an 'unavoidable fact of life' (Brugnach et al., 2008).

The Rhine-Meuse estuary is no exception to the aforementioned challenges. With a dense population of people and economic activities (the Rotterdam region is responsible for 8% of the GDP of the Netherlands), there is a large incentive to reduce flood risk. Sea level rise, increasing peak discharges and changing storm conditions increase hydraulic loads in the estuary, while land subsidence leads to a reduction in resistance of flood defences. At the same time, important water infrastructure that guarantees the flood risk safety in the Rhine-Meuse estuary is approaching its functional life-time. It remains to be seen if the current strategy is preferable to satisfy the flood risks for the coming decades or centuries, or if new strategies need to be developed for the Rhine-Meuse estuary.

1.2 Problem statement

Changing climate results in higher water levels which increase the probability of floods in the Rhine-Meuse estuary. The current strategy that is developed by the Delta Program reduces the flood risk by increasing the resistance. In other words, dike reinforcements compensate for the larger hydraulic loads in the Rhine-Meuse estuary to keep the flood risk within socio-politically established norms. An alternative adaptation option is to reduce the hydraulic loads using pumps. However, the potential of pumps in reducing the hydraulic loads in the Rhine-Meuse estuary is unknown. Hence, it is not possible to assess whether pumps are a genuine alternative for dike reinforcements, or if a combination of dike reinforcements and pumps is a promising way to adapt against sea level rise.

Recently, the theory of adaptive delta management gained prominence in flood risk management in the Netherlands. This is motivated by two key concerns; 1) society can no longer afford to manage floods and droughts reactively and 2) existing scenario-planning can not support the dynamic adaptation over time in response to unknown future developments. Although this approach introduces some new features, it must be noted that flood risk management has always had an adaptive character. However, as the rate of change is increasing, the socio-political system needs to increase its adaptability in the Rhine-Meuse estuary. Although there are many studies about the theoretical aspects of adaptive delta management, there are very limited empirical studies that connect adaptive delta management to social learning. Lin et al. (2017) state that very little work has been done to evaluate the current use of adaptive delta management and its utility to practitioners and decision-makers.

Moreover, flood risk management is in theory "neutral" to the choice of type and order of measures. In practice, however, the selected or preferred strategy often contains incremental measures in the short term, firmer measures in the middle term and (possibly) transformational measures in the long term. Incremental measures imply a gradual improvement in the resilience of the present system. Therefore, they can be considered to be protective and foster lock-in by increasing transfer costs to a new or significantly modified system (Bloemen et al., 2019). Several scholars have addressed the difficulty of adopting transformational strategies (Folke et al., 2010; de Haan et al., 2014; Lonsdale et al., 2015; Rijke et al., 2013) into flood risk management but this has not yet been tackled completely.

1.3 Research objectives

This research offers insights about delta management for the Rhine-Meuse estuary from three perspectives: a physical, a socio-political and an integrated perspective. This leads to three research objectives.

For the physical perspective, the research objective is to quantify the potential of pumps in reducing the hydraulic loads and failure probabilities of the flood defences in the Rhine-Meuse estuary under sea level rise. The physical perspective is centred around the case study of Delta21: a plan to construct an artificial lake with an area of 35 km^2 next to the Maasvlakte 2 in combination with a pump capacity of 10 000 m^3/s. The objective of Delta21 is threefold: 1) improve flood risk protection, 2) improve the ecological condition and 3) provide a positive contribution to the energy transition. The plan consists of different components, which is elaborated in more detail in the remainder of the report (Section 2.3). The objective of the physical perspective is reached by comparing the current configuration of flood defences with a configuration including Delta21.

For the socio-political perspective, the research objective is to improve decision-making in delta management by enhancing adaptive social learning. As denoted in the problem statement, there is a gap in adaptative delta management between decision-making and social learning. Hence, the concept of adaptive social learning is coined to address the interactions between decision-making and learning explicitly. The processes around adaptive social learning are investigated in the context of the Delta Program, which is a collaboration between the national government, provinces, municipalities and water boards. Special focus is on one of the affiliated sub-programs: the Knowledge Program Sea Level Rise. The Knowledge Program Sea Level Rise (in Dutch: Kennisprogramma Zeespiegelstijging) is a joint research program of the minister of Infrastructure and Water Management, and the Delta Commissioner. Together with other partners, the program aims to deliver insight on the rate of sea level rise, the consequences for water-related challenges and spatial adaptation. This research is set out to assess how learning occurs in practice, and how its effectiveness and flexibility can be increased to stimulate adaptive social learning in the Rhine-Meuse estuary.

For the integrated perspective, the research objective is to integrate the physical and socio-political perspective in technical studies. By integrating the physical and socio-political perspective, it investigated how the theoretical notions from the first two perspectives can be applied in practice.

1.4 Research questions

Along with the introduced perspectives, multiple research questions have been formulated. In the following sections, research questions are discussed related to the physical, socio-political and integrated perspective.

1.4.1 Physical perspective

The research objective for physical perspective is to quantify the potential of pumps in reducing the hydraulic loads and failure probabilities of the flood defences in the Rhine-Meuse estuary under sea level rise. This leads to the first research question:

> **RQ-I: What is the potential of Delta21 in reducing both the hydraulic loads and failure probabilities of flood defences in the Rhine-Meuse estuary under sea level rise?**

Five sub-questions have to be answered to solve the main research question and make the research question more transparent:

SQ-I.a What are the present and future boundary conditions for the Rhine-Meuse estuary? (Chapter 2)
First, the present and future boundary conditions are evaluated. This provides the necessary information about the boundary conditions for modelling and gives insight into the development of adverse climate change effects.

SQ-I.b How can the hydrodynamic behaviour of the current system, and the system with Delta21, be modelled with a computationally efficient model? (Chapter 3)
To quantify the impact of Delta21 we need a modelling approach that allows comparing two configurations. The current configuration and a configuration with pump capacity and extra storage capacity.

SQ-I.c What is the influence of Delta21 on the water flows in the Rhine-Meuse estuary? (Chapter 4)
Water systems are characterized by complex interactions. The main hydraulic processes and system interactions are evaluated to enhance insights about the impact of Delta21.

SQ-I.d What is the influence of Delta21 on the hydraulic loads in the Rhine-Meuse estuary? (Chapter 5)
Climate change is expected to raise the hydraulic loads in the Rhine-Meuse estuary. Pump and storage capacity could reduce the hydraulic loads in the Rhine-Meuse estuary.

SQ-I.e How do the failure probabilities of flood defences change due to Delta21, taking into account the most important failure mechanisms? (Chapter 6)
In the end, flood defence systems are evaluated against safety targets. The influence on failure probabilities provides a preliminary indication about the potential of Delta21 to enhance flood risk safety in the Rhine-Meuse estuary.

1.4.2 Socio-political perspective

The research objective for the socio-political perspective is to improve decision-making in delta management by enhancing adaptive social learning. This leads to the second research question:

> **RQ-II: How can factors in decision-making and social learning be integrated into a conceptual model and support adaptive social learning in the Rhine-Meuse estuary?**

The Delta Program and Knowledge Program Sea Level rise serve as case-studies in this research. The following sub-questions are formulated to support the main-research question:

SQ-II.a How can decision-making be characterized in delta management of the Rhine-Meuse estuary? (Chapter 8 & 10)
First, the current decision-making structure is analysed. Insights in the decision-making characteristics and actors serve as a point of departure for the socio-political perspective.

SQ-II.b What theories and frameworks are important in social learning and decision making in delta management? (Chapter 11)
Valuable factors in decision-making and (social) learning are extracted from literature. The answer to these research questions provides the necessary theoretical background.

SQ-II.c How can the insights from these theories and frameworks be combined in a conceptual model? (Chapter 12)
The insights of the theories and frameworks are combined in a conceptual model for adaptive social learning. This conceptual model covers both decision-making and social learning mechanisms.

SQ-II.d How is the concept of learning defined and used by the Delta Program? (Chapter 13)
To understand the perspective of the Delta Program, it is interesting how the Delta Program defines and uses the concept of learning. This can be used to improve the conceptual model.

SQ-II.e How can the conceptual model be used to enhance adaptive social learning in the Knowledge Program Sea Level Rise? (Chapter 14)
The Knowledge Program Sea Level Rise develops knowledge for long-term delta management of the Netherlands. The conceptual model is used to develop recommendations for improving adaptive social learning which ultimately strengthens the decisions made in delta management.

1.4.3 Integrated perspective

The research objective for the integrated perspective is to integrate the physical and socio-political perspective in technical studies. This leads to the final research question:

> **RQ-III: How can the socio-political and physical perspective be integrated to enhance adaptive social learning in technical studies?**

The answer to this question is provided in Chapter 16, which covers the synthesis of this research and aims to show how both perspectives pick up on each other. The premise is that delta management can only be truly adaptive if those perspectives are integrated.

1.5 Approach

Generally speaking, there are two main approaches to (climate) risk assessment for adaptation. Most of the literature in adaptation planning can be characterised as 'science-first' (also known as 'top-down' in Pielke et al. (2012), 'science-based' in Gregory et al. (2012) or 'scenario-led' in Wilby and Dessai (2010)). In the case of climate change, multi-decadal projections from General Circulation Models (GCMs) are downscaled under a range of greenhouse gas emission scenarios. Downscaling results in local scenarios, which in turn can be fed into impact models, to determine the flood probability of flood defences for instance.

The other approach can be characterized as 'decision-centric', also known as the decision-analytic approach in Brown et al. (2011), 'policy-first' in Ranger et al. (2010), 'bottom-up' in Pielke et al. (2012), assess risk of policy in Dessai and Hulme (2007) or risk management approach Willows et al. (2003). This approach places the understanding of the decision-problem, the vulnerability of the system and the options themselves at the heart of the analysis. Hence, a complete picture of the objectives and values of stakeholders, trade-offs, constraints and decision-criteria of the decision problem is vital.

In this research, both approaches are complemented. The science-first approach is dominant in the physical perspective, while the decision-centric approach is prevailing in the socio-political perspective. Integration takes place when both approaches are linked to one another.

1.6 Thesis outline and guide for reading

This report consists of three parts (Figure 1.1). The first part elaborates on the physical perspective (Part I), the second part discusses the socio-political perspective (Part II) and the last part covers the integration (Part III).
Part I consists of six chapters. Chapter 2 elaborates on the present and future (boundary) conditions governing the water systems of the Rhine-Meuse estuary. Chapter 3 relates to the followed approach and elaborates upon the hydrodynamic model. In the subsequent three chapters, the results are discussed on the water flows (Chapter 4), hydraulic loads (Chapter 5) and failure probabilities (Chapter 6). Part I is concluded by Chapter 7 containing conclusions and discussions related to the physical perspective.

Next, part II is segmented in eight chapters. This part starts with Chapter 10 which describes the broader decision-making context. Chapter 9 discusses the methodology that is used in the socio-political perspective. In Chapter 8, the results of the actor analysis are presented. The theoretical framework in Chapter 11 provides the theoretical basis, which is translated into practice with a conceptual model (Chapter 12). Subsequently, two cases of the Delta Program (Chapter 13) and Knowledge Program

Sea Level Rise (Chapter 14) are discussed. Similar to the first part, the second part ends with a closing (Chapter 15).

Part III consists of one chapter, the synthesis in which the physical and socio-political perspectives are integrated (Chapter 16). In chapter 17, conclusions are drawn related to the main research questions. The discussion can be found in Chapter 18.

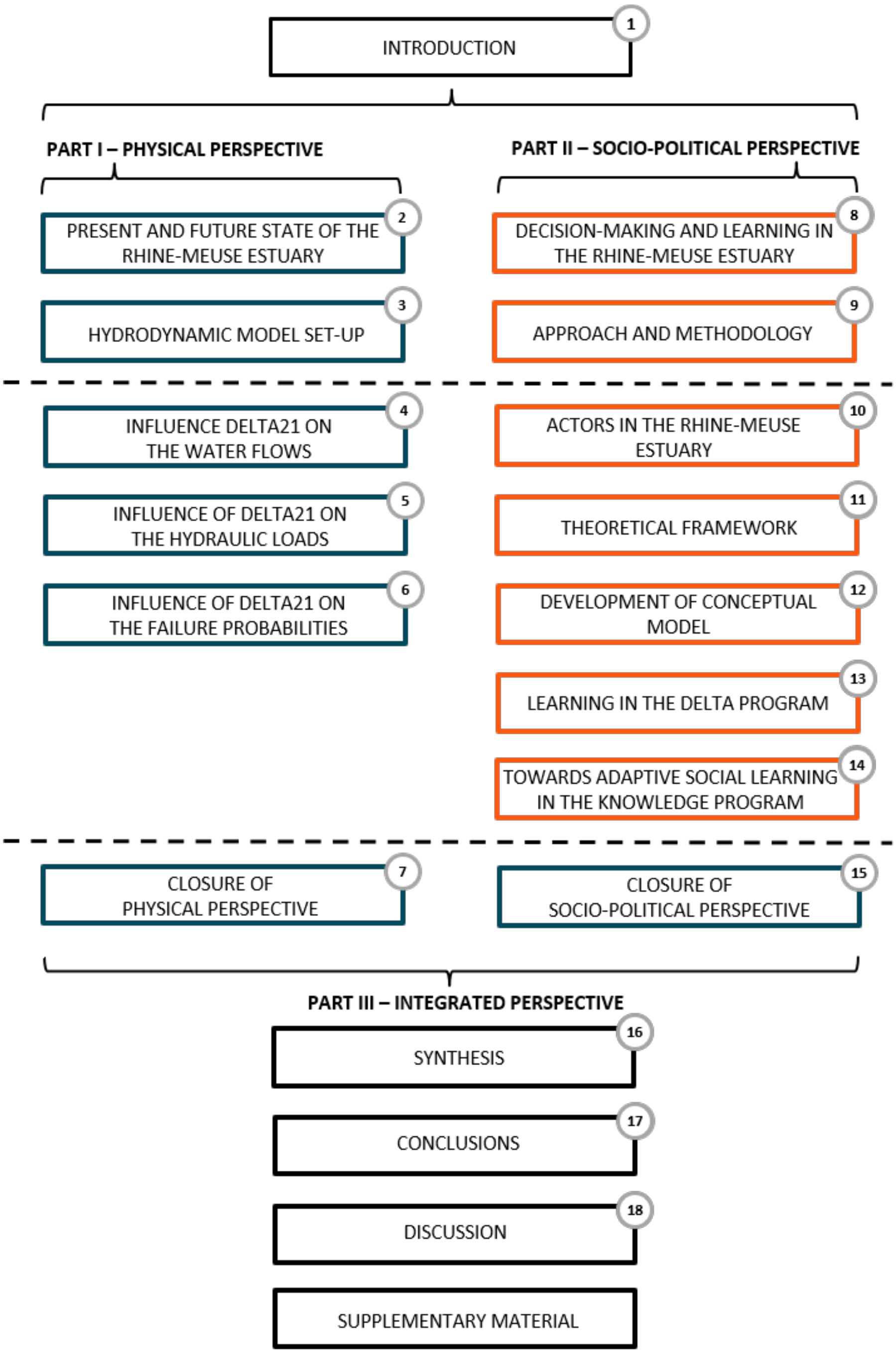


Figure 1.1: Thesis outline. After a general introduction, the thesis is divided in two parallel parts. Part I belongs to the physical perspective and part II discusses the socio-political perspective. In the remainder of the research, the two parts are integrated and closed with conclusions and a discussion.

I

Physical perspective

Chapter 2

Present and future state of the Rhine-Meuse estuary

> "The world is not a solid continent of facts sprinkled by a few lakes of uncertainties, but a vast ocean of uncertainties speckled by a few islands of calibrated and stabilized forms."
>
> Bruno Latour, Reassembling the Social: An Introduction to Actor-Network-Theory, 2003

Estuarine systems are characterized by dynamic boundary conditions. In this chapter, the boundary conditions of the Rhine-Meuse estuary are discussed from a physical perspective. Focus is on the boundary conditions that are relevant to describe the hydrodynamic behaviour within the water bodies. As such, it answers the first sub-question:

SQ-I.a What are the present and future boundary conditions for the Rhine-Meuse estuary?

First, the physical system is described including the lay-out of the branches and human interference over time (Section 2.1). Subsequently, the boundary conditions are elaborated which are relevant for hydrodynamic modelling (Section 2.2). To conclude this chapter, the case study of Delta21 is described. This case study is used to investigate the potential of pumps to reduce the hydraulic loads in the Rhine-Meuse estuary (Section 2.3).

2.1 Description of the physical system

2.1.1 Hydraulics

The Rhine-Meuse estuary as it is today is the result of centuries of water and flood management practices. The Rhine-Meuse estuary consists of the downstream branches of the rivers Rhine and Meuse and is characterized by the influence of river discharges and the North Sea water level, which is under influence of the tide and storm surges. The stochastic variables that are important in the determination of the hydraulic load levels are river discharge (Rhine and Meuse), sea water level, wind speed, wind direction, the state of storm surge barriers (open or closed) and the prediction of the water levels at the Maasmond (Chbab, 2017; Geerse, 2013a; Nicolai et al., 2014). Depending on the location in the Rhine-Meuse estuary, different processes are dominant (Chbab and Groeneweg, 2017).

2.1.2 Human interference

Ever since the Middle Ages (500 to 1.500 A.D.) humans have had a large impact on the RMD (Kleinhans et al., 2013). For the purpose of this thesis, only the recent history is evaluated. In response to the catastrophic flood in 1953, the Dutch government established the Delta Commission to come up with plans to prevent similar disasters from happening. The Haringvliet Barrier, Volkerakdam and Beerdam were built as part of the Deltaworks (1970). To further enhance the flood safety, other delta works have been constructed like the Maeslantkering (1997), Hartelkering (1997) and Ramspolkering (2002). Besides the Delta works, many other measures have been taken to facilitate navigation among others. This included the construction of the Dordtsche Kil (17th century), the New Waterway (1868), construction of the Europoort and Eerste Maasvlakte (1960s), removal of the Beerdam (1997) and construction of the Tweede Maasvlakte (2013) (Huismans and Hoitink, 2017).

Table 2.1: Storm surge barrier including intended lifetime of the irreplaceable parts and sea level rise that has been taking into account during the design.

Barrier (construction year)	Intended lifetime [year]	Included sea level rise [cm]
Hollandsche IJssel (1958)	100	20
Haringvlietsluizen (1970)	200	20
Oosterscheldekering (1986)	200	20
Hartelkering (1996)	100	50
Maeslantkering (1997)	100	50

These developments have had a substantial impact on the mixed fluvial-tidal hydraulics. Among others, the flow division between the channels changed considerably over the century (Figure 2.1).

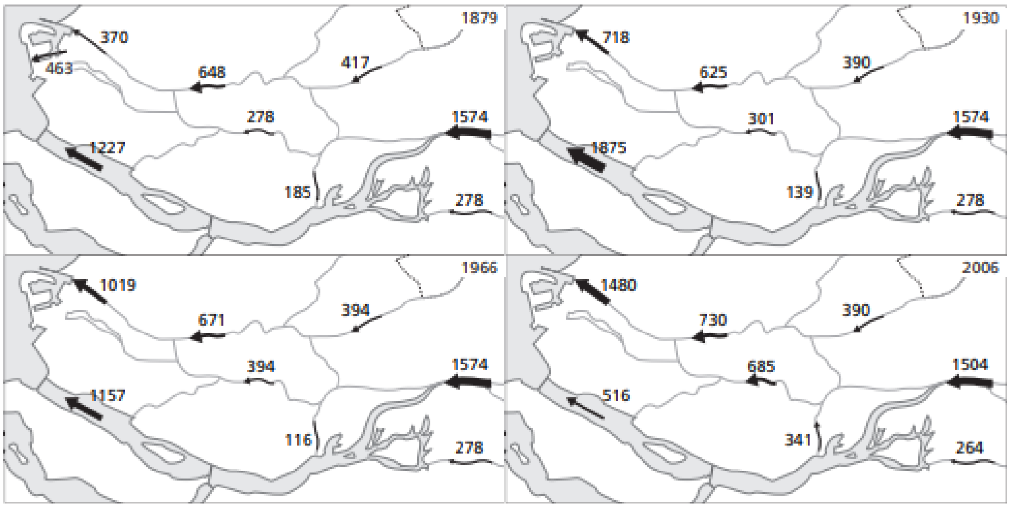


Figure 2.1: Division of mean river discharge (in m^3/s) over channels in the RMD over the past century (Huismans and Hoitink, 2017). Major changes in discharge can be observed in the Nieuwe Waterweg and Haringvliet.

2.1.3 Adaptation options

In coastal regions, there are several adaptation options. The history of human interference shows the adaptation options that have been chosen in the past. An important feature of adaptation options is the timescale. Not every option has the same lead time and functional life time (Table 2.2), which is important in delta management planning. It also explains why it is hard to reduce uncertainty, as the uncertainty in scenarios increases sharply after a few decades.

Table 2.2: Timescales of different adaptation options. The lead time of the adaptation option indicates the load time for planning and implementation while the life time refers to the envisioned functional life time (adapted from (Hallegatte, 2009; Haasnoot et al., 2020)).

Adaptation option	Lead time [year]	Lifetime [year]
Storm surge barrier	20-40	50-200
Dikes and dams	Tens of km per year	>50
Sand nourishment	Annually - every five years	1-10
Pump	2-10	20-50
Land reclamation	5-20	>100
Flood-proofing building	2-10	30-150
Planned retreat	decades	>100

Generally, adaptation options can be divided into two categories. These two categories are related to the flood risk probability. The probability of a flood prone area to actually flood depends on the hydraulic loads (e.g. storm surges, discharge, wave conditions) and the strength of flood defences. To adapt to increases in hydraulic loads, one can either mitigate the change in loads or increase the strength of flood defences. The current preferential strategy that is adopted by the Delta Program is concerned with increasing the strength of flood defences, while the primary objective of Delta21 is to decrease the hydraulic loads in the Rhine-Meuse estuary.

2.2 Present and future boundary conditions

The Rhine-Meuse estuary is a low-lying coastal area and therefore threatened by both extreme river discharges from the Meuse and Rhine rivers and storm surges along the North Sea coastline. Moreover, climate change is expressed in the changing of those boundary conditions. First, the rate of sea level rise is discussed (Section 2.2.1). Next, the development in (extreme) river discharge is discussed (Section 5.1.3. Subsequently, the present and future storm surge is analyzed (Section 2.2.3). The influence of the boundary conditions on the water levels in the Rhine-Meuse estuary is influenced by the operation of the Europoort barrier. Hence, the closing frequency and failure probability are discussed in Section 2.2.4. Finally, the lay-out and characteristics of Delta21 are discussed. This case study is used to quantify the influence of pump capacity and extra storage on the water levels and failure probabilities of the flood defences (Section 2.3).

2.2.1 Rate of sea level rise

The presence of a clear trend in sea level rise is well documented (Nicholls and Cazenave, 2010). The rate, however, is deeply uncertain (Cazenave et al., 2014). In the next century the rate of sea level rise can increase, or if global policies to reduce emissions are effective, remain stable (Appendix A). Until 2050, high-end sea level projections are very similar to the current scenarios used in the Delta Program (Haasnoot et al., 2020). After 2050, the sea level rise scenarios start to deviate considerably (Figure 2.2). This difference is caused by the estimated contribution of Antarctica, which is currently one of the main topics among scholars in the field of climate change.

Current global sea level rise is 3.2 mm/year. Due to the favourable location of the Netherlands concern-

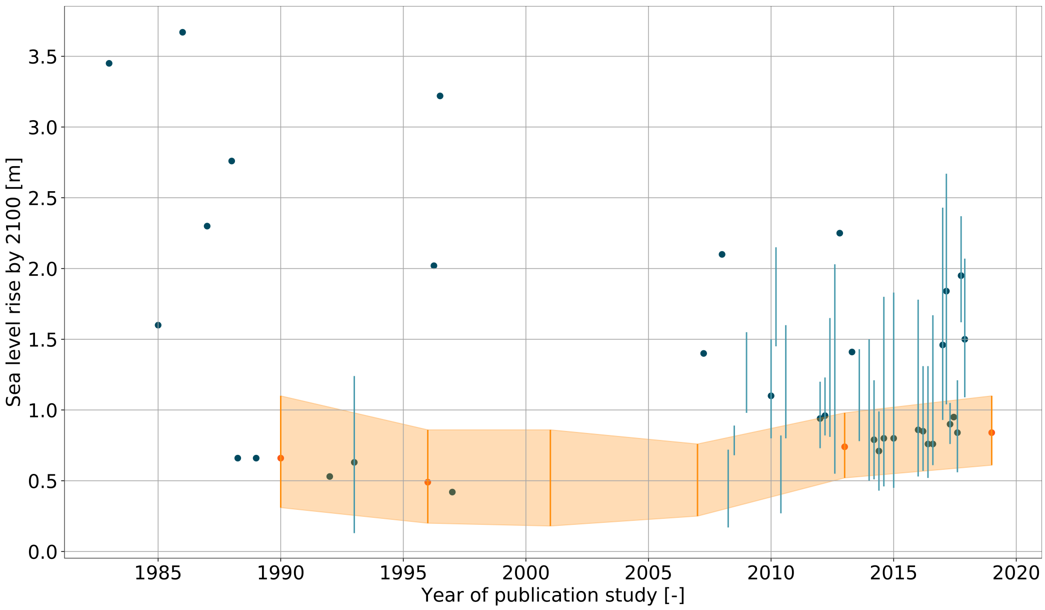


Figure 2.2: Estimates of sea level rise by 2100 under high emission scenarios, published between 1983 and 2018. Dots represent the central estimate, while bars represent the bandwidth between the low- and high-end estimate (when available). Orange lines indicate IPCC estimates and the orange regions connect sequential IPCC estimates. Based on data from Garner et al. (2018). List of included studies can be found in Appendix A.

ing melting ice the sea level rise along the Dutch coast is lower than the average global sea level rise, this is known as the gravitation effect (Clark and Lingle, 1977). This gravitation effect makes that the current sea level rise is about 2 mm/year along the Dutch coast. (Baart et al., 2019). As the uncertainty about the rate of sea level rise is large and the time horizon connected to system interventions - such as Delta21 - is long (>100 years), a sea level rise up to 2 meters will be investigated in this research. The sea level rise of 2 meters is in line with recent studies for the Delta Program (e.g. (Haasnoot et al., 2018a; Kind et al., 2019)). As denoted, for many decisions it is not so much a question whether sea level will rise to certain levels, but when this will occur.

2.2.2 Uncertainty in river discharge

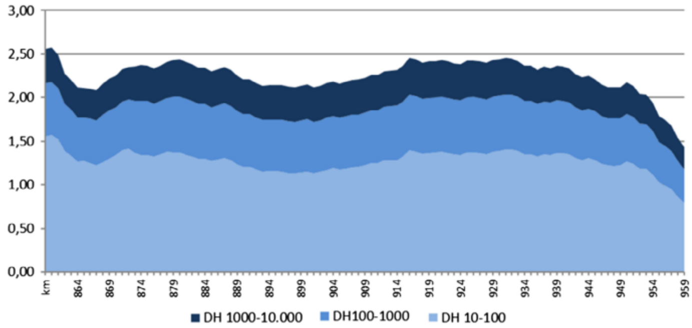
The Rhine and Meuse Rivers are the largest rivers in the Netherlands. The Rhine River originates in Switzerland and enters the Netherlands at Lobith. Its average discharge, at the point when it enters the Netherlands is about 2200 m^3/s (Klijn et al., 2018). The Rhine River splits into three major branches after the Dutch-German border: the Waal-Merwede, the Nederrijn/Lek and the IJssel. During flood stage, the proportions of the discharge are about 6:2:1 respectively. The branches Waal-Merwede and Nederrijn/Lek enter the Rhine-Meuse estuary. Together with the Meuse River, which has an average discharge of 230 m3/s when it enters the Netherlands, these branches provide the majority of water influx into the estuary (Klijn et al., 2018).

Uncertainty is inherent to nature and future discharges cannot be predicted exactly unless large interventions are undertaken. To determine the required height of dikes, a so-called design discharge was used in the past. The design discharge is the maximum discharge a river can convey without causing floods, and is valid for a given return period. It is based on an extrapolation of measured and modelled discharge data, which means that uncertainty becomes substantial for higher return periods. This uncertainty is introduced by various sources, such as relatively short time series (50-100 year) of river discharges compared to the return period of interest (1000 - 10 000 years). The following additional sources result in a larger uncertainty of future river discharge: the effects of upstream policies and flood mitigation measures, the erosion of the riverbed, possible future updates of flood protection standards, the impact of climate change, and the limited possibilities for statistical detection of the impact of climate change (Delta Commissioner, 2014; Prinsen et al., 2015; Cramer et al., 2014; Diermanse et al., 2010; Klijn et al., 2012; Attema et al., 2014; Sperna Weiland et al., 2015; Hegnauer et al., 2014). Due to this uncertainty among others, the agreed upon design discharge has changed over time (Table 2.3). Changes did not only have roots in progressive physical insights but can be partly ascribed to socio-political developments.

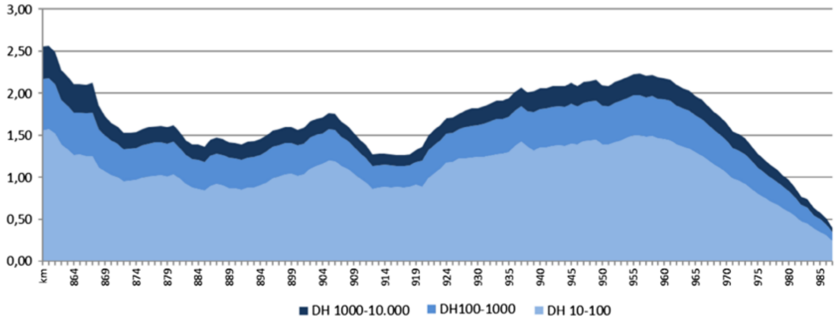
Currently, flood protection standards are no longer based on design discharges but on the probability of dike breaching. This means that we take into account the whole range of relevant flood levels. In Figure 2.3, flood levels are showed over the length of the rivers. These flood levels show the decimation heights as they correspond to a difference of a factor of 10 in occurrence probability. Hence, these figures provide insight into how much the flood levels differ depending on the investigated return period. For example, the Waal River has larger decimation heights compared to the other branches. This is because the Waal River is relatively narrow which makes it more sensitive to increase in discharge.

Table 2.3: Historical and current (design) discharges for the river Rhine (Kind et al., 2018). Reasons for change were not directly related to climate change, but had roots in: floods (1953), large river discharges (1993 and 1995) and civil protests. Since 2017, flood probabilities are governing instead of design discharges.

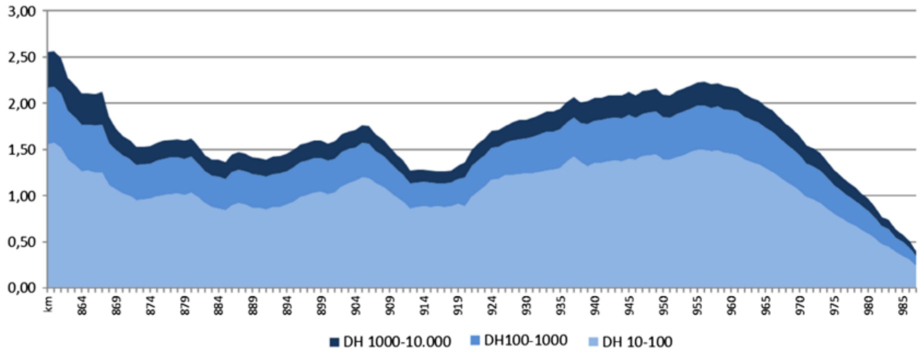
Period	(Design) discharge [m^3/s]	Standard or return period [yr]
1926 - 1956	13 500	
1956 - 1975	18 000	3000
1975 - 1993	16 500	1250
1993 - 2001	15 000	1250
2001 - 2017	16 000	1250



(a) Bovenrijn/Waal.



(b) Bovenrijn-Nederrijn/Lek.



(c) Meuse River.

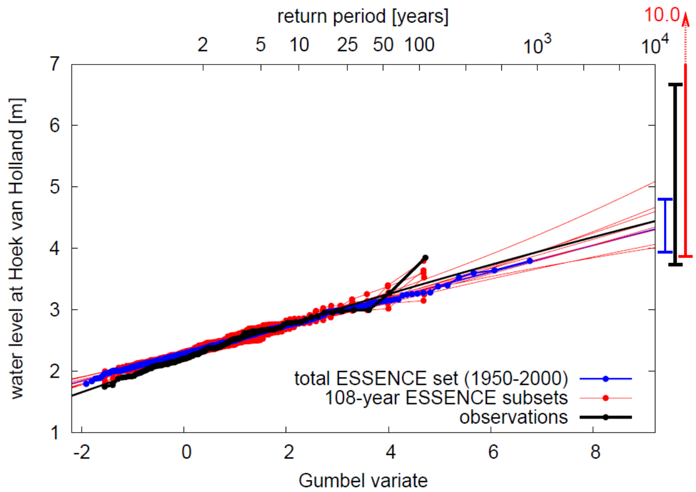
Figure 2.3: Cumulative decimation heights for the Bovenrijn-Nederrijn/Lek, Bovenrijn-Waal and Meuse River. The figure depics the differences in flood water levels with probabilities of occurrence ranging between 1:10 to 1:10,000 per year. On the x-axis, the chainage of the corresponding branch is denoted (Hegnauer et al., 2014; Klijn et al., 2018).

2.2.3 Storm surge height and duration

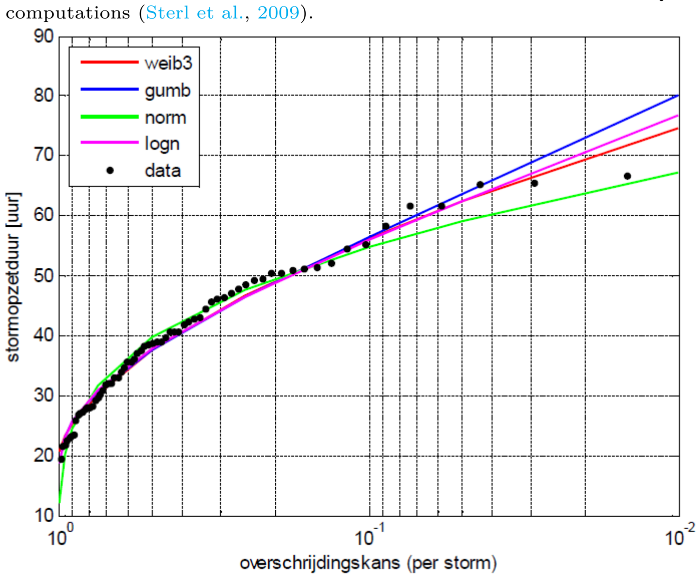
The height of storm surges is extremely important for the low-lying Rhine-Meuse estuary and depends on the sea water level, wind speed and wind direction. In Figure 2.4a, the water level at different return periods is depicted at the location of Hoek van Holland. Besides the storm surge height, the storm surge duration is an important characteristic for the Rhine-Meuse estuary. As denoted, one of the critical situations from a flood risk perspective is combined occurrence of storm surges and high discharges. Therefore, both the height and the duration govern how much water must be stored in the estuary during a storm. The storm surge duration contains inherent uncertainty as well (Figure 2.4b).

Storm surge intensity may change as a consequence of climate change, as well as wave height characteristics, and that change is particularly marked for extreme events (Menéndez and Woodworth, 2010; Young et al., 2011). Not only the wind speed is important for the height of storm surges, but also the wind direction. The highest storm surges in the Netherlands are caused by north-westerly because of their long fetch and geometry of the coastline. Hence, the extreme surges are expected to be unaffected by increasing wind speeds. For the Rhine-Meuse estuary, surges caused by south-westerly winds are most dangerous. Those winds are expected to increase in the future together with the corresponding storm surges (Katsman et al., 2011; Sterl et al., 2009). More elaboration about the storm surge duration and shape can be found in (Tijssen and Diermanse, 2010).

Flood protection in the Rhine-Meuse estuary has to deal with the combined occurrence of storm surge in the North Sea and high river discharges in the Rhine and Meuse Rivers. High sea water levels at Hoek van Holland and high Rhine discharges at Lobith show significant dependence (Geerse, 2013b; Klerk et al., 2015). At the same time, the dependence shows a time lag between the extremes which means that the extremes do not tend to arrive at the same time. Hence, the storm surges and discharges are modelled as if they are statistically independent.



(a) Gumbel plot for water levels at Hoek van Holland. Observations of water levels and the corresponding generalised extreme value fit are shown in black. The blue and red dots indicate data from different WAQUA computations (Sterl et al., 2009).



(b) Estimated probabilities of exceedance for different storm surges. The figure depicts the exceedance probabilities per storm ("overschrijdingskans per storm") for different storm surge durations ("stormopzetduur") (Tijssen and Diermanse, 2010).

Figure 2.4: Storm surge height and storm surge duration plotted against the return period or probability of exceedance. The figures are computed for the location of Hoek van Holland.

2.2.4 Closing frequency and failure probability of Europoort barrier

The possible consequences of the combined impact of sea level rise, peak river discharge and storm surges become apparent when considering the Rhine-Meuse estuary. The Hartel barrier and Maeslant barrier together are called the Europoort barrier, whereby the closure of the Hartel barrier follows the closure of the Maeslant barrier. The estuary is protected by the Europoort barrier, which closes automatically when a forecasted water level at Rotterdam exceed NAP+ 3 m. Formally, the barrier also closes if the level in Dordrecht exceeds 2.90 m+NAP. Nonetheless, this is very unlikely to happen without exceeding the threshold set for Rotterdam. With the current conditions, this was expected to happen once in approximately 10 years. Based on this expected value, the required failure probability per closure was set to 1/100 (Rijkswaterstaat, 2013). Increases in sea level rise will enhance the probability that the storm surge barrier needs to be closed. This development yields multiple adverse effects:

- The Nieuwe Waterweg is closed more often, which impacts shipping;
- More heavy conditions for mechanical requirements of the movable barrier;
- Larger probability of closure during summer period, currently reserved for maintenance and testing;
- Larger probability of double closure. The barrier might be damaged during closure, which makes the barrier vulnerable to a second critical condition.

Because of the mentioned reasons, the closure frequency is set to a maximum of 3 times a year. This requirement has some implication for the closure levels in case of high-end sea level rise scenarios. Hence, it is investigated what the relation is between sea level rise and closure requests. Following Van Den Brink and De Goederen (2017), a Gumbel distribution can be fitted to the water level at sea:

$$G(y) = exp\{-exp[-\frac{y-\mu}{\sigma}]\} \tag{2.1}$$

The return period, the average recurrence time between two closures, is defined as:

$$T_s = \frac{1}{1-G(y)} \tag{2.2}$$

The combination of equation 2.1 and 2.2 leads to the following equation (in case of large return periods):

$$y \approx \mu + \sigma log(T_s) \tag{2.3}$$

For the increase in closure frequency, the derivative of equation 2.3 is interesting:

$$\frac{T_{s,2}}{T_{s,1}} = exp\{\frac{y_2 - y_1}{\sigma}\} \tag{2.4}$$

Following this relation, the frequency of closure is doubled with a sea level rise of 0.18 m. Equation 2.4 will be used to compute the closure levels that are needed to limit the expected number of closures per year. This relation holds under the assumptions that there are no changes in the wind climate, there is no effect of sea level rise on the surge and astronomical tides, and there is no change in river discharge.

2.3 Description of case study: Delta21

Several adaptation options can be considered to reduce the flood probabilities in the Rhine-Meuse estuary (Section 2.1.3). This research is about the potential of pump capacity and extra storage in reducing the hydraulic loads and failure probabilities in the Rhine-Meuse estuary. This is investigated based on the conceptual design of Delta21. Delta21 is a plan to construct a basin between the Maasvlakte 2 and the Haringvliet. The objective of Delta21 is threefold: 1) improve flood risk protection, 2) improve the ecological condition and 3) provide a positive contribution to the energy transition. The plan consists of different components, which is elaborated more detail in Delta21 (2019).

- Energy storage lake. This lake of 35 km^2 serves as a battery for the energy transition. The surplus in wind and solar energy is stored in the lake. In Figure 2.5, the energy storage lake is constructed within the yellow dike sections. To drain water to the sea in critical conditions, a pump capacity of 10 000 m3/s becomes available.

- Tidal lake. The tidal lake is bounded by the Haringvliet sluices and the energy storage lake. The plan is that this lake remains in open connection to the sea.

- Storm surge barrier. The boundary between the sea and the tidal lake is a new storm surge barrier. The exact lay-out of this storm surge barrier is not yet known.

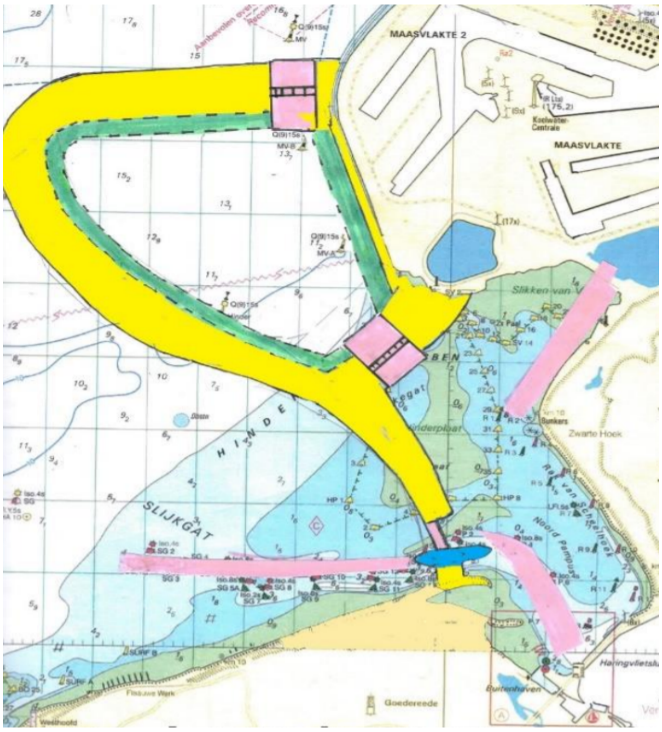


Figure 2.5: Illustration of the Delta21 plan (Delta21, 2019). The energy storage lake is constructed within the yellow dike sections. Between the Harinvlietsluices (bottom right) and the energy storage lake, a tidal lake is created. This tidal lake is connected to the North Sea with a storm surge barrier in between.

Chapter 3

Hydrodynamic model set-up

> "Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful."
>
> George E. P. Box, Empirical Model-Building and Response Surfaces, 1987

This chapter discusses set-up of the hydrodynamic model and the simulation approach that is used to gain the necessary information for the comparative analysis between Delta21 and the current system. As such, it answers the following sub-question:

SQ-I.b How can the behaviour of the current configuration, and the configuration with Delta21, be modelled with a computationally efficient model?

This chapter provides the necessary background for the modelling approach used in this research. Generally, the approach could be divided into three parts; hydrodynamic computations (Section 3.1), probabilistic computations (Section 3.2) and failure mechanisms (Section 3.3).

The first part is related to the hydrodynamic computations. In this part, a hydrodynamic model is used to model the water levels, discharges, wave conditions subjected to a range of boundary conditions. This step resulted in a database of hydrodynamic computations without statistical information about the probability of occurrence of different discretization of stochastic variables. In the second step, statistical information was added to the loads in the Rhine-Meuse estuary. This resulted in water level frequency

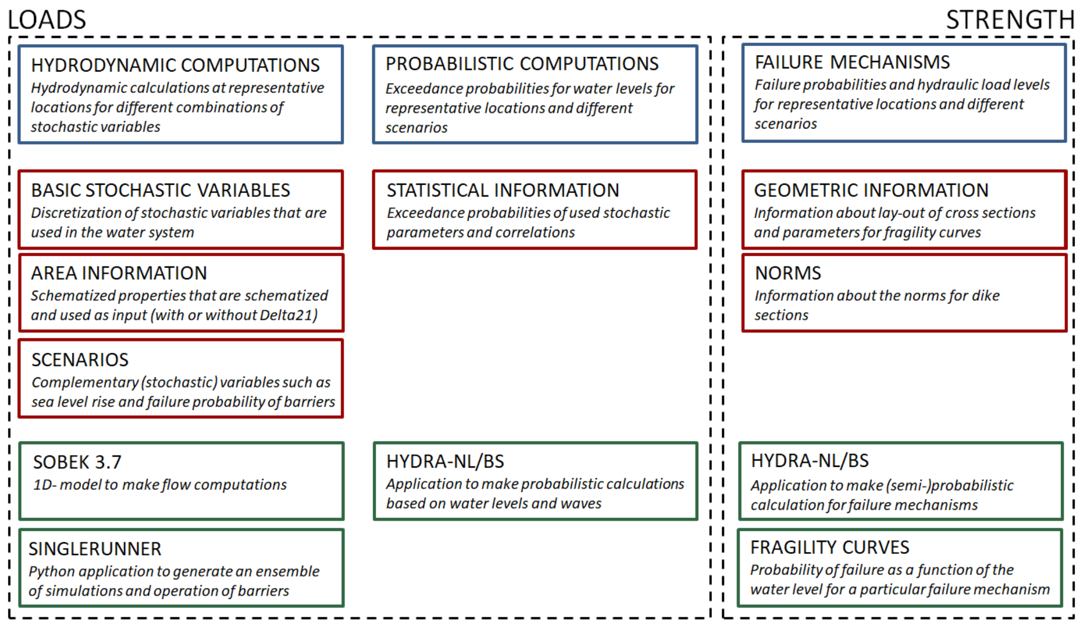


Figure 3.1: Structure of modelling approach. The blue boxes indicate the different steps undertaken in this research. The results of the hydrodynamic computations, probabilistic computations and failure mechanisms are discussed in Chapter 4, 5 and 6 respectively. The boxes with a red outline indicate which information serves as input, where the green boxes represent the used application or method.

lines which are valuable in analysing the performance of flood defences. To gain insights on the impact of Delta21 on failure probabilities of the barrier, information about the strength was needed. For this first assessment of failure probabilities, semi-probabilistic methods have been used. Descriptions, justifications and limitations of the used model and the approach will be provided throughout this chapter.

3.1 Method for hydrodynamic computations

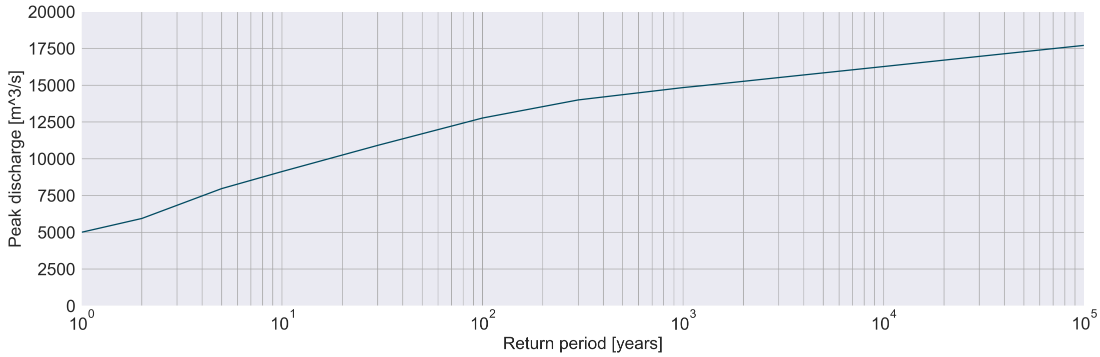
The objective of this step was to obtain results about the hydrodynamic interactions in the systems. Basic stochastic variables (Subsection 3.1.1) , area information and scenarios were used in the SOBEK3.7 (Subsection 3.1.4) and Singlerunner application (Subsection 3.1.4). More detailed information about the technical specifications of the used applications can be found in Appendix B.

3.1.1 Basic stochastic variables of boundary conditions

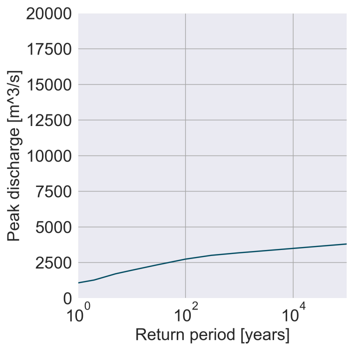
At both ends of the model, boundary conditions needed to be prescribed for both the flow and water levels. At the landward end, three discharge boundaries were used to prescribe the inflow of water, whereas at the seaward ends water level were subjected to the water system.

Landward boundary condition

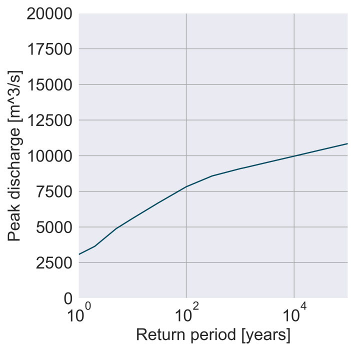
The discharge was considered as a fundamental stochastic variable and was taken explicitly into account using exceedance probabilities of the discharge. The discharge confirm the ”legal assessment WBI2017” (In dutch: Wettelijk Beoordelingsintrumentarium WBI-2017) was used (Agtersloot and Paarlberg, 2016), which is depicted in Table B.5. One can see that a direct relationship between discharges was followed - a certain discharge on the Waal corresponded to a certain discharge on the Lek and Meuse.



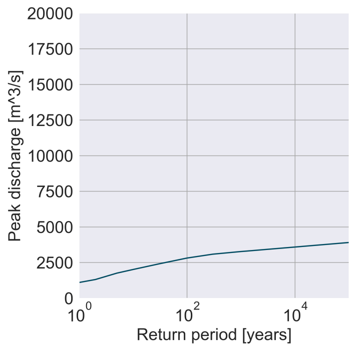
(a) Rhine (Lobith).



(b) Lek (Hagesteijn).



(c) Waal (Tiel).

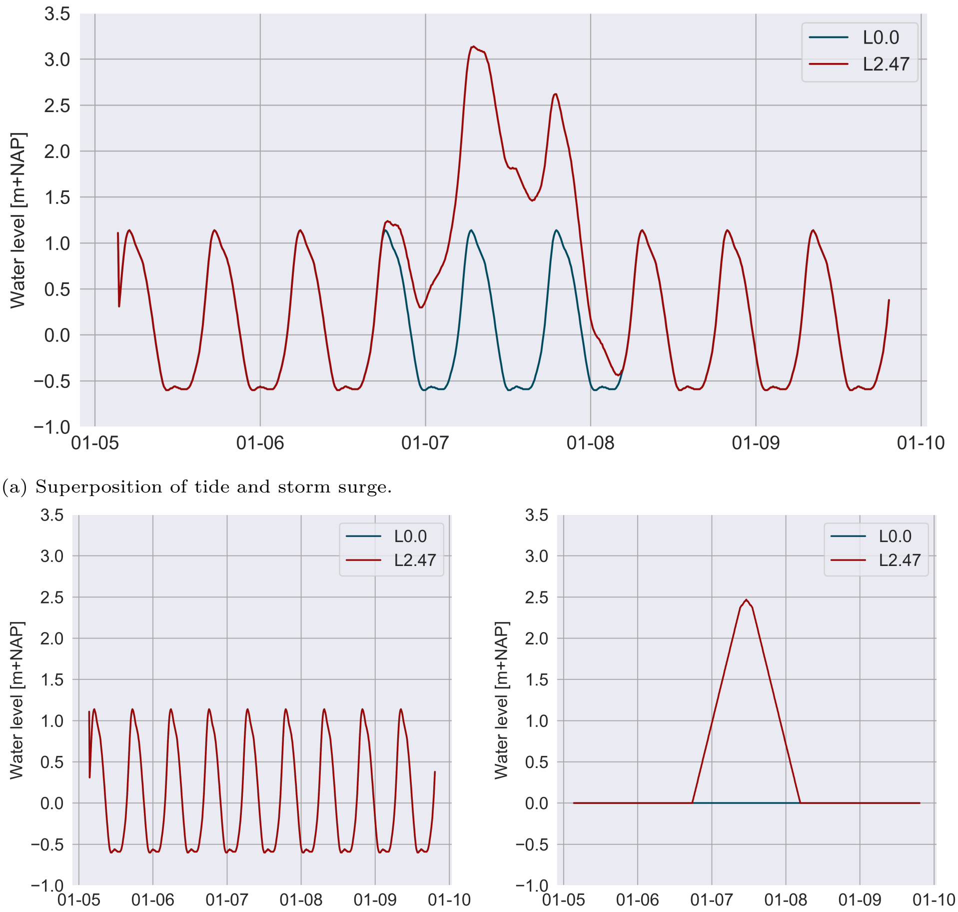


(d) Meuse (Lith).

Figure 3.2: Frequency discharge curves for the Rhine branches and the Meuse. In the top graph the frequency discharge curve of the Rhine at Lobith is presented. In this research, the discharge at the Lek, Waal en Meuse river were coupled directly and is confirm WBI-2017 (Hegnauer et al., 2015; Agtersloot and Paarlberg, 2016) .

Seaward boundary condition

The storm surge subjected to the system follows from the ”legal assessment WBI-2017”(in Dutch: Wettelijk Beoordelingsintrumentarium WBI-2017) (Chbab, 2015). The notion that the storm surge might increase in the future has not been incorporated in the seaward boundary (Figure 3.3). The increase in storm surge set-up leads to similar increase in hydraulic loads due to sea level rise. Hence, the choice has been made to not explicitly include an increase in storm surge as this would lead to many extra computations.



(a) Superposition of tide and storm surge.

(b) Tide.

(c) Storm surge.

Figure 3.3: Illustration of boundary conditions at the Maasmond. In this figure, two different boundary conditions are shown; one with a storm surge set to zero (blue line) and one with a storm surge set to 2.47 m (red line). In the lower graphs, the tide and storm surge are shown, in the upper graph the superposition of the tide and the storm surge is depicted. Six different storm surges are subjected in this research: 0, 1.29, 2.47, 3.54, 4.57 and 5.59 m. Each simulation covers about five days, in this case from January 5th to January 10.

3.1.2 Scenarios

The scenarios about the rate of sea level rise differ significantly (Section 2.2.1). Hence the approach is followed to make the hydraulic computation with 5 different sea level rises: 0.0, 0.5, 1.0, 1.5 and 2.0 m. These scenarios are considered as what-if scenarios, which means that the scenarios do not contain information about the likelihood. The time to reach those levels depends on the considered scenario. Nonetheless, it must be noted that the what-if scenarios are on the high-end, sea level rise larger than 1.0 m is not likely to happen before 2100.

3.1.3 Geometric information

The height of the bed level in the main channels and floodplains is needed to compute results with the hydrodynamic model. Those values are measured with different techniques and their accuracy may vary. One of the sources of geometric information is the Digitaal Topografisch Bestand (DTB) which consists the height information of all objects and the ground surface. In this thesis, the bed levels are assumed to be equal to the measured state of the riverbed. This means that the influence of dynamic bed elevation is not included in the simulations.

3.1.4 Failure modes of the Europoort barrier

The Europoort barrier is implemented in the model in a probabilistic way. As discussed before in this research, the Europoort barrier has certain reliability in functioning. Three modes are considered in this thesis:

1. Correct functioning; the barrier closes when the barrier has to close and opens when the barrier has to opens;
2. Failure due to not closing; the barrier succeeds in closing in time, but is unsuccessful in opening;
3. Failure due to not opening; the barrier does not succeed in closing.

The different modes have an enormous impact on the water levels, especially in the storm surge dominant area (Figure 3.4). Based on the requirement to keep the closure frequency to 3 times per year, closure levels are derived that depend on the amount of sea level rise (Table 3.1) . Up to 1 meter sea level rise, the closure level remains equal to the current closure level.

Table 3.1: Relation between sea level rise, closure levels and closure frequency. The values are based on the relation that is derived in Section 2.2.4.

SLR	CL RDAM [m+NAP]	CL DORDT [m+NAP]	Closure frequency [per year]
0.0	3.0	2.9	1/15
0.5	3.0	2.9	..
1.0	3.0	2.9	3
1.5	3.5	3.4	3
2.0	4.0	3.9	3

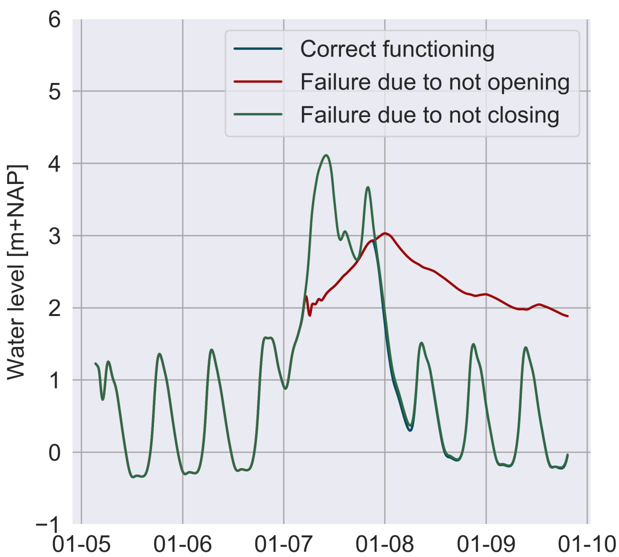


Figure 3.4: Illustration of the effect of the failure modes on the water level in the Rhine-Meuse estuary. In the case of the correct functioning (red line) the Europoortkering succeeds in "clipping-off" the peak of the storm surge. In case of failure, either the peak becomes higher (failure due to not closing) or the water level is higher for a longer duration (failure due to not opening). The data corresponds to the realization with a discharge of 10 000 m^3/s and a storm surge of 3.54 m, the water levels are depicted for Rotterdam.

SOBEK 3.7

In modelling, there is always a trade-off between prediction accuracy and computational efficiency (Bhave et al., 2016; Walker et al., 2013). Since the outcomes of this model are used to provide insight into water levels and connected hydraulic load levels, a correct representation of hydrodynamic processes is the most important feature. In this research, the hydrodynamic computations are done with the SOBEK 3.7 suite, part of D-Flow (1D) (Deltares, 2020). The software is best used in a situation where simulation effort and robustness are considered more important than a high level of accuracy.

The available Rhine-Meuse Mouth model (RMM-model) is used (Figure 3.5), developed by Deltares. This Hydrodynamic 1D model is able to compute water levels, discharges and velocities (averaged over the wetted area) corresponding to particular boundary conditions by solving the De Saint Venant equations (Appendix B). The boundary conditions that are used in this research are discussed in Section 3.1.1.
Alterations to the RMM-model have been made in order to 1) solve integration issues between the different models and applications that led to instabilities, 2) make the results more reliable in case of high-end sea level rise scenarios and 3) implement Delta21. Because of those reasons, the following adjustments have been made:

- Adjustment to real-time control of the Haringvliet sluices. The real-time control of the Haringvliet sluices became unstable when it was integrated with the other models and applications. The sluices were modelled with a standard trigger (Deltares, 2019) which compares two input variables and returns True or False. Due to the standard trigger approach, the doors became unstable - closed and opened - in subsequent timesteps. Hence, a dead band is added to the control scheme of the Haringvliet sluices to prevent rapid opening and closing and produce more reliable results. A more detailed description of this process can be found in Appendix B.
- Enable water overflow over the Haringvliet sluices. The gates of the Haringvliet gates have a height of NAP+ 5 m (when closed). During high water levels, due to storm surges and/or sea level rise, water will flow over the barriers. However, in the current RMM-model, overflow over the gates is not allowed. Particularly for high-end sea level rise scenarios, it would be relevant to allow flow over the barrier. Hence, in the adjusted model, the Haringvliet sluices are altered in such a way that overflow is allowed. It must be noted that the model does not account for wave overtopping.

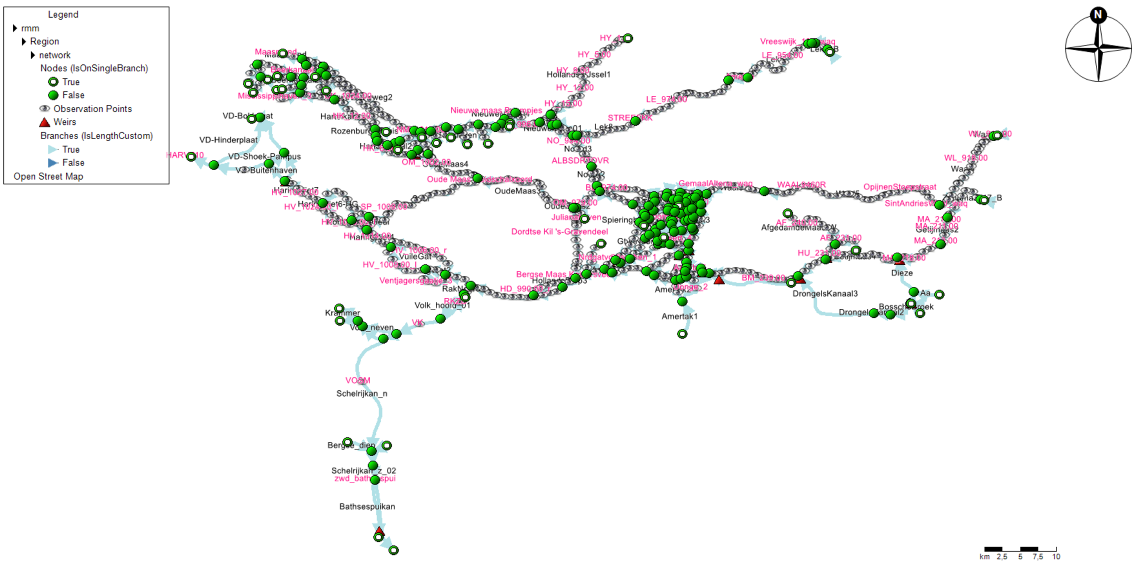


Figure 3.5: The RMM-model in SOBEK3. The arrows and green dots represent the branches and nodes respectively. Moreover, all structures are included. The boundaries on the east side of the domain are governed by the discharge of the rivers Lek, Waal and Maas. The boundary nodes on the west side are governed by the water level at the North Sea.

- Implementation of Delta21. The two key characteristics of Delta21 in terms of flood risk reduction are an extra storage area and the pump capacity to drain water to the sea:
  - The storage area of 35 km^2 is implemented by adding a (fictitious) branch with the length of 10 km and cross section width of 3.5 km. The branch is located at the Haringvliet (upstream) side of the Haringvliet sluices.
  - The pump capacity of 10 000 m^3/s is placed on the Haringvliet sluices. In the modelling approach, the time period of simulation is five days. Of those five days, two days are subjected to storm surge. During the complete simulation, the minimum pump capacity is set to 3.000 m^3/s. Based on a trigger level at the upstream side of the Haringvliet barrier, the remaining 7.000 m^3/s can be requested. The idea behind this control scheme is that in reality, high discharges and storms can be predicted a few days beforehand. It is desirable to gain extra storage volume by draining water to the sea before the storm surge arrives. Hence, part of the capacity is called in advance, while the remaining part of the discharge becomes available during peak water levels. The schematization of Delta21 in this approach does not fully comply with the proposed design. Nonetheless, the response to the extra storage area and the pump capacity is expected to be accurate enough for exploratory modelling of system effects.

The adjustments result in two models; one configuration with Delta21 and one configuration without. For both configurations, the adjustments to the Haringvliet sluices have been taken into account.

SingleRunner

The SingleRunner is a python application which deploys an ensemble of SOBEK simulations (Deltares, 2018). The SingleRunner application manages the behaviour of the barriers. It can implement the normal operation and failure modes of barriers. In reality, the barriers are forecast driven. This means that forecasts are made based on the current water levels. For example, the Maeslantkering must close if the water level in Rotterdam is expected to reach NAP+ 3 m. This is deployed in the SingleRunner; each decision time step, it is checked whether a barrier needs to change its state (open, closed, etc.). The different states are governed by a barrier specific management system (BOS; in Dutch: ”Beslissing en Ondersturings System”).

Different characteristics, such as the gate height, closing speed, opening speed can be specified in a detailed way. In doing so, different failure modes of the barrier can be simulated. For example, by setting the closing speed to zero, failure due to not closing can be modelled. In the simulation approach, the different combinations of normal operation and failure modes are discussed.

3.2 Method for probabilistic computations

3.2.1 Hydra models

A probability of occurrence of a water level cannot be viewed in isolation from the period of time to which it refers. This time period is called the reference period. The probabilistic Hydra model computes the magnitude and likelihood (depending on the reference period) of water levels at a certain location, yielding so-called water level frequency curves. Two different levels are important in this thesis:

- Water level frequency curves. These curves represent the local water level plotted against the return period.
- Hydraulic load levels. This level equals the sum of the local water level and the wave overtopping height. These levels are important in the design of flood defences. Flood defences are prone to different failure mechanisms. Hydraulic load parameters are used to analyse the failure mechanisms for overflow and overtopping, but are also used in additional failure mechanisms.

There are two kinds of Hydra models for the Rhine-Meuse estuary: 1) Hydra-NL (Duits, 2019) and 2) Hydra-BS (Duits, 2013). Hydra-NL is able to model different failure modes of the Europoortkering. Hydra-BS can model six different combinations of normal operation and failure modes, of which the following two are used throughout this report:

- Type 2: Europoortkering, Haringvlietsluices and Volkerraksluices;
- Type 6: Europoortkering.

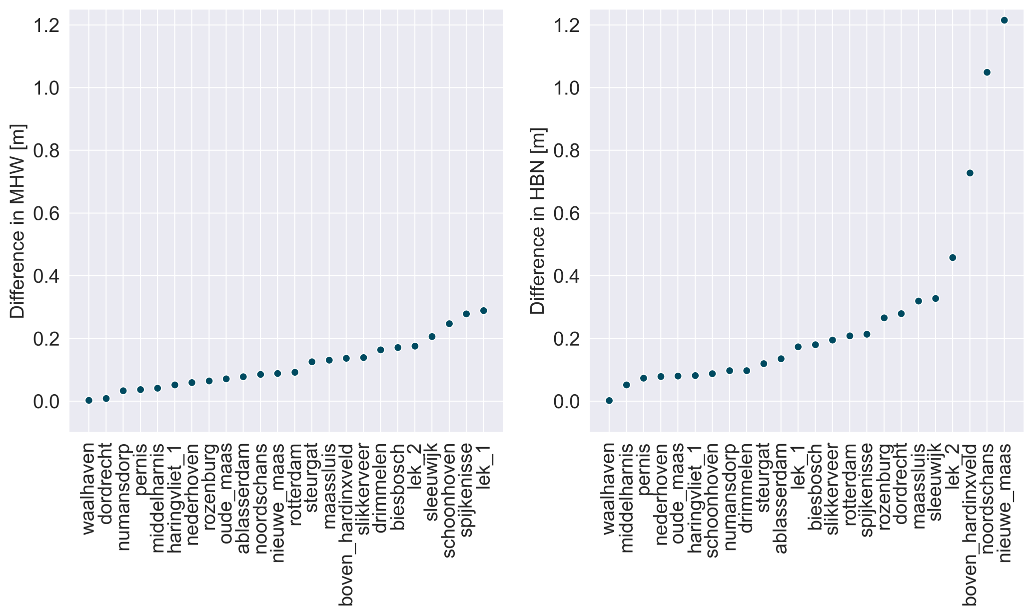
In this research, both Hydra-NL and Hydra-BS are used. This choice has been made as Hydra-NL is more user-friendly and Hydra-BS offers more simulation options.

3.2.2 MHWp5

The "Maatgevend Hoogwater Processor (MHWp5-processor) is a python application that is developed to guide the complete process of probabilistic calculations - from hydraulic boundary conditions to water level frequency lines. This application is developed by HKV - Lijn in water. The MHWp5-processor consists of several different models, more information about these models can be found in Thonus (2019a,b,c,d). As the application is still under development, this research can be considered as the first use of the MHWp5-processor.

3.2.3 Hydrodynamic validation

Currently, the WBI-database is used to analyse the hydraulic loads in the Rhine-Meuse estuary. To make comparisons relevant for this research, alternative databases are computed. It is interesting to compare the used approach - including SOBEK3.6, SingleRunner and Hydra-NL - with current computations of the WBI-database and Hydra-NL (Figure 3.6b). As can be seen, the governing water levels deliver similar results as computed with the WBI-database (Figure 3.6a). The differences remain within acceptable limits, especially for the most important locations - Rotterdam and Dordrecht. The hydraulic load levels tend to differ distinctly at four locations. These can be ascribed to the 2D wave effects, which are not included as the used model makes use of Brettschneider which only takes into account 1D wave effects (Bretschneider, 1964).



(a) Difference in governing water levels (MHW). (b) Difference in hydraulic load levels (HBN).

Figure 3.6: Comparison of MHWp5 database to the WBI database. The difference - in absolute values - between the databases for the water levels and hydraulic load levels for different locations throughout the Rhine-Meuse estuary. The values are sorted from lowest to highest.

3.2.4 Simulation approach

One of the aims of this research is to compare the influence of Delta21 on the water system in the Rhine-Meuse estuary. In order to take into account the inherent uncertainty related to natural variability, nine discharges (Section 3.1.1) and six (Section 3.1.1) storm surges are used. These 54 (9 x 6) simulation form the core of the modelling approach and allow to compute water level frequency lines for different locations in the domain. To take into account the effect of a correct functioning, not closing and not opening Europoort barrier. The core simulation is expanded to 162 (54 x 3) simulations. In order to take into account two different systems - Delta21 and the current systems and 5 levels of sea level rise (up to 2 meters with steps of 0.5 m) an total of 1620 simulations is used in this research (Figure 3.7).

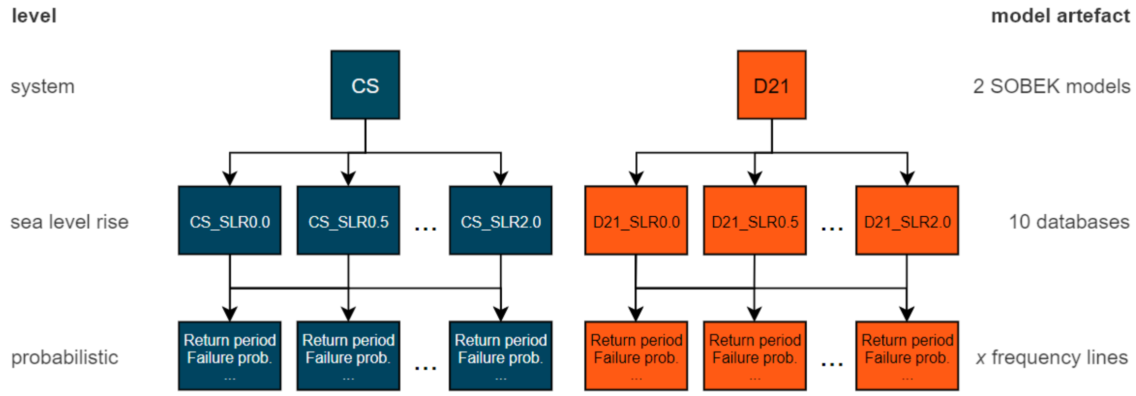


Figure 3.7: Graphical representation of the simulation approach. The blue boxes indicate simulations in which the current system is used. The orange boxes represent simulations with the properties of Delta21. For each step of sea level rise 0f 0.5 meters, 164 simulations are made corresponding to 9 discharges, 6 storm surges and three operation states of the Europoort barrier.

3.3 Method for failure probability computations

3.3.1 Failure mechanisms

Dikes serve as revetments to protect the hinterland during high water events. Dikes are composed of different segments, which can be again divided into dike sections. Where dike segments consist of different geometries, orientations and subsoils, dike sections are considered to be statistically homogeneous. This system is evaluated as a series system if failure occurs at one of the cross-sections for one of the failure mechanisms, the whole segment fails (Figure 3.8).

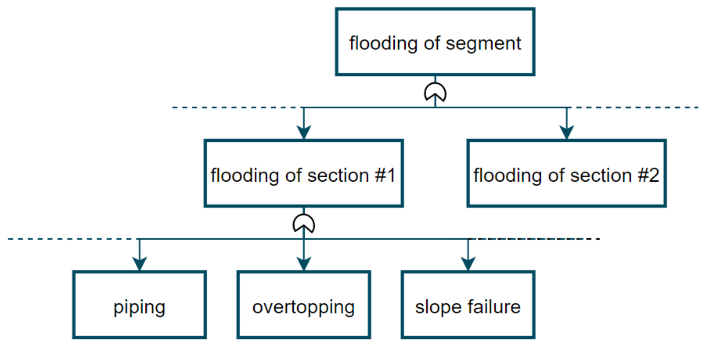


Figure 3.8: Fault tree of a dike segment. Different failure mechanisms are involved in the failure of the dike. On a dike section level, the probabilities are determined and translated to a dike segment level (adjusted from Jonkman et al. (2018)).

In the design of flood defences, each failure mechanisms may have a certain "failure budget". To determine the budget for the considered failure mechanism, the following formula can be used (equation 3.1). The safety requirement for height ($P_{i,j}$) depends on the safety standard for the segment ($P_{segment}$), the maximum failure probability contribution of the failure mechanism under consideration (ω) and the length effect on segment scale (N) (Rijkswaterstaat, 2016):

$$P_{norm,height} = \frac{P_{segment} * \omega}{N} \tag{3.1}$$

The focus in this graduation project will be on the influence of water levels on failure mechanisms. As Delta21 will result in a reduction of the hydraulic loads, the failure mechanisms that are most sensitive to this reduction are the most interesting to cover. The analysis presented in this chapter, therefore, serves only as an illustration of the effects that Delta21 could have on the failure probability of certain dike sections, for a full assessment the other failure mechanisms should be evaluated as well.
The failure mechanisms that are discussed below are a failure due to overflow or overtopping and failure due to piping.

3.3.2 Requirements for the failure mechanisms height and piping

Specifications for the failure mechanism height
To determine the budget for failure mechanism height, equation 3.1 is used for the height. The safety requirement for height ($P_{norm,height}$) depends on the safety standard for the segment ($P_{segment}$), the maximum failure probability of overflow and overtopping (ω_{height}) and the length effect for overflow and overtopping on segment scale (N_{height}) (Rijkswaterstaat, 2016):

$$P_{norm,cross,height} = \frac{P_{segment} * \omega_{height}}{N_{height}} \tag{3.2}$$

The aforementioned formula translates the norm for a segment to a norm for an arbitrary cross-section of a dike stretch within the segment. The greater the length of a dike segment, the more likely there will be a weak spot. This phenomenon is known as the length-effect (N) and takes the increase of failure probability with increasing length into account. The factors for the length-effect differ per dike section (Rijkswaterstaat, 2015).

Table 3.2: Safety standards for the failure mechanism height. On a segment level, the norm for the failure mechanism of height is determined for the selected dike segments. Two examples are given in the table. In total, 526 dike sections are evaluated. The norm of the cross-section belongs to the lower limit, and not the signalling value.

Section	Segment	Lower limit [year]	N [-]	Norm cross section [1/year]	Min. return period [year]
14001001	14-1	30000	2	4.00e-06	2.50e05
..	..	..	..	..	
16001001	16-1	30000	1	8.00e-06	1.25e06
..	..	..	..	..	

Specification for the failure mechanism piping
To determine the budget for failure mechanism overtopping and overflow, equation 3.1 is used, but then specified for piping. The safety requirement for height ($P_{norm,piping}$) depends on the safety standard for the segment ($P_{segment}$), the maximum failure probability of piping (ω_{piping}) and the length effect for piping on segment scale (N_{height}) (Rijkswaterstaat, 2016):

$$P_{norm,cross,piping} = \frac{P_{segment} * \omega_{piping}}{N_{piping}} \tag{3.3}$$

For piping, the translation of the norm from a cross section to a dike section cannot be made 1:1 as this would lead to an over-conservative norm as the length-effect for piping is relatively large. The large value of the length-effect indicates that there is a large variety in strength and load characteristics over the segment length. Hence, an extra step is added to the procedure to translate the norm to a dike section. The norm per dike section depends on the part of the segment that is sensitive to the respective failure mechanism (a), the length of an independent equivalent section for the considered failure mechanism (b) and the length of the dike section:

$$P_{norm,section,piping} = P_{norm,cross,piping} * L_{section} * \frac{b}{a} \tag{3.4}$$

The values for a and b are equal to 0,4 and 300 m respectively (Rijkswaterstaat, 2015).

Table 3.3: Safety standards for the failure mechanism piping. On a dike section level, the norm for the failure mechanisms of piping is determined for the selected dike segments. Two examples are given in the table. In total, 526 dike sections are evaluated. The norm of the cross section belongs to the lower limit, and not the signaling value.

Section	Segment	Lower limit [year]	Norm cross section [1/year]	Length section [km]	Norm dike section [1/yr]
14001001	14-2	30000	7.80e-06	0.71	7.29e-06
..	..	..	..	..	..
16001001	16-1	30000	7.86e-06	2.33	2.44e-05
..	..	..	..	..	..

3.3.3 Limit state and fragility curves

Fragility curves give information about the probability of failure as a function of the water level and are increasingly common components of flood risk assessments (van der Meer et al., 2008; Schultz et al., 2010). These curves are governed by failure modes and type of flood defence.

Limit state for failure mechanism overflow and overtopping

Overflow occurs when the water level exceeds the crest level of a dike. Overflow is related to the still water level meaning that flow over a dike due to waves is excluded for this mechanism. The limit state function of this mechanism is:

$$Z = h_d - h_{water} \tag{3.5}$$

The limit state function for overflow depends on the crest level of the levee (h_d) and the still water level (h_{water}).

Overtopping considers the damage due to local waves and seiches. A dike can fail due to overtopping when the flow over the dike meets a critical flow. The critical flow is related to the moment when revetment on the inner side of the levee starts to erode. This results in the following limit state function:

$$Z = m_{qc}\ q_c - m_q 0\ q_0 \tag{3.6}$$

Limit state and fragility curve for failure mechanism piping

Failure due to piping is related to three different mechanisms; uplift, heave and piping. Uplift is caused by excessive pressure in the aquifer which causes the aquitard to lift. Subsequently, groundwater starts to flow towards the leak (seepage) and the flow starts to erode granular material (heave). These processes combined result in a pipe that threatens the stability of the dike. Failure due to piping occurs when the limit state functions are reached for all three mechanisms. To simplify, only the mechanism of piping is discussed in this graduation project. The exclusion of heave and uplift can be considered as a conservative assumption. Hence, only the revised formula of Sellmeijer is of importance in the remainder of the analysis:

$$Z_p = m_p H_c - (h - h_b - 0.3d) \tag{3.7}$$

The limit state function depends on the model factor that states the uncertainty in the model for the critical water level (m_p), the critical difference in water level (H_c), the local occurring water level (h), the water level at the exit pint (h_b) and the blanket layer thickness (d). The critical difference in water level can be determined by:

$$H_c = F_{resistance}\ F_{scale}\ F_{geometry} L \tag{3.8}$$

$$F_{resistance} = \eta(\frac{\gamma_s}{\gamma_w} - 1)\ tan(\theta) \tag{3.9}$$

$$F_{scale} = \frac{d_{70m}}{\sqrt[3]{\frac{vkL}{g}}} (\frac{d_{70}}{d_{70m}})^{0.4} \tag{3.10}$$

$$F_{geometry} = 0.91 \left(\frac{D}{L}\right)^{\frac{0.28}{(D/L)^{2.8}}+0.4} \tag{3.11}$$

The critical height depends on many (geological) parameters such as the leakage length (L), the coefficient of White (η), the dry volumetric weight of sand (γ_s), the volumetric weight of water (eta_w), the internal friction of sand grains (θ), the viscosity of water (v), the specific conductivity of acquifer (k), the gravitational constant (g), the 70% quantile of the grain size distribution (d_{70}), the mean d_{70} in small scale laboratory tests (d_{70m}) and the thickness of the aquifer (D).

Table 3.4: Input parameters for computing fragility curves related to the failure mechanism piping. Based on the (geological) characteristics of the location, input parameters may vary between different dike sections. The variables that govern the fragility curve are given below. The dots indicate that the values differ per dike stretch, the values that are given represent values that are the same for each dike stretch.

Variable	Distribution	Mean	Standard deviation
m_p	Normal	..	..
h_b	Deterministic	..	..
d	Lognormal	..	..
L	Lognormal	..	..
η	Lognormal	..	..
γ_s	Normal	27	0.27
γ_w	Deterministic	10	-
v	Deterministic	$1.33 * 10^{-6}$	-
k	Lognormal	..	..
g	Deterministic	9.81	-
d_{70}	Lognormal	..	
$d70m$	Deterministic	$2.08 * 10^{-4}$	-
D	Lognormal	..	..

The fragility curve for piping shows the probability of piping as a function of the water level. When the loads and strength are defined the failure probability can be found. This is done by using the limit state function and numerical integration. Assuming independence between load and strength, the failure probability can be computed by:

$$P(Z < 0) = \int_{-\infty}^{+\infty} F_R(h) f_S(h)\, dh \tag{3.12}$$

where $F_R(h)$ is the cumulative distribution function of the resistance and $f_S(h)$ is the probability density function of the load (Figure 3.9). The probability density function of the load can be generated by the hydrodynamic model, discussed in the previous section.

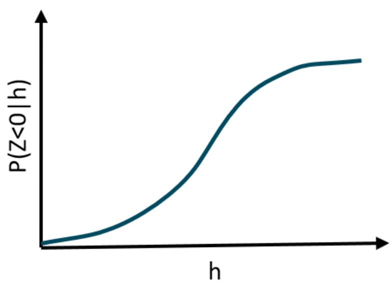


Figure 3.9: Illustration of a fragility curve. The conditional failure probability is depicted on the vertical axis, and the water level on the horizontal axis

Chapter 4

Influence of Delta21 on the water flows

> We live on a island of knowledge surrounded by a sea of ignorance. As our island of knowledge grows, so does the shore of our ignorance.
>
> John Archibald Wheeler, Scientific American, Vol. 267, 1992

Pumps influence the water system of the Rhine-Meuse estuary. In this chapter, the influence on the hydrodynamic processes is discussed. It is focused on the water flow within the water system and answers the following sub-question:

SQ-I.c What is the influence of Delta21 on the water flows in the Rhine-Meuse estuary?

The answer to this question is formulated in two steps. First, the influence of pump capacity on the water levels, discharges and velocities at different locations throughout the Rhine-Meuse estuary are evaluated (Section 4.1). Subsequently, system interactions are explored (Section 4.2 and 4.3). These interactions provide insight into what ways Delta21 interferes in the water system. This chapter discusses the model results, more detailed information about the model set-up can be found in Chapter 3.

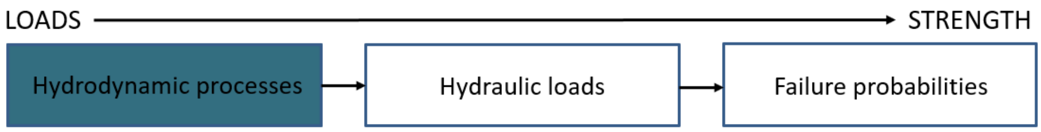


Figure 4.1: Schematic overview of the three parts within the results of the physical perspective. This chapter analyses the hydrodynamic processes, rendered in blue.

4.1 Comparative analysis of sub-areas

In this analysis, different locations are compared to each other. The primary goals of this section is to compare the influence of Delta21 on the hydrodynamic processes. One realization - a particular combination of boundary values - without sea level rise is explored. Hence, it provides limited insight into the influence of Delta21 on hydraulic loads.

4.1.1 Classification of sub-areas based on hydrodynamic processes

The domain of the model can be divided into sub-areas with different dominant processes (Chbab and Groeneweg, 2017). The hydraulic processes in each branch of the domain are interesting because they determine the water levels and erosion patterns among others. Hence, locations are selected corresponding to each branch in the domain and categorized based on the dominant hydraulic process (Table 4.1). The dominant processes depend on the combination of four treats: discharge, sea level, wind and operation of the storm surge barrier. The reason that different drivers are dominant in each location is mainly related to proximity to the sea, and more specifically to the Europoort barrier.

Table 4.1: Locations with corresponding branches. The sub-area indicates which process is dominant; storm sturge, flood storage, discharge or transition. The latter relates to a sub-area where none of the processes is dominant. In the rightmost column, reference is made to the section in which the sub-area is discussed.

Sub-area	Location	Branch	Section
Storm surge dominant	Maassluis Rotterdam	Nieuwe Waterweg Nieuwe Maas	4.1.2
Flood storage dominant area	Hellevoetsluis Zuidoord Willemstad 's Gravensdeel	Haringvliet Spui Hollandsch Diep Dordtse Kil	4.1.3
Discharge dominant	Schoonhoven Gorinchem Keizersveer	Lek Waal Maas	4.1.4
Transition area	Ablasserdam Dordrecht Heinenoord Krimpen aan de IJssel	Noord Beneden Merwede Oude Maas Hollandse IJssel	4.1.5

In areas more upstream the river discharge becomes prominent. This also means that locations outside the storm surge dominant are less sensitive to the failure probability of the Europoort barrier. The most critical condition takes place when high discharges and high sea water levels occur at the same time. In this case, water is discharged into the system and prevented from flowing out due to closed storm surge barriers. The evaluated locations are scattered throughout the whole domain (Figure 4.2). Because of sea level rise, the discharge dominant area becomes smaller as sea related processes have a larger share in reaching the maximum water level.

A brief analysis of the illustration points also supports the division of different sub-areas. Illustration points are a combination of discharge, sea water level, wind speed and state (e.g. open) of the barriers at a particular location. The combination is such that just failure occurs (load is exactly equal to resistance) and the probability of occurrence of this combination is the highest compared to other combinations that lead to just failure (Geerse, 2003). So, illustration point only contain information about the combination of boundary conditions, not about the geographic location in the domain.

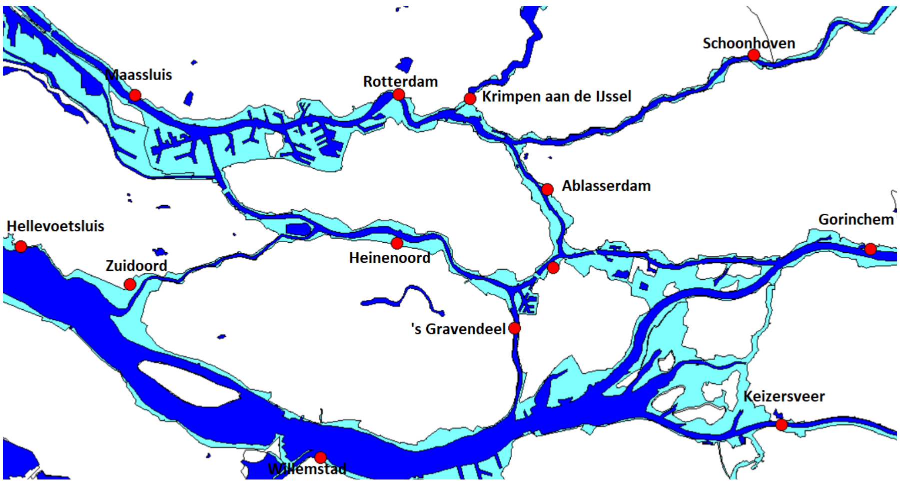


Figure 4.2: Selected locations in the domain. The locations correspond to the location mentioned in Table 4.1. The locations belong to a particular dike section. The water level, discharge, water velocity are retrieved from the nearest sobek node.

To be able to analyse the hydraulic processes, one set of boundary conditions is selected (Table 4.2). In the remainder of the report, a particular combination of boundary conditions is referred to as realization. The investigated realisation corresponds the most to the illustration point of Dordrecht. In the subsequent subsections, the results are discussed for the water levels, discharges and velocities (average flow velocity in the wetted area) for different location throughout the domain. It must be stressed that this results only hold for this particular realisation in case of correct functioning Europoort barrier. For each location, results are shown that belong to a simulation of five days. A more detailed description of the model and the used approach can be found in Chapter 3.

Table 4.2: Illustration points for different locations. Discharges and sea water levels belonging to illustration points of four locations. The last row of the column represents the reference realization used in the comparative analysis.

Location	Area	Discharge [m^3/s]	Sea Water Level [m+NAP]
Rotterdam	Storm surge dominant area	2283	3.70
Hellevoetsluis	flood storage dominant area	10953	3.41
Dordrecht	Transition area	11450	3.26
Schoonhoven	Discharge dominant area	16680	1.71
Illustration point		10.000	3.54

4.1.2 Storm surge dominant area

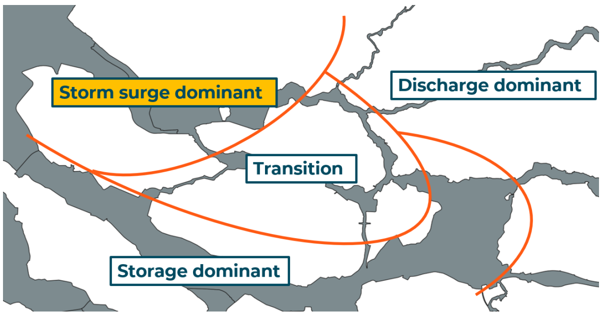


Figure 4.3: Location of storm surge dominant area.

The Nieuwe Waterweg and Nieuwe Maas are located in the storm surge dominant area. These branches are represented by the location of Maassluis and Rotterdam respectively. The effect of a closing storm surge barrier is visible in the graphs (Figures 4.4, 4.5 and 4.6). During the storm, water levels are raised and the discharge and velocity is close to zero due to a closed Europoort barrier. The water levels of the two configurations - with and without Delta21 - diverge sharply during the peak of the storm. For this realisation, the water levels during the storm are flat while the water level for the current configuration continues to rise. For the location of Rotterdam, the maximum water level during this realisation is reduced with almost 1.5m. The slope of the water level at Rotterdam is explored in more detail in the remainder of this report (Section 4.3.1).

When the storm surge barrier opens, the discharge in the Nieuwe Waterweg is larger for the current situation than in the case of Delta21. In the graphs below, this moment is at the date 01-08 (Figures 4.4, 4.5 and 4.6). This can be ascribed to the fact that Delta21 can discharge water to sea in case of storm surge, which means that less water is stored in the Rhine-Meuse estuary. The difference between the discharge at Rotterdam in case of Delta21 or the current situation is quite similar. The surplus in water discharged in the current situation in mainly originating from the Oude Maas, as the discharge at the location of Heienoord is also higher for the current situation (Figure 4.17).

The velocities for both configurations differ not that much. In the case of Delta21, the maximum velocity at Maassluis is reduced with 0.1 m/s. A reduction of flow velocity can indicate less damage for the scour protection at the Measlant barrier. However, as this velocity is depth-averaged over the cross-section it does not necessarily mean that the flow velocity at the scour protection is reduced.

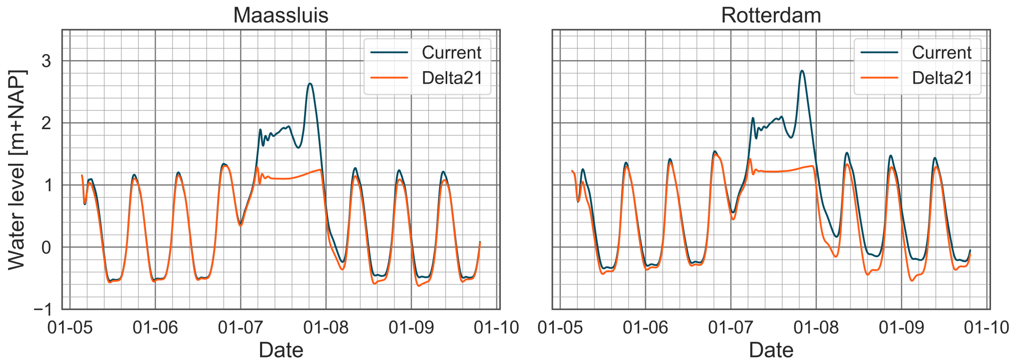


Figure 4.4: Water levels for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m3)/s and storm surge (L) of 3.54 m. Locations are in the storm surge dominant area.

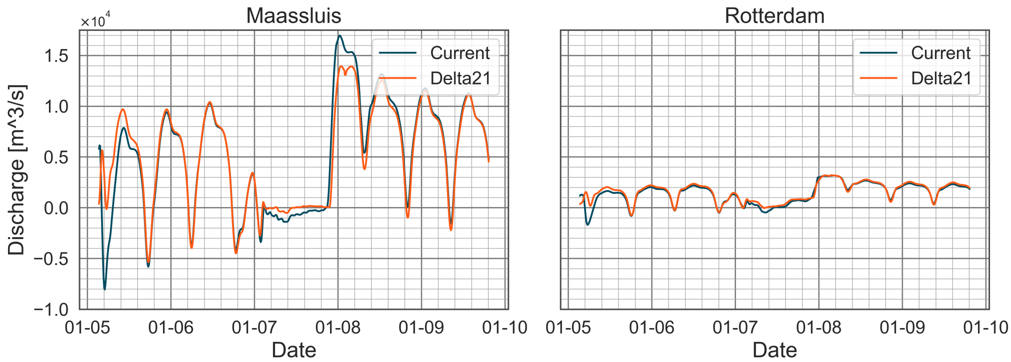


Figure 4.5: Discharges for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the storm surge dominant area.

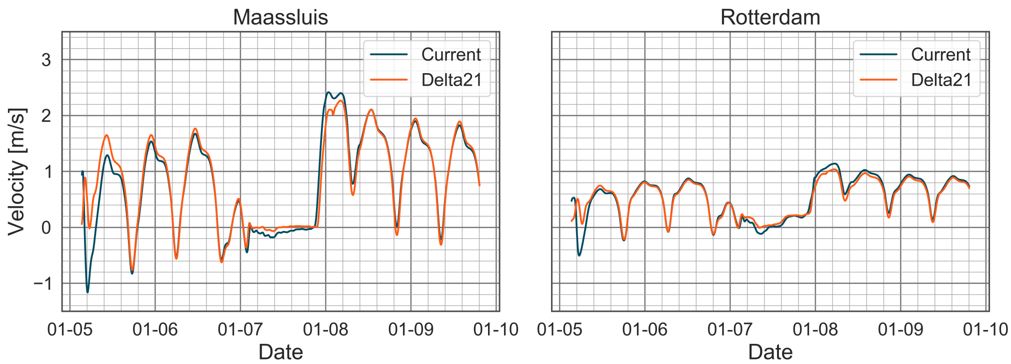


Figure 4.6: Velocities for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the storm surge dominant area.

4.1.3 flood storage dominant area

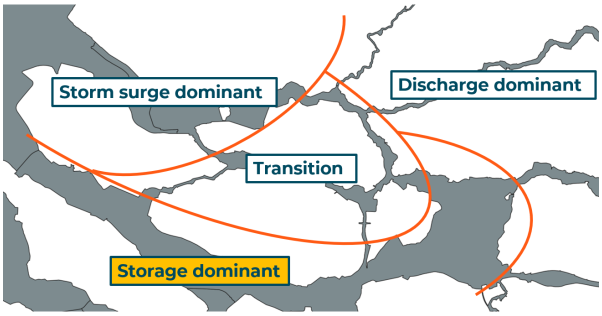


Figure 4.7: Location of flood storage dominant area.

In the flood storage dominant area, Delta21 could lead to a reduction of about 1 m in the maximum water level during this particular realisation (Figure 4.8). Again, the main deviations occur during the storm surge. The water level reduction in the Dordtse Kil ('S-Gravendeel), is smaller than the reduction for locations that are directly connected to the Haringvliet or Hollands Diep.

In the discharges of Hellevoetsluis and Willemstad, one can observe higher discharges during the peak of the storm (Figure 4.9). This can be assigned to the pump installation of Delta21, which makes it possible to drain water to the sea during the storm. One does also see the step-wise deployment of pump capacity. Just before 01-07, the sluices close which means that for the current situation the discharge at Hellevoetsluis becomes nearly zero. For Delta21, the first step of pump capacity (3000 m^3/s) is employed. From this moment, the slope of the water level at Hellevoetsluis becomes slightly negative. However, as the storm surge increases, the slope in the Haringlviet starts to increase as well (01-07 around noon). At that time, the remainder of the pump capacity is applied as well. The pump capacity mitigates for the storm surge as water can still be discharged during a storm.

Velocities do change over the simulation period but remain within the same bandwidths (Figure 4.10). The largest difference can be observed at the branches Spui (Zuidoord) and Dordtse-Kil ('s-Gravendeel). As these branches are relatively small, they are more sensitive to changes in discharge. The maximum velocity in the Spui is larger and occurs at longer consecutive period.

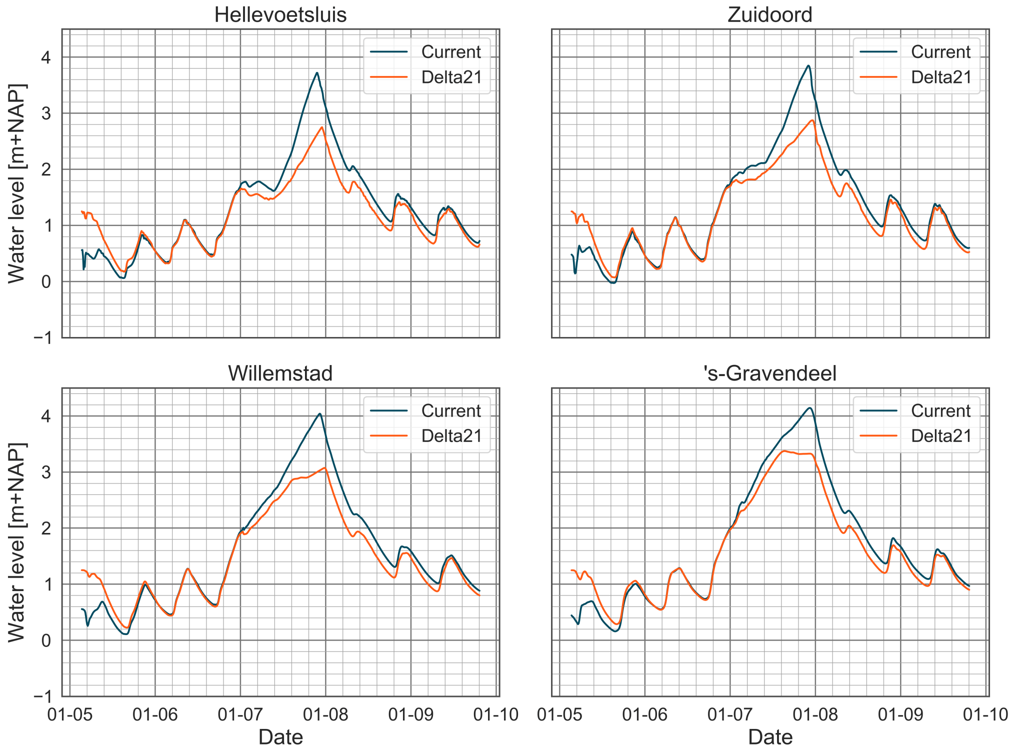


Figure 4.8: Water levels for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the flood storage dominant area.

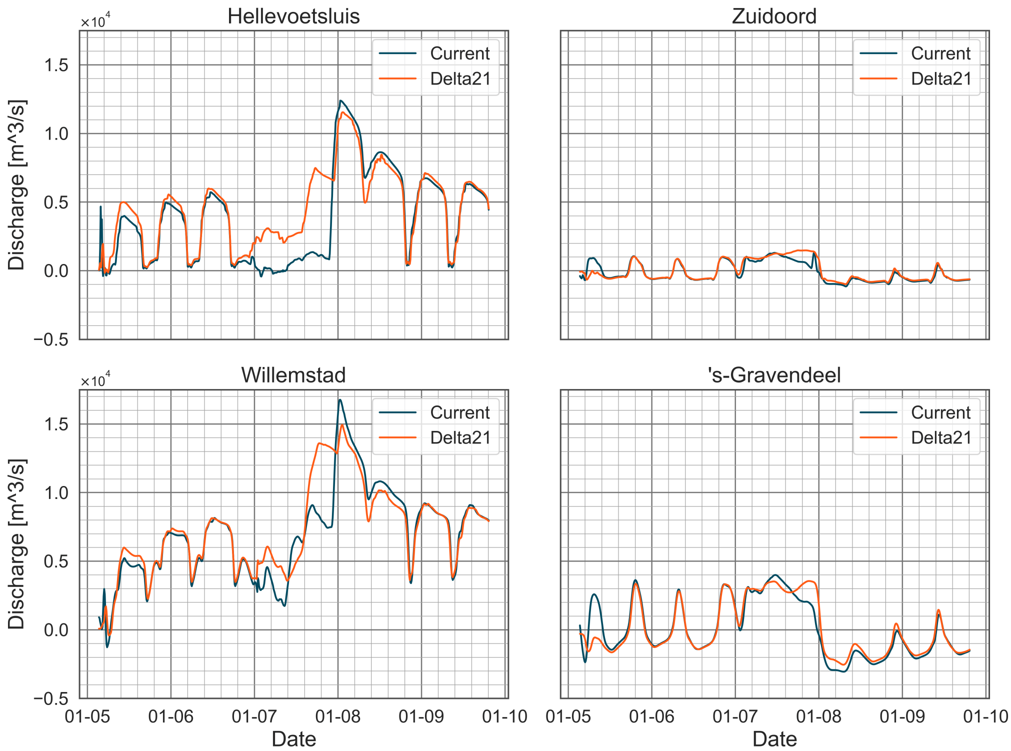


Figure 4.9: Discharges for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the flood storage dominant area.

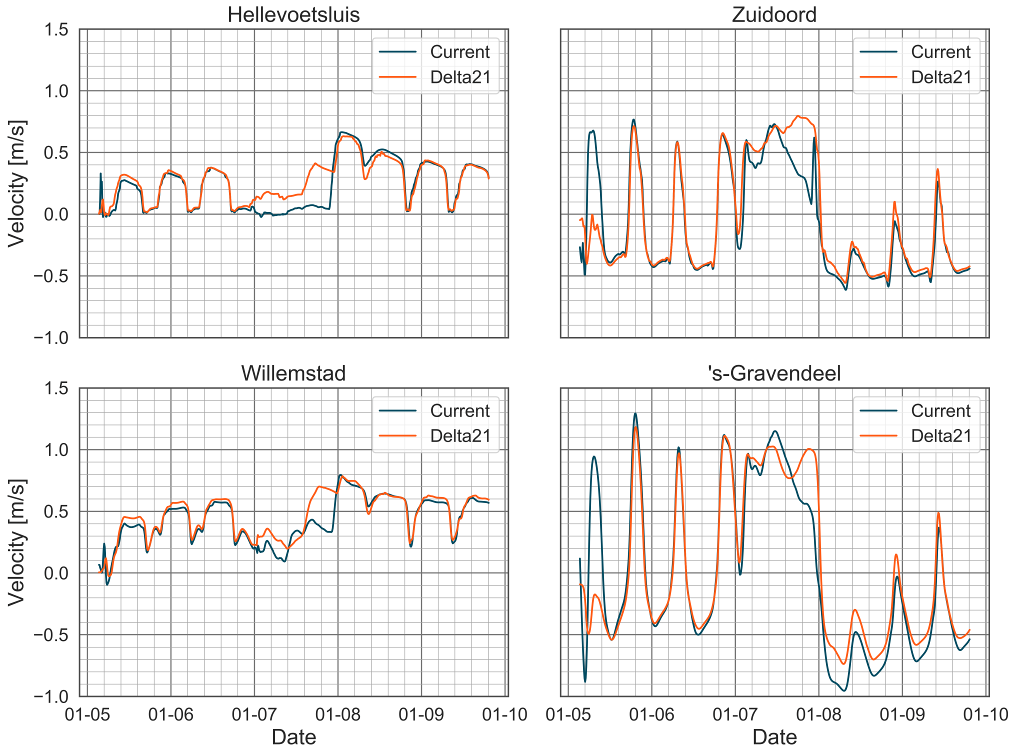


Figure 4.10: Velocities for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the flood storage dominant area.

4.1.4 Discharge dominant area

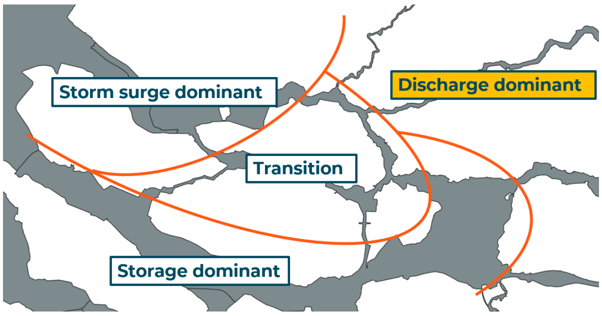


Figure 4.11: Location of discharge dominant area.

Delta21 has a minor influence on the discharge dominant area. However, the reduction in water level is still in the order of decimal centimetres for Keizersveer and Schoonhoven during this particular realisation. Furthermore, one can recognize the shape of the tide and storm surge in the locations of Keizersveer and Schoonhoven, while the dominance of the sea in Gorinchem is fairly limited. This can be ascribed to the different layout of rivers, as is described in Chapter 2. Discharges and velocities remain largely unaffected when the results of Delta21 and the current configuration are compared. Again, this shows that the influence of Delta21 is limited for areas less subjected to conditions at sea.

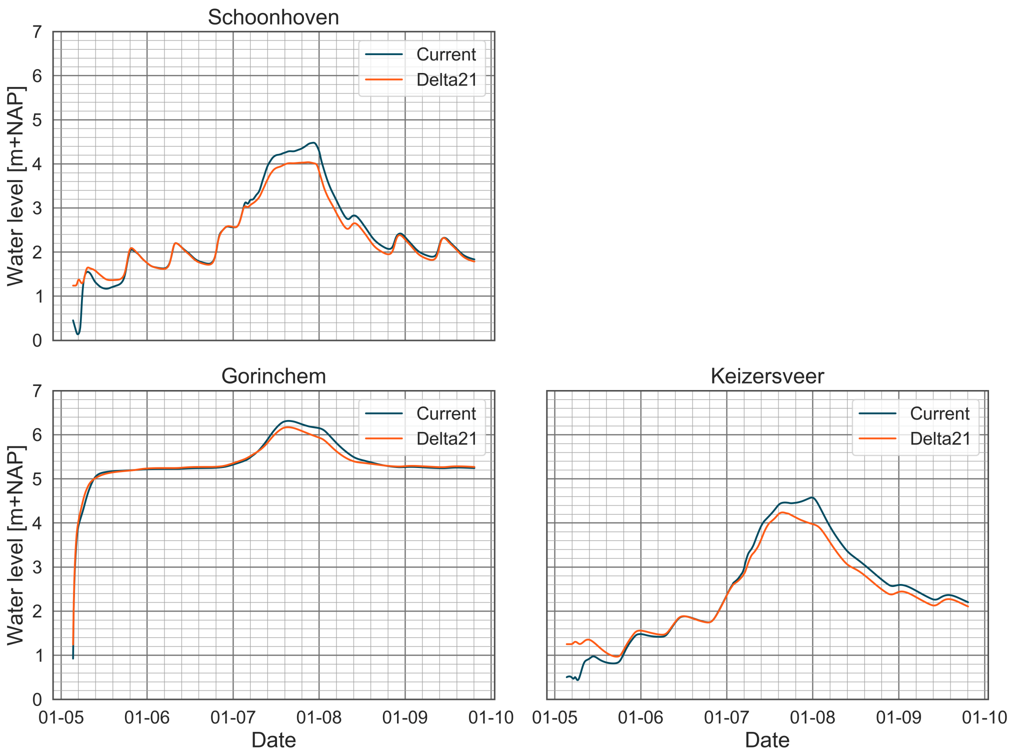


Figure 4.12: Water levels for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the discharge dominant area.

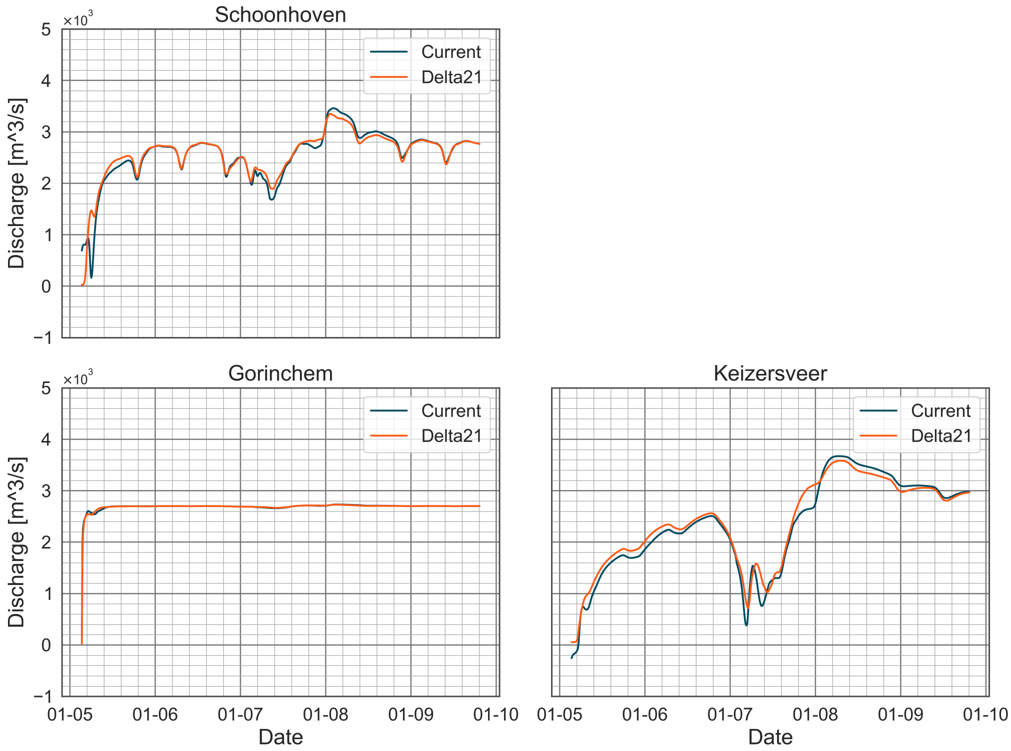


Figure 4.13: Discharges for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the discharge dominant area.

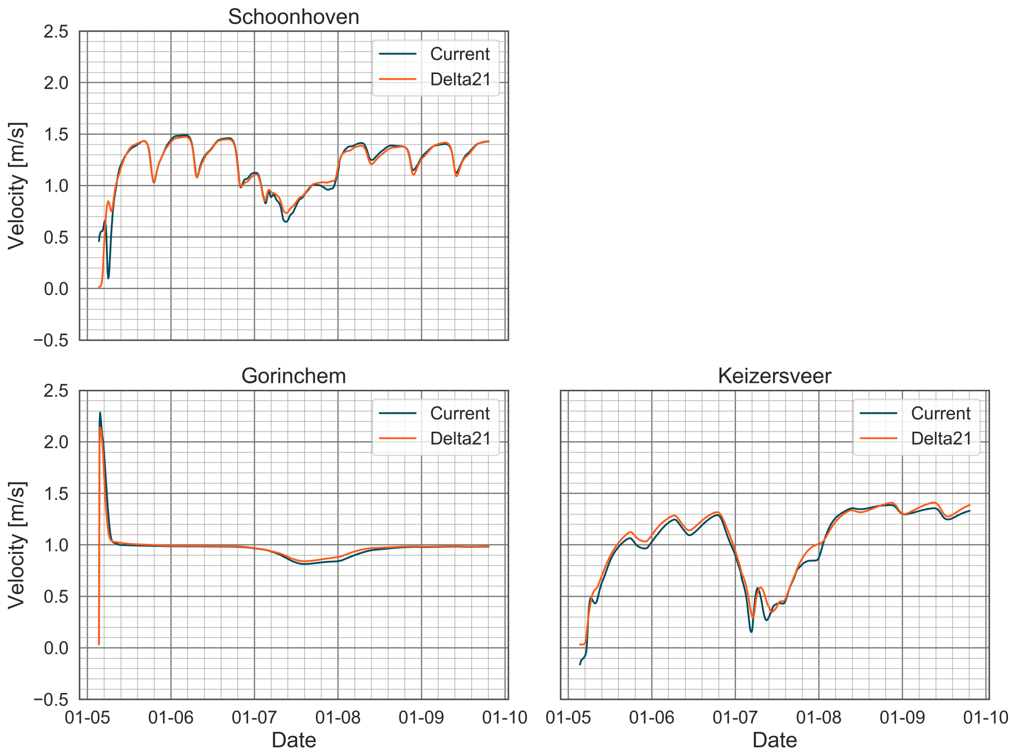


Figure 4.14: Velocities for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the discharge dominant area.

4.1.5 Transition area

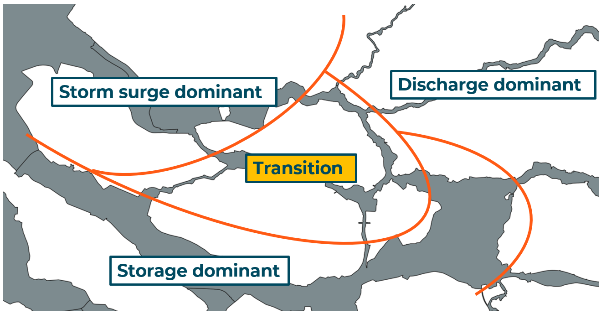


Figure 4.15: Location of transition area.

For the transition area, maximum water levels are lowered with about 60 cm for this realisation. Again, the reduction is profoundly visible during the closure of barriers. River discharge is more dominant in these areas, which means that lower reduction is achieved compared to the flood storage dominant area. The reduction at Dordrecht is compromised as discharge pumped out by Delta21 is flowing past Dordrecht. This is reflected by the higher discharge for Delta21 during the closure of the barrier. At the same time, velocity increases during periods of maximum discharge at Dordrecht which results in reductions in water levels for Delta21 compared to the current system. Water levels at other locations show a similar shape.

Discharges are more distinct for various locations in the transition area. For example, the discharge at Krimpen aan de IJssel is influenced by the Hollandse IJssel barrier to a large extent. This barrier closes during the storm surge, which corresponds with zero discharge during the third day of the five-day simulation. Following the decreased discharge in the Nieuwe Waterweg and Hartel canal (Section 2), discharge decreased at Heijenoord and Ablasserdam.

Velocities for the four locations remain between the same maxima and minima for the current configuration and Delta21, except for Krimpen aan de IJssel. The velocities at Krimpen aan de IJssel show alternative behaviour as the velocities are largely affected by the Hollands IJssel barrier.

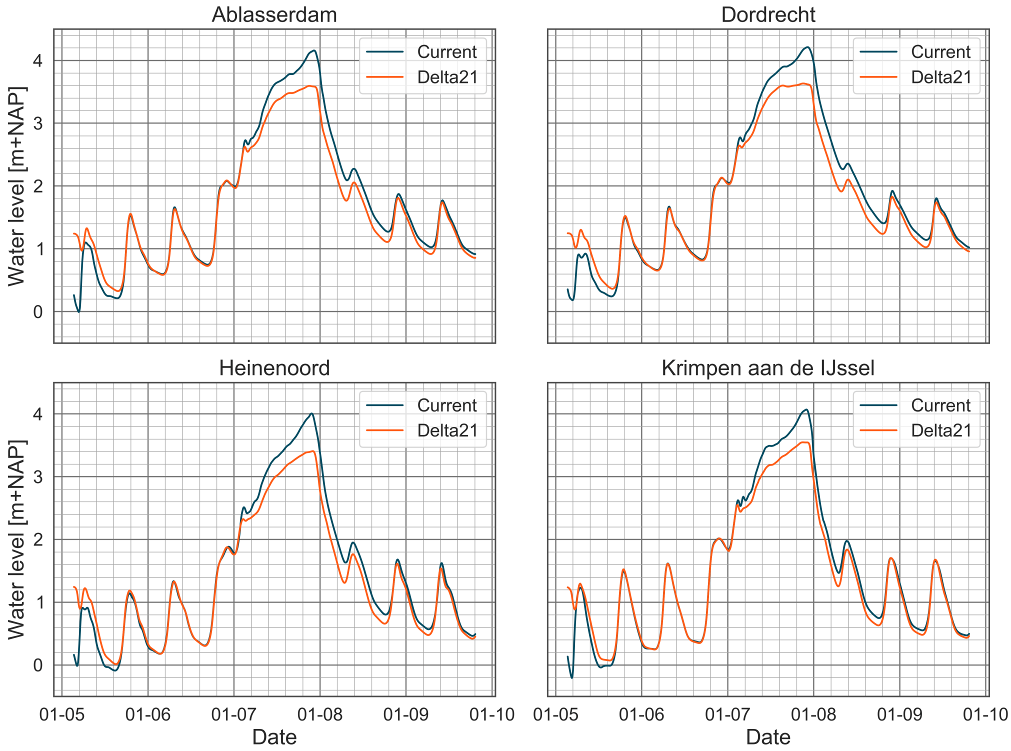


Figure 4.16: Water levels for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the transition area.

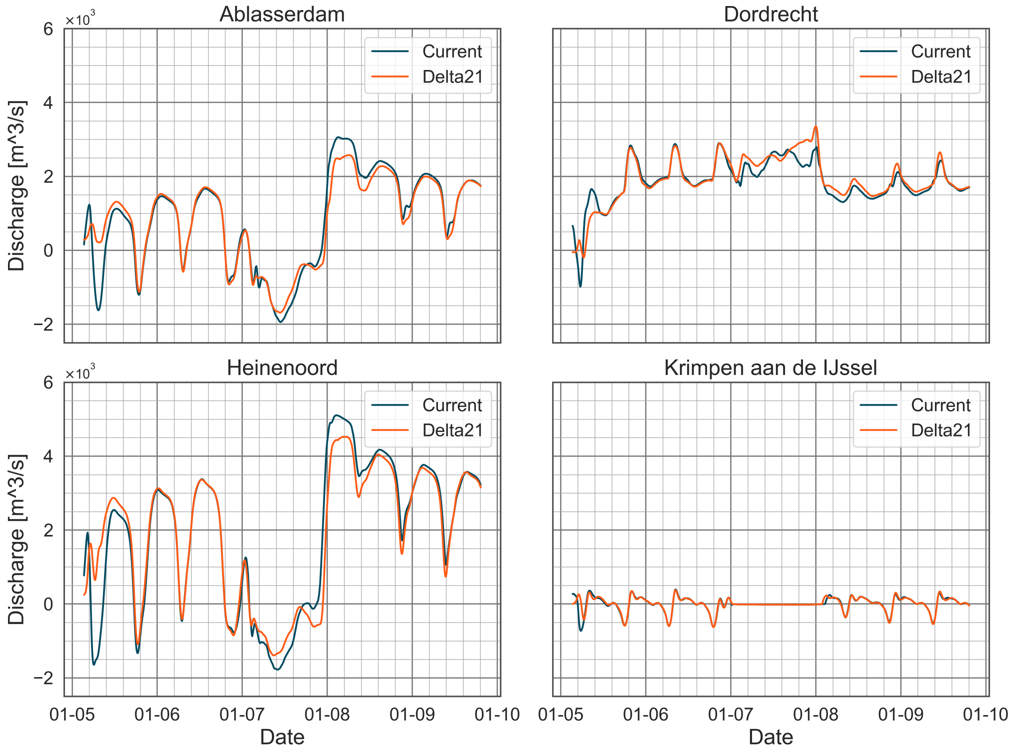


Figure 4.17: Discharges for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the transition area.

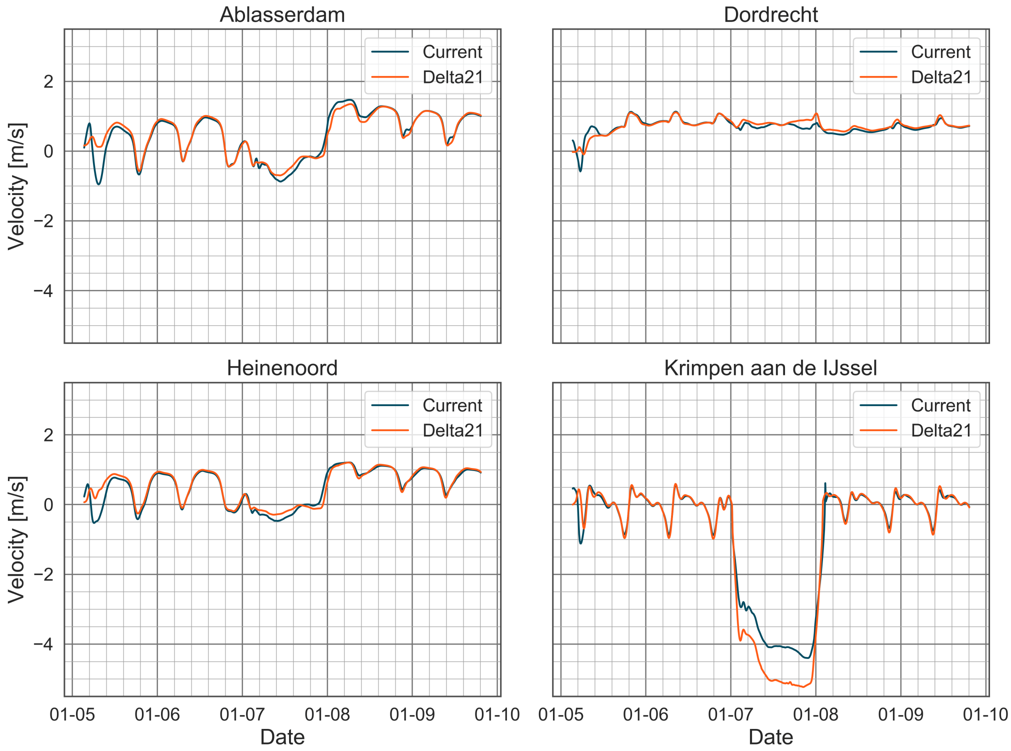


Figure 4.18: Velocities for both configurations during a storm with a Rhine discharge (Q_{Lobith}) of 10 000 m^3/s and storm surge (L) of 3.54 m. Locations are in the transition area.

CONCLUDING REMARKS

The used realisation corresponds to the illustration point, which is the combination that just failure occurs, and the probability of occurrence belonging to this combination is the highest compared to other combinations that lead to just failure. The used realisation had a storm surge level of 3.54 m, discharge of 10.000 m^3/s and a correct functioning Europoort barrier. In general, Delta21 did not have a drastic (adverse) effect on the hydrodynamic processes. The effects on water level, discharge and velocity were not equal for every location in the Rhine-Meuse estuary. For the investigated realisation, the maximum water level in the storm surge area is reduced with 1.5 m, in the flood storage dominant area with 1 m, in the transition area with 60 cm and in the discharge dominant area 20 cm.

4.2 Influence of Delta21 on deployment of storage in Volkerak-Zoommeer

The Volkerak lake can provide water storage during critical conditions. Via the Volkerak sluices, water can be discharged from the Hollands Diep to the Volkerak lake. This storage is utilized when the water level exceeds a level of NAP + 2.6 m. Since Delta21 lowers the water level in the Haringvliet and the Hollands Diep, the model outcomes showed that the frequency of deployment is reduced (Figure 4.19). Hence, the storage capacity of the Volkerak lake was not used in this particular configuration of Delta21. Nonetheless, the real-time operation of the Delta21 can be adjusted to enable the possibility to store water in the Volkerak lake. When it is desirable that the storage of the Volkerak lake is used, the Volkerak sluices must be opened before the pumps of Delta21 become active. Otherwise the water level in the Hollands Diep is lowered to such a degree that opening of the sluices won't further contribute to lowering of the water level in the Hollands Diep.

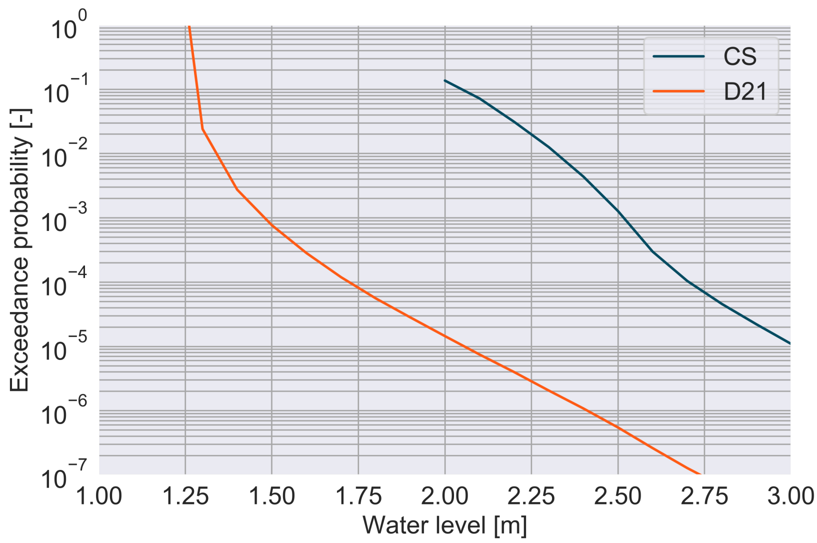


Figure 4.19: Exceedance probability of water level at Willemstad. The current system is depicted in blue and Delta21 is rendered in orange. Willemstad is located right next to the Volkerak sluices. In case of Delta21, the threshold water level of NAP+ 2.6 m is exceeded less.

4.3 Interaction between Europoort barrier and Delta21

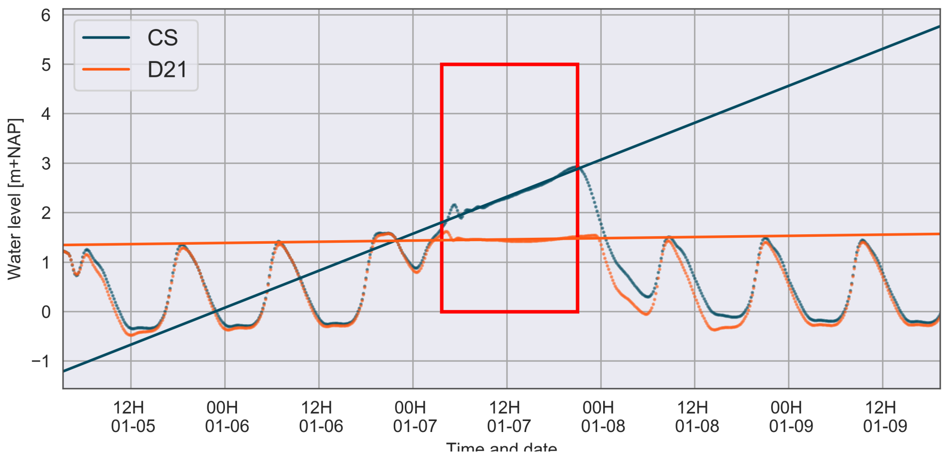
Delta21 lowers the water level in the Rhine-Meuse estuary. The closure of the Europoort Barrier - Maeslant Barrier and Hartel Barrier - depends on the expected water level and the upstream and downstream water level at the storm surge barrier itself. In this section, the interaction between Delta21 and the Europoort Barrier is explored in a more detailed way.

4.3.1 Water surface gradient and maximum water level at Rotterdam

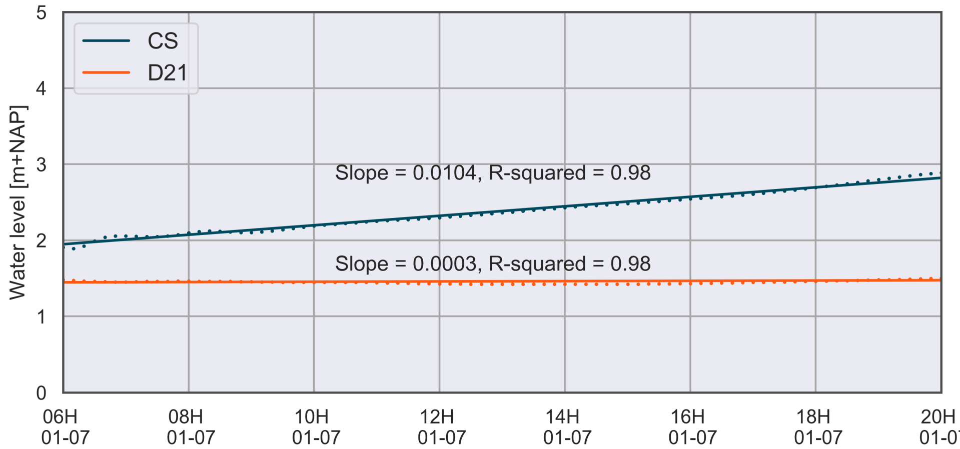
In this section, the gradient of the water level and maximum water level during a five-day simulation is evaluated. It is interesting to compute the slope for different realisation (combinations of discharge and storm surge) to see whether Delta21 is capable to minimize the water level gradient during the closure of the storm surge barriers. In this context, the water level gradient represents the increase, or decrease, in water level over time.

In Figure 4.20a, a five-day simulation corresponding to a storm surge of 3.54 m, Boven-Rijn discharge of 10 000 m^3/s and a correct functioning Europoort barrier. During this simulation, the water level gradient during closure - indicated by the red square - was almost zero. This indicates that Delta21 succeeds in discharging water from rivers to the sea during the critical condition of closed storm surge barriers. The reduction in terms of maximum water level is about 1.5 m.

For other combinations of storm surge and river discharge, the water level gradient and maximum water level are computed as well (Figure 4.21). In all those combinations, the Europoort barrier operated as expected (no failure). When discharge increases, the reductions of Delta21 increase as well. When the discharge became larger than 10 000 m^3/s, the reductions started to decrease (Figure 4.21e). The storm surge has also an influence on the water level gradient and maximum water level. This is mainly profound in the figures for the current system (Figure 4.21a) and 4.21c). For example, when a discharge of 16 000 m^3 is subjected together with a storm surge of 3.54 m, the maximum water level is 1.3 m lower than when the same discharge is subjected together with a storm surge of 5.59 m. A system with Delta21 is less sensitive to an increase in discharge. The water level gradient and maximum water level are to a large extent governed by the discharge of the Boven-Rijn.

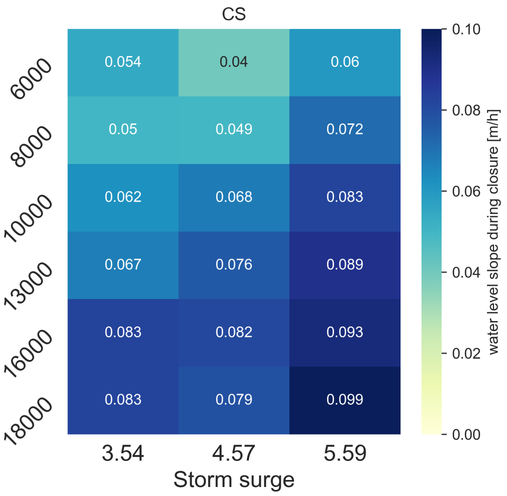


(a) Water level at Rotterdam over simulation period. The dots indicate the output of the hydrodynamic model. The two straight lines are fitted to the dots present in the red rectangle.

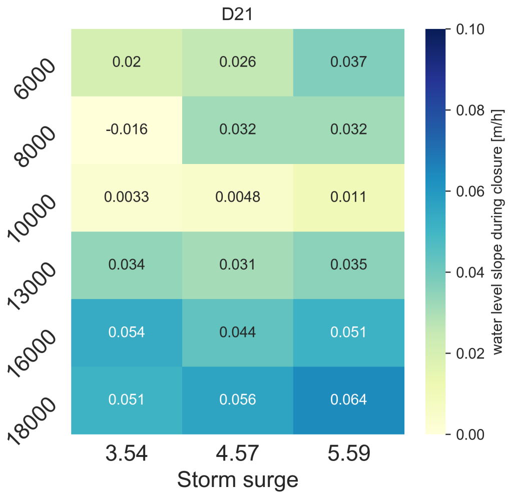


(b) Water level at Rotterdam during the closure of the Europoort barrier. The red square of the upper plot corresponds with the boundaries of this plot. A linear regression line is fitted through the observation points of the simulation, including the slope [m/h] and R-squared.

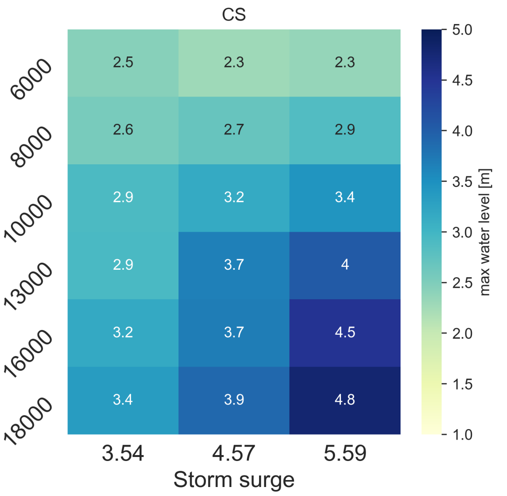
Figure 4.20: Water level at Rotterdam during the simulation period. In the upper plot the full simulation period is expressed. In the lower plot, the water level during closure is presented, which corresponds to the red square in the upper plot. The presented realization consists of a discharge of 10 000 m^3/s and storm surge of 3.54 m.



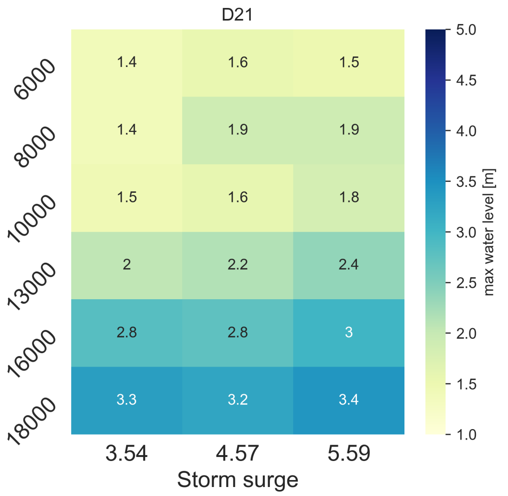
(a) Water level gradient for current system.



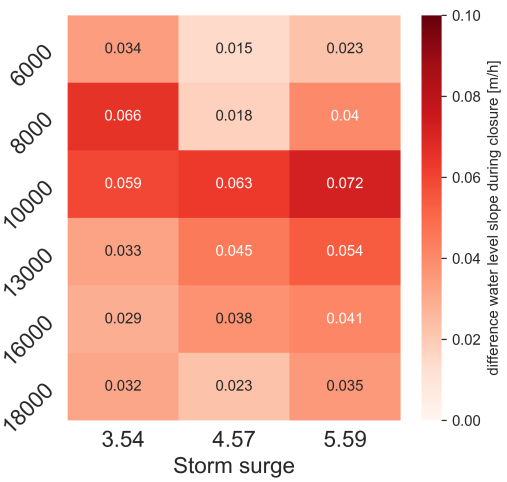
(b) Water level gradient for Delta21.



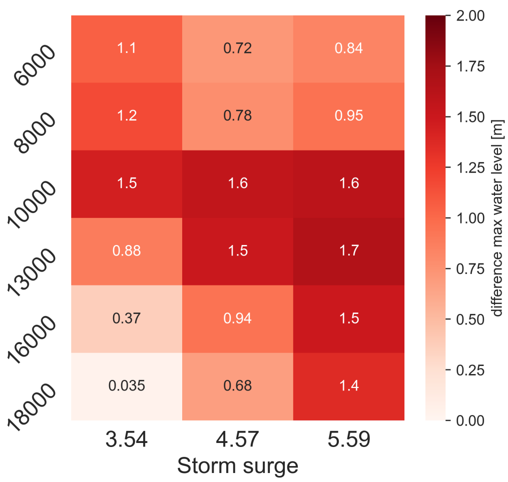
(c) Maximum water level for current system.



(d) Maximum water level for Delta21.



(e) Difference in water level gradient between current system and Delta21.



(f) Difference in maximum water level between current system and Delta21.

Figure 4.21: Heat map of slope and water level for different discharge and storm surge combinations. In all simulations, the Europoort barrier operates as supposed (no failure). The first two figures illustrate the water level gradient of the water level at Rotterdam, for a particular combination of storm surge and discharge at the Boven-Rijn (Figure 4.21a and 4.21b). The maximum water levels during the five-day simulation for both system is depicted in Figure 4.21c and 4.21d. The remaining figures show the difference between Delta21 and the current system for the water level gradient and maximum water level. In Figure 4.20 an example of the slope and water level is presented for the realization with a discharge of 10 000 m^3/s and storm surge of 3.54 m.

4.3.2 Duration of closure

For both systems - Delta21 and the current configuration - the closure duration differs of the Europoort Barrier. The Europoort Barrier is operated following a certain system with different states. Detailed information about the states and the governing criteria can be found in the Appendix (Figure B.4). Depending on the water level at the storm surge barrier and the projected water level in the Maasmond, the barrier is changing from one state (e.g. open) to the other (e.g. horizontally closing). One explanation that the current system has a shorter closure in some situation is that the Delta21 lowers the water level at Rotterdam. To open the barriers again, the water level at the Nieuwe Waterweg needs to be equal to the water level at sea. As the water level in the Nieuwe Waterweg is lowered, it could take more time to reach an equal water level at both sides of the storm surge barrier.

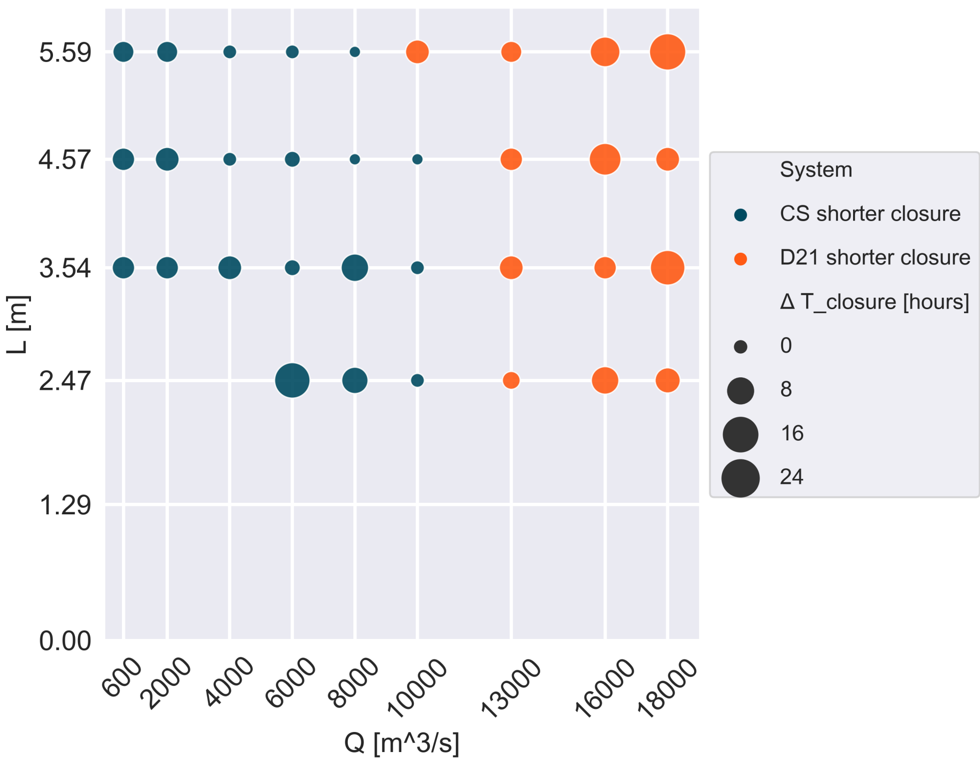


Figure 4.22: Difference in closure duration of the current configuration and a configuration with Delta21. The size of the circles indicates difference in number of hours. An blue circle corresponds to a shorter closure of the current configuration, an orange circle represents an shorter closure for Delta21.

4.3.3 Influence of sea level rise and failure probability on the performance of Delta21

The effectiveness of pumps in reducing the water level depends on the failure probability of the Europoort barrier. In this section, the relation between the Europoort barrier and Delta21 is investigated. The main point in this section is to investigate the relation between the failure probability of the Europoort barrier. Hence, the following failure probabilities are evaluated:

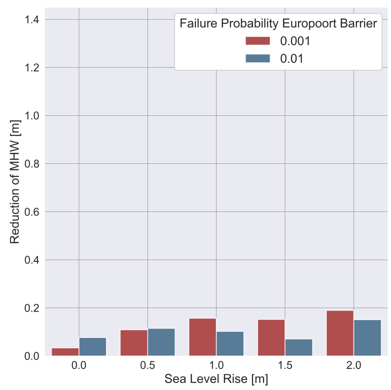
- Failure, due to not closing: 1 per 100 closing requests;
- Failure, due to not closing: 1 per 1000 closing requests.

One of the ways to show the dependence on the failure probability is by looking at the governing water level. The governing water level is the water level which corresponds to the return period relevant for a particular dike segment. This relevant return period is determined by the norm of dike stretch. A stricter norm leads to a larger relevant return period which in turn results in a larger governing water level. The governing water level is composed of multiple contributions belonging to different realisations.

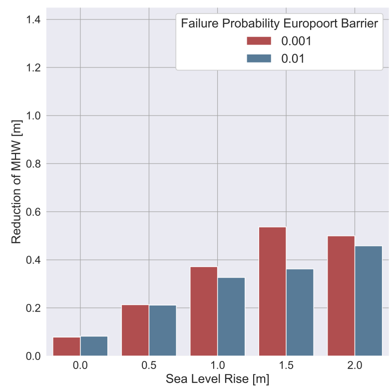
Some realisations work with a correct functioning Europoort barrier, others with a failing Europoort barrier (Section 3.2.4). Again, the locations are evaluated based on the categories depicted in Table 4.1, as can be seen in Figure 4.23 on the next page. The reductions on the MHW of Delta21 differed considerably depending on the location and sea level rise. Increasing sea level between 0 and 1.5 m resulted in larger reductions in water levels due to Delta21 at Hellevoetsluis. From 1.5 m onwards the effectiveness decreases as sea level increases. For the storm surge area, the difference between an improved Europoort and present Europoort barrier is largest for 1.5 m.

CONCLUDING REMARKS

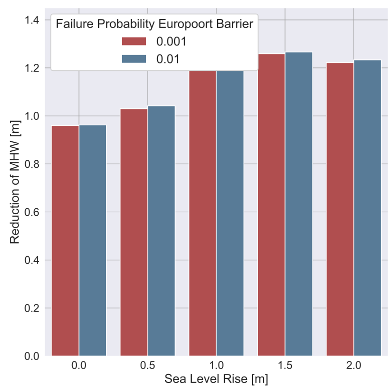
The water level at Rotterdam, and the water level reductions due to Delta21, are considered in more detail. The sensitivity of those reductions is investigated for various discharges and steps of sea level rise. In case of correct functioning Europoort barrier and a discharge of 10 000 m ^{3} /s at the Boven-Rijn, Delta21 succeeds to keep the slope of the water level during a storm surge to lower than 1 cm/h. The maximum reduction in water level between the current situation and Delta21 is achieved for the combination with an discharge of 13 000 m^3/s and a storm surge of 5.59 m. For larger discharges than 13 000 m^3/s, the effect of Delta21 on the maximum water level is less profound. For discharges lower than 10 000 m^3/s, the closure duration for the current situation is shorter compared to the configuration including Delta21. This is due to the lowering of the water level which delays the moment when the inside and outside water level are equal around the Maeslant barrier. This equal water level is required to open the barrier. Delta21 enables shorter closure of the Maeslant barrier for discharges larger than 13 000 m^3/s.



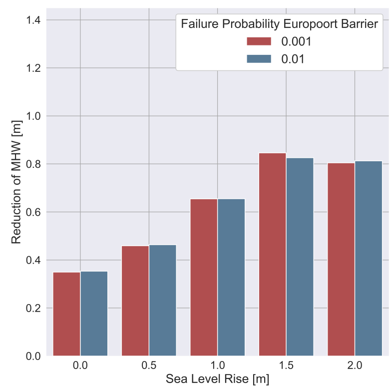
(a) Rotterdam (storm surge dominant).



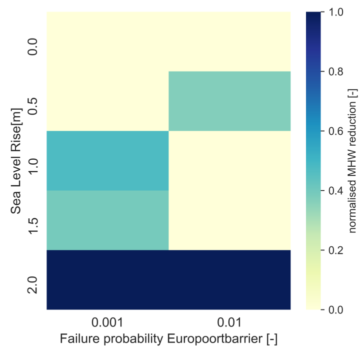
(b) Schoonhoven (discharge dominant).



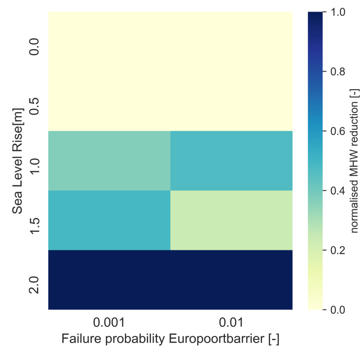
(c) Hellevoetsluis (storage dominant).



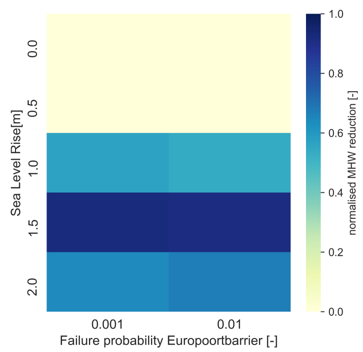
(d) Dordrecht (transition).



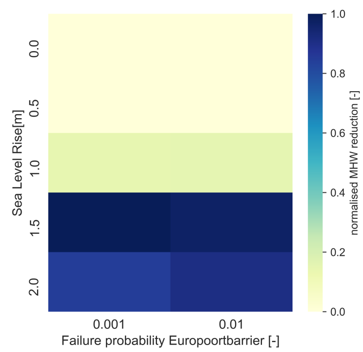
(e) Rotterdam (storm surge dominant).



(f) Schoonhoven (discharge dominant).



(g) Hellevoetsluis (storage dominant).



(h) Dordrecht (transition).

Figure 4.23: Effect of Delta21 on governing water levels (MHW) for different sea level rises and failure probabilities of the Europoort barrier. For each step step of sea level rise, the effect on the governing levels is compared at four different locations in a bar chart, corresponding to storm surge dominant (a), discharge dominant (b), storage dominant (c) and transition (d). The remaining figures represent the governing water level reduction normalised per location in a color scale mapping.

Chapter 5

Influence of Delta21 on the hydraulic loads on flood defences

The aim of system interventions such as Delta21 is to mitigate the consequences of sea level rise by reducing the hydraulic loads. In this chapter the influence of Delta21 on the hydraulic loads is investigated. Hence, it answers the following research question:

SQ-I.d What is the influence of Delta21 on the hydraulic loads in the Rhine-Meuse estuary?

As denoted in the simulation approach, hydrodynamic and probabilistic computation have been made to draw conclusions about the influence of Delta21 (Chapter 3). The main objective of this chapter is to distil the effect of Delta21 under a range of sea level rises. As Delta21 is located at the Haringvliet sluices, it is interesting to see how the reduction of Delta21 is distributed throughout the Rhine-Meuse estuary.

First, the computed water level frequency lines are discussed and compared (Section 5.1). These lines provide insight in the reduction of water levels for different return periods. Subsequently, the geographic distribution is investigated by computing the hydraulic loads for each dike segment in the Rhine-Meuse estuary (Section 5.2).

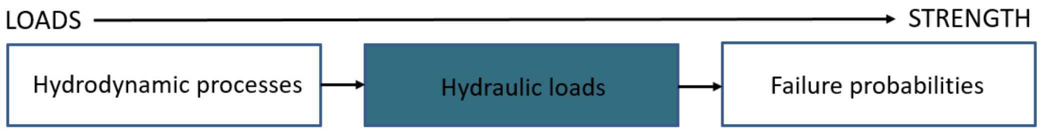


Figure 5.1: Schematic overview of the three parts within the results of the physical perspective. This chapter analyses the hydraulic loads, rendered in blue.

5.1 Change in water level frequency lines

The water level frequency lines were evaluated for the locations presented in Table 5.1. Water level frequency lines are compared between Delta21 and the current configuration for various steps of sea level rise. Delta21 results in lower water level frequency lines, indicating that the probability of exceedance of water levels is lower (Figure 5.2).

Table 5.1: Locations with corresponding branches. The sub-area indicates which process is dominant; storm sturge, flood storage, discharge or transition. The latter relates to a sub-area where none of the processes is dominant. In the rightmost column the reference is made to the section in the sub-area is discussed.

Sub-area	Location	Branch	Section
Storm surge dominant	Rotterdam	Nieuwe Maas	5.1.1
Flood storage area	Hellevoetsluis	Haringvliet	5.1.2
Discharge dominant	Schoonhoven	Lek	5.1.3
Transition area	Dordrecht	Beneden Merwede	5.1.4

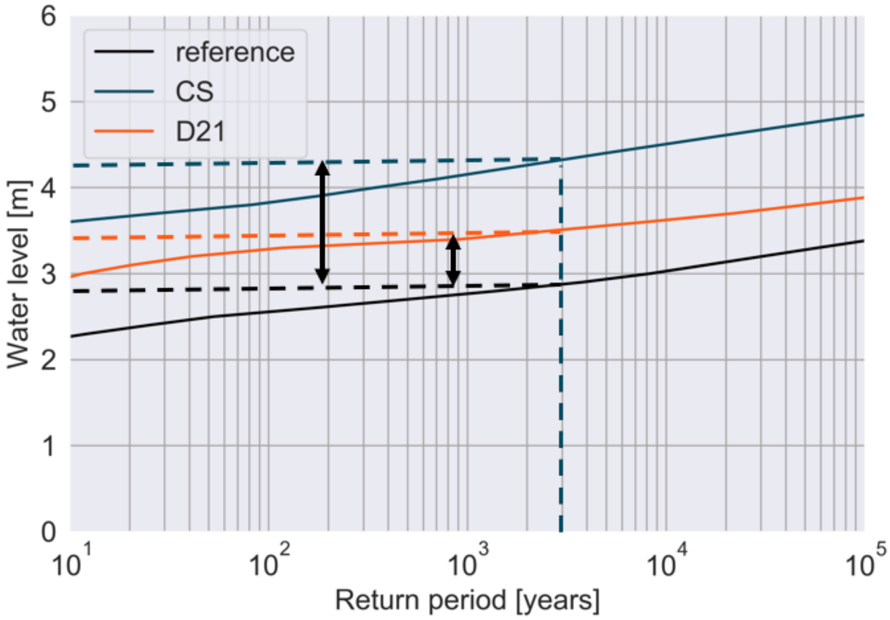


Figure 5.2: Illustration on how the change in governing water level is computed. The black line indicates the reference level. This is water level frequency line for a particular location in the current configuration without sea level rise. The blue line indicates the water level frequency line for the current configuration with sea level rise. In this illustration, a sea level rise of 2 m is subjected. The orange line indicates the water level frequency line for Delta21, again when the water system is subjected to 2 m sea level rise. The double-headed arrows indicate the difference between the current system and the reference, and the difference between Delta21 and the reference.

5.1.1 Storm surge dominant

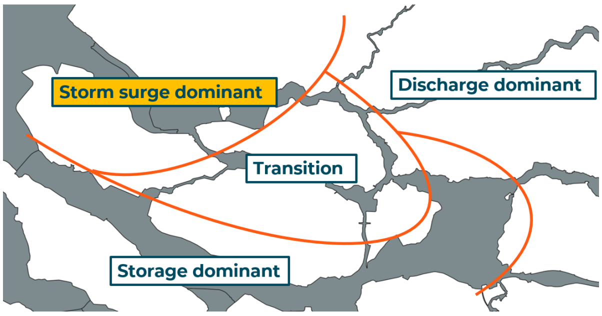
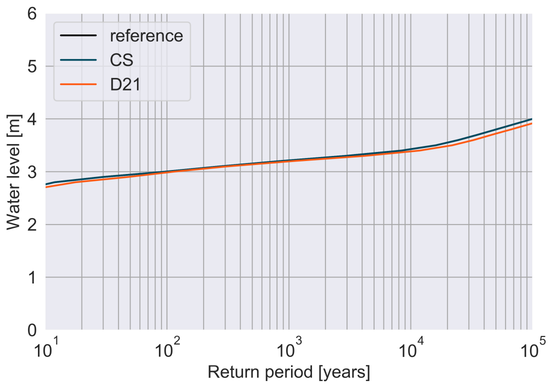
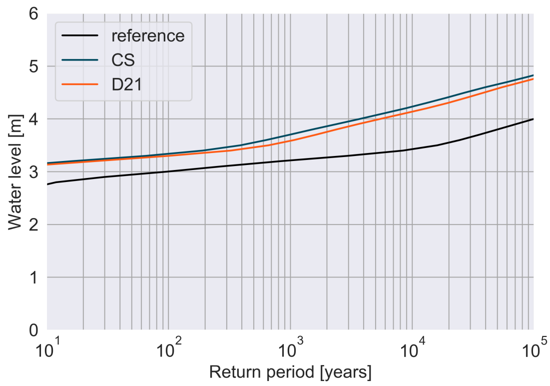


Figure 5.3: Location of storm surge dominant area.

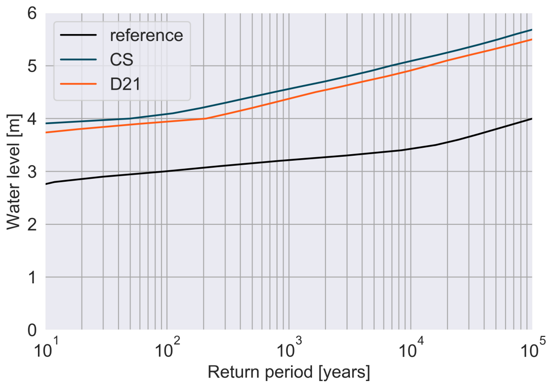
The model simulations with Delta21 showed fairly limited impact on the water level frequency lines in the storm surge dominant area. This can be assigned to the Maeslant Barrier. As there is a relatively high failure probability compared to the referred return period, the water level at Rotterdam is largely determined by the sea water level. Delta21 does not have the capacity to mitigate the consequences of a not closing Europoort Barrier. Moreover, during common conditions the Rhine-Meuse estuary has an open connection to the sea. This open connection leaded to higher water levels at the closure moment of the Europoort barrier. This means that sea level rise resulted in less capacity to store water in the Nieuwe Waterweg and Nieuwe Maas during closure of the Europoort barrier.



(a) Sea level rise of 0 m.



(b) Sea level rise of 1 m.



(c) Sea level rise of 2 m.

Figure 5.4: Water level frequency lines at Rotterdam for different sea level rise. The current system is indicated with the blue line, Delta21 with the orange line.

5.1.2 Flood storage area

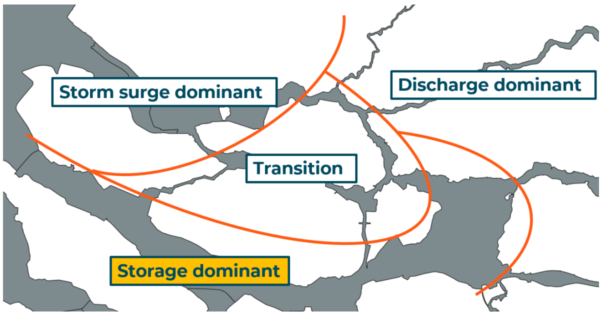
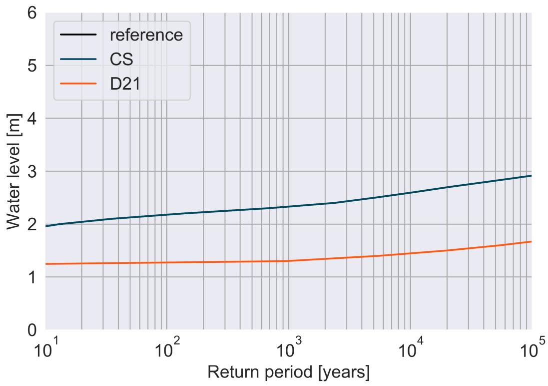


Figure 5.5: Location of storage dominant area.

For the flood storage area, major reductions in water levels can be obtained, as the pumps directly drain water from the Haringvliet. The reduction compared to the current system is somewhat reduced in the case of sea level rise of 2 m, but is still considerably large. For a sea level rise of 1 m, Delta21 still succeeded in achieving a lower water level frequency line than the reference situation. The pump capacity makes it possible to drain water from the Haringvliet to the North Sea. The model simulations showed that the reduction in the flood storage area is larger compared to other sub-areas mainly because the pumps are directly connected to the water bodies in the flood storage area.



(a) Sea level rise of 0 m.

(b) Sea level rise of 1 m.

(c) Sea level rise of 2 m.

Figure 5.6: Water level frequency lines at Hellevoetsluis for different sea level rise. The current system is indicated with the blue line, Delta21 with the orange line.

5.1.3 Discharge dominant

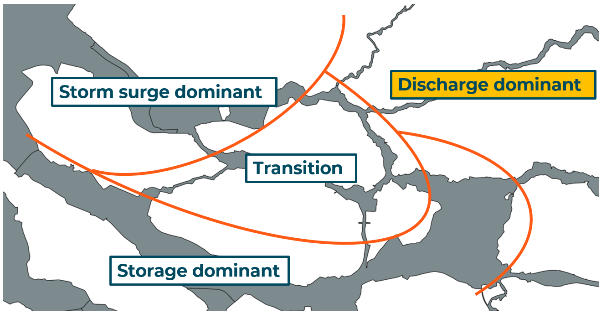
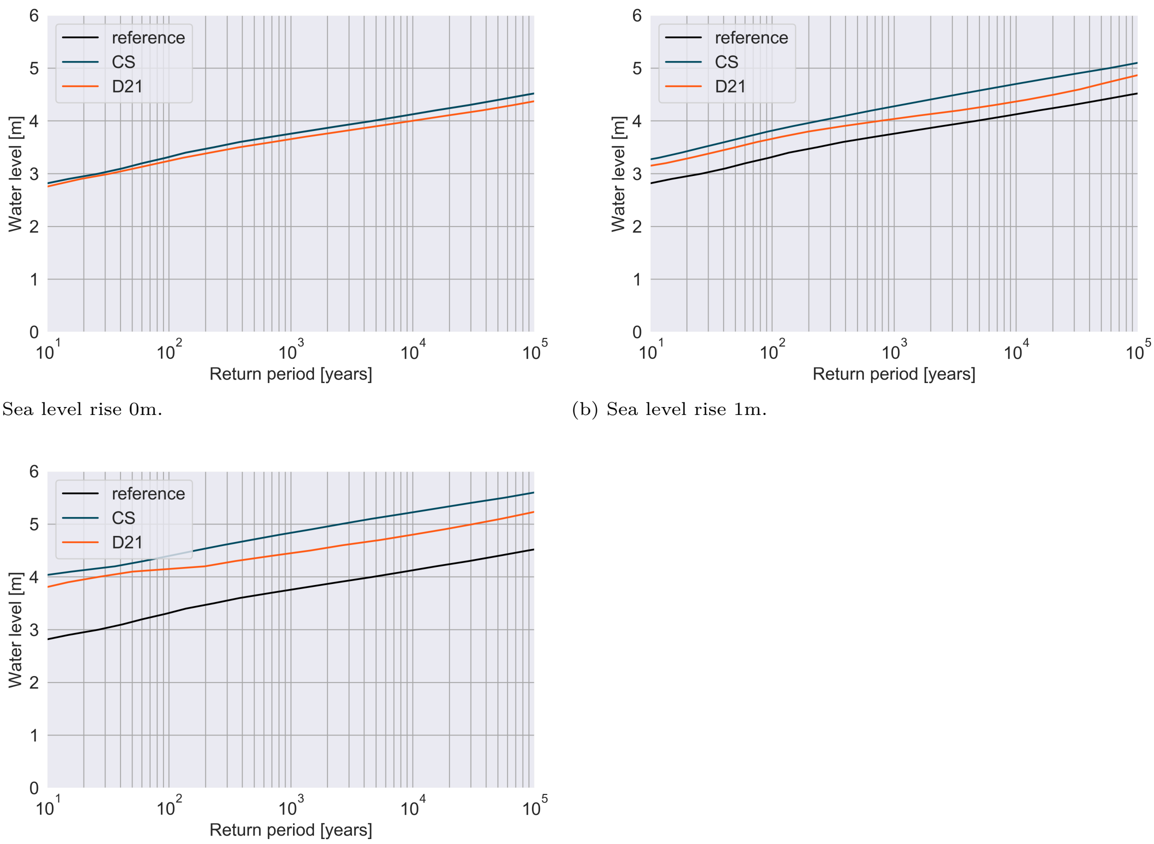


Figure 5.7: Location of discharge dominant area.

For the discharge dominant area, minor reductions are achieved. This can be assigned to the fact that Delta21 does not change the incoming discharge and therefore has less influence on the water levels. For a sea level rise of 1 m, Delta21 succeeded in limiting the increase due to sea level rise by 50 percent compared to the current situation. In case of 2 m sea level rise, the relative reduction is smaller (about 30 percent), but the absolute reduction is centimeters is larger. Partly, this can be assigned to the fact that when sea level increases, the discharge dominant area looses ground to the transition area.



(a) Sea level rise 0m.

(b) Sea level rise 1m.

(c) Sea level rise 2m.

Figure 5.8: Water level frequency lines at Schoonhoven for different sea level rise. The current system is indicated with the blue line, Delta21 with the orange line.

5.1.4 Transition area

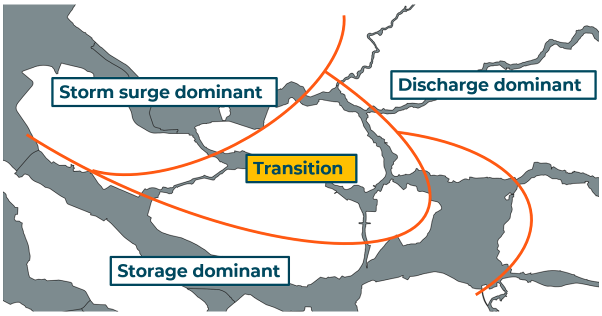
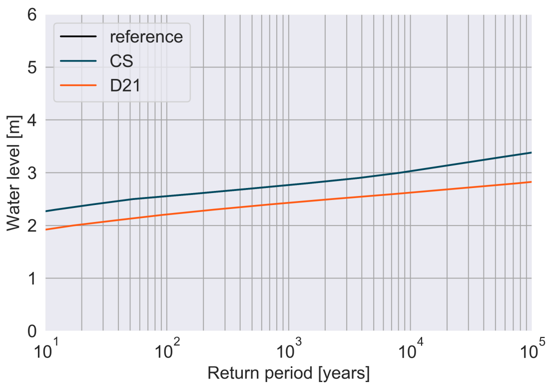


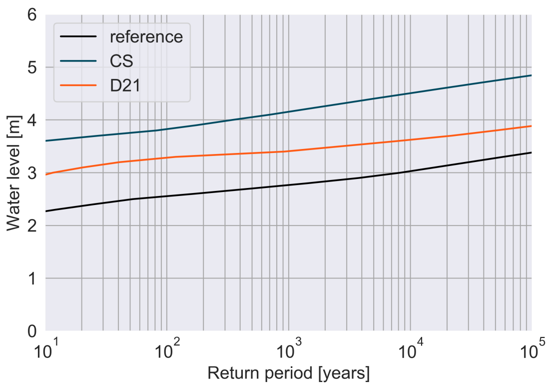
Figure 5.9: Location of transition area.

Delta21 can achieve significant reductions in the transition area (Figure 5.9). The absolute reduction increases with sea level rise. As denoted in the remainder of the report, the reduction throughout the transition area vary. For a sea level rise of 2 m, a larger closure level for the Europoort barrier is used. This directly results in higher water levels in the transition area.



(a) Sea level rise of 0 m.

(b) Sea level rise of 1 m.



(c) Sea level rise of 2 m.

Figure 5.10: Water level frequency lines at Dordrecht for different sea level rise. The current system is indicated with the blue line, Delta21 with the orange line.

5.1.5 Comparative analysis of return period factor

In the figures above, the water level frequency lines are shown. In this section, the return period factor is discussed. The return period factor is the ratio between the return period for Delta21 and the return period for the current system. In other words, when the factor is 2, a water level that has a return period of 1000 years for the current system has a return period of 2000 years for Delta21. This factor is valuable for assessing flood-prone areas outside the dikes (In Dutch: Buitendijkse gebieden) as it provides insights in the exceedance probability of particular water levels for which damage can occur. The return period factors are computed for zero sea level rise (Figure 5.11). Although the factors differed when different sea levels are subjected to the system, the deviation is fairly limited.

For the storm surge dominant area the mean of the return period factor is 1.6 (95% interval 1.4 and 1.8), for the flood storage dominant are the mean is 56 (95% interval 7.9 and 104.8), discharge dominant area the mean is 2.8 (95% interval 1.2 and 4.9) and for the transition area the mean is 20.4 (95% interval 1.3 and 44.2). The 95% interval indicates the dispersion in return period factors for locations within one sub-area (e.g. storm surge dominant area). Again, this illustrates that the reduction of Delta21 is distinct for the different locations. Furthermore, the reduction within the storm surge dominant and discharge dominant area is quite similar, while the reduction within the flood storage dominant area and the transition area shows a larger variation.

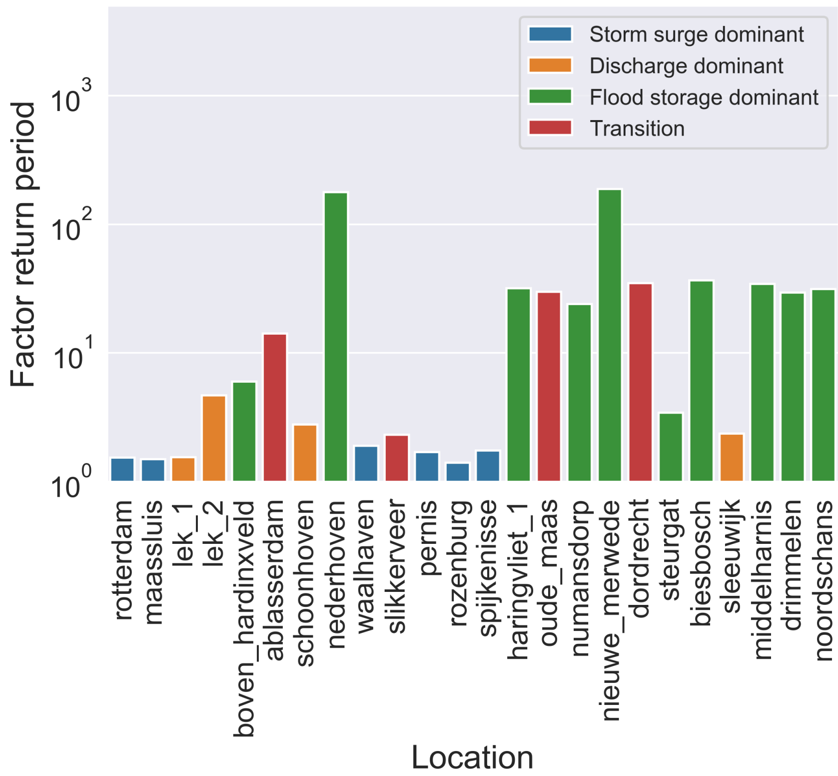


Figure 5.11: Factor return period for different locations. This factor indicates the ratio between return periods for the current system and Delta21 for a particular water level. Note that the scale on the vertical axis is logarithmic.

CONCLUDING REMARKS

The return period for a particular water level is increased due to Delta21. The order of magnitude of the return period factor - return period in the case of Delta21 divided over the return period for the current system - differs between 1 and 100. For the storm surge dominant area and the discharge dominant area the order of magnitude is 1, for the transitions area it is ranging between 1 and 10 and for the flood storage dominant area it is ranging between 10 and 100 for most locations.

5.2 Change in governing water levels

In this section, the governing water levels are compared for various sea level rises. These are the water levels corresponding to the norm of a particular dike segment (Figure 5.2). Simulations have been made for 24 locations in the Rhine-Meuse estuary, whereby each location is placed in the middle of a particular dike segment. First, the increase - or decrease - is shown for governing water levels (MHWs) under various steps of sea level rise. The increase - or decrease - is computed at a dike traject level, as each of the 24 locations represents one dike traject. Subsequently, the effect of a combination of Delta21 and an improved Europoort barrier are discussed.

5.2.1 Geographic representation of governing water levels

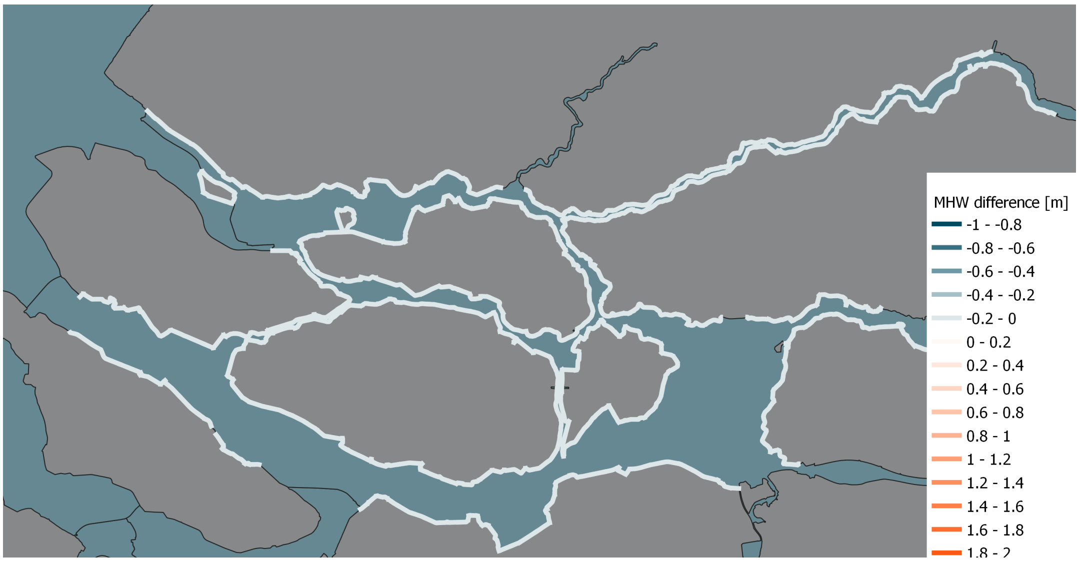
The ability of Delta21 to reduce the hydraulic loads is not spread evenly over the Rhine-Meuse estuary. In the results on the next page, the geographic distribution of the reduction in governing water levels (MHWs) is given for three different configurations:

1. The current system for a sea level rise of 1, 2 or 3 m and the current failure probability of the Europoort barrier of 1/100 per closure (Figure 5.12);
2. Delta21 for a sea level rise of 1,2 or 3 m and the current failure probability of the Europoort barrier of 1/100 per closure (Figure 5.13);
3. Delta21 for a sea level rise of 1,2 or 3 m and an improved failure probability of the Europoort barrier of 1/1000 per closure (Figure 5.14).

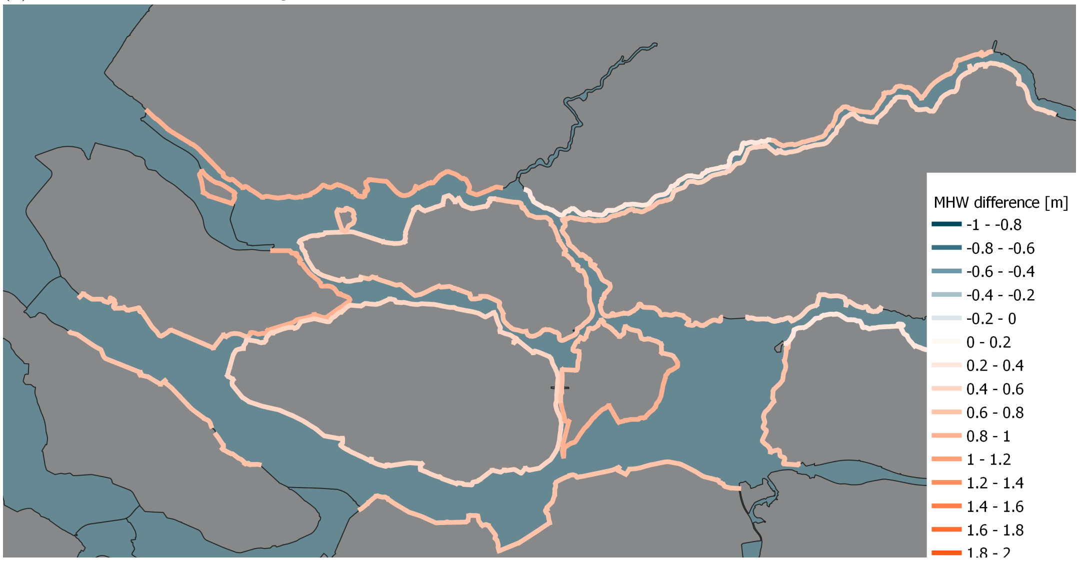
As can be seen in the following graphs, Delta21 has a major effect on the governing water levels in the flood storage dominant area and transition area. In line with earlier observations, the influence on the storm surge dominant area and discharge dominant area is limited. For the current sea level, Delta21 has the most strong effect in the flood storage area. Generally, locations that are located further away from the Haringvliet sluices show a smaller reduction that location directly located at the Hollands Diep or Haringvliet. The reduction realised by Delta21 varies from 10 cm to 1 m.

When the sea level is raised from 0 to 1 m, the governing water levels in case of the current situation increase with about 70-80 cm in the storm surge area and 50-70 cm in the transition area. Delta21 leads to a reduction of about 10 cm which leads to an increase of 60-70 cm in the storm surge area. An improved Europoort barrier largely mitigates the sea level rise from 0 to 1 m. For both configurations, the governing water level is 55 cm lowers compared to the configuration with the current failure probability. At Dordrecht (transition area), the sea level increase from 0 to 1 m is largely mitigated by Delta21. For the current situation, the increase is equal to 70 cm, while in case of Delta21 the increase in governing water level is about 5 cm.

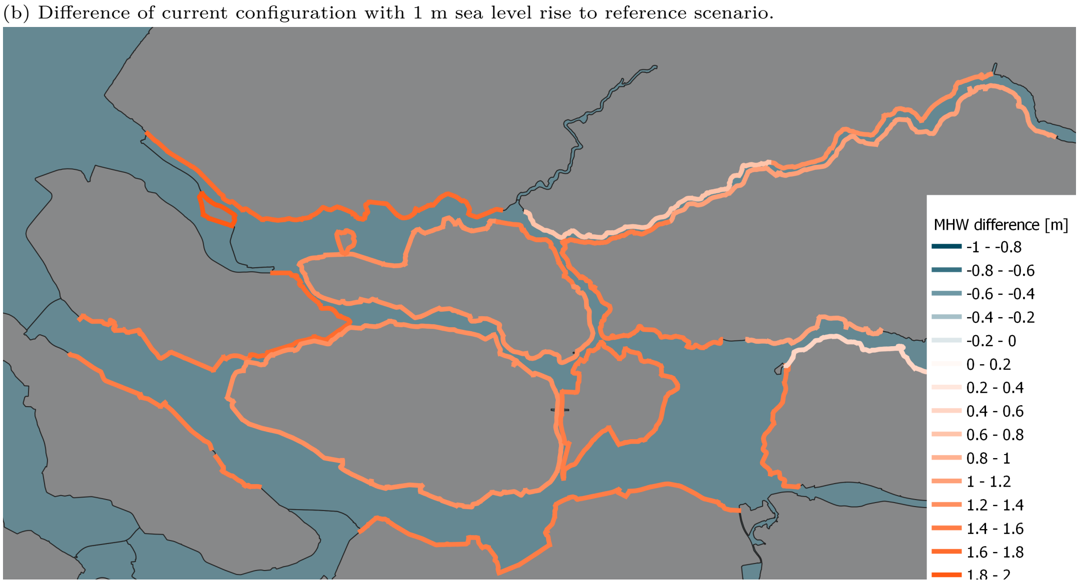
As the sea level is raised from 0 to 2 m, dramatic changes in the governing water level are visible for all three configurations. The effect is less in the discharge dominant area as discharges of the Rhine and Meuse are kept constant as sea level rises. Delta21 does succeed in mitigating the increase in governing water levels for the flood storage area. At the same time, the water level in the storm surge dominant area continues to increase. Even in the case of Delta21 and an improved Europoort barrier, the governing water level is still increased with 1.5 m. It must be noted that the translation from sea level rise to governing water levels in the storm surge area is also influenced by the return period. As the norm is stricter for locations is this area, the return period in determining governing water level is larger. For high return periods, the share of a failing Europoort barrier in the governing water level is also larger. This effect further increases the governing water level for the storm surge dominant areas.



(a) Difference of current configuration with 0 m sea level rise to reference scenario.

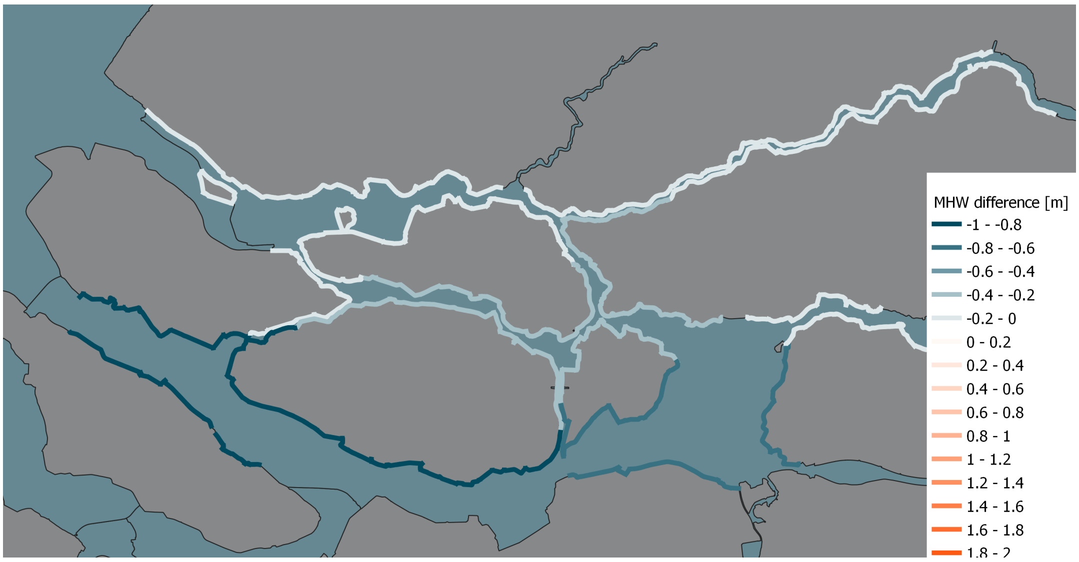


(b) Difference of current configuration with 1 m sea level rise to reference scenario.

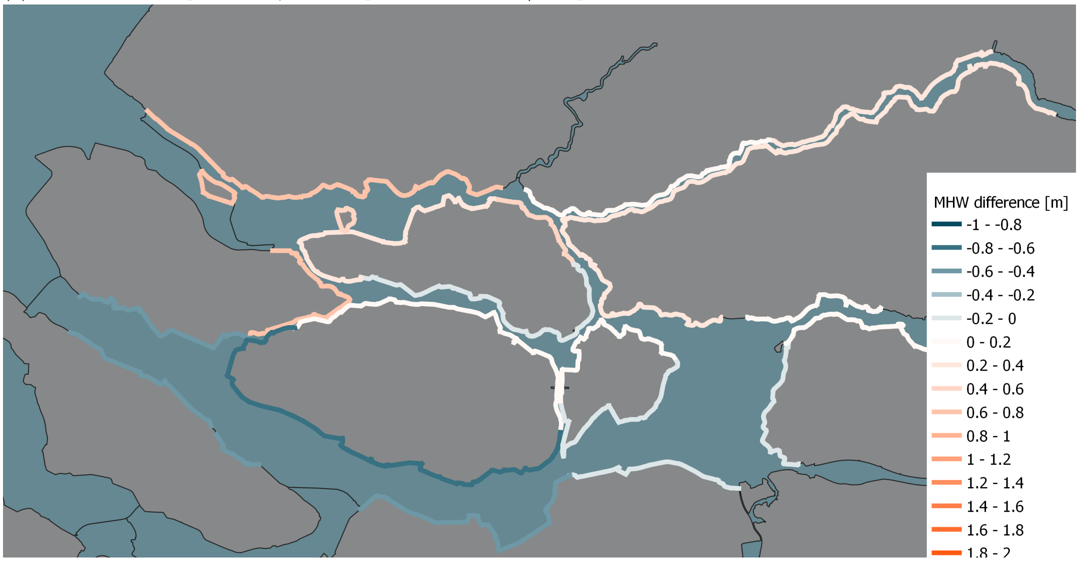


(c) Difference of current configuration with 2 m sea level rise to reference scenario.

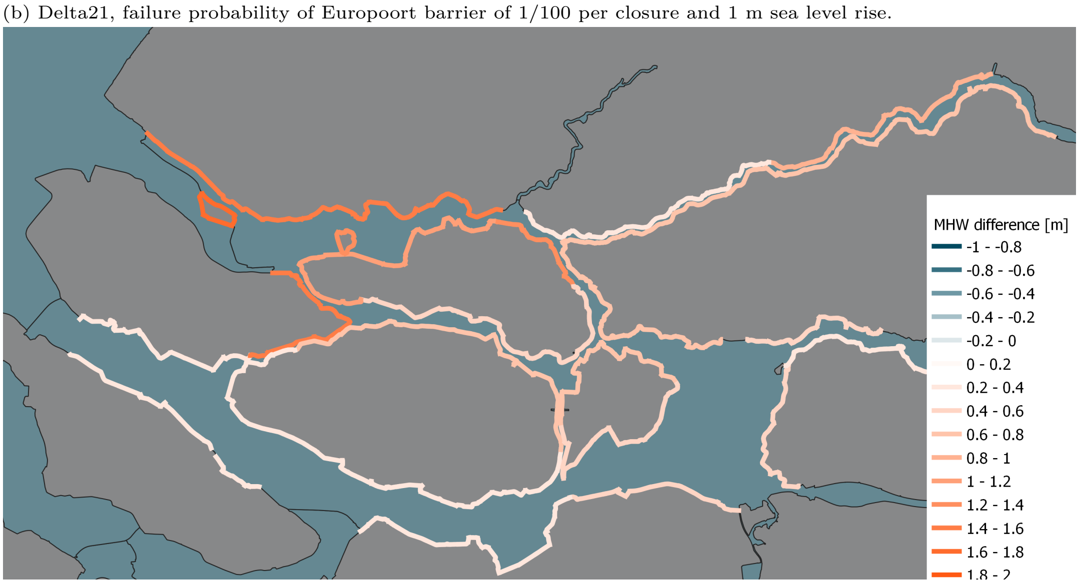
Figure 5.12: Difference of current system with a failure probability of the Europoort barrier of 1/100 per closure. Under a range of sea level rises the configuration is compared to the reference scenario. Orange indicates that the MHW is higher than the reference, blue indicates that the MHW is lower.



(a) Delta21, failure probability of Europoort barrier of 1/100 per closure and 0 m sea level rise.

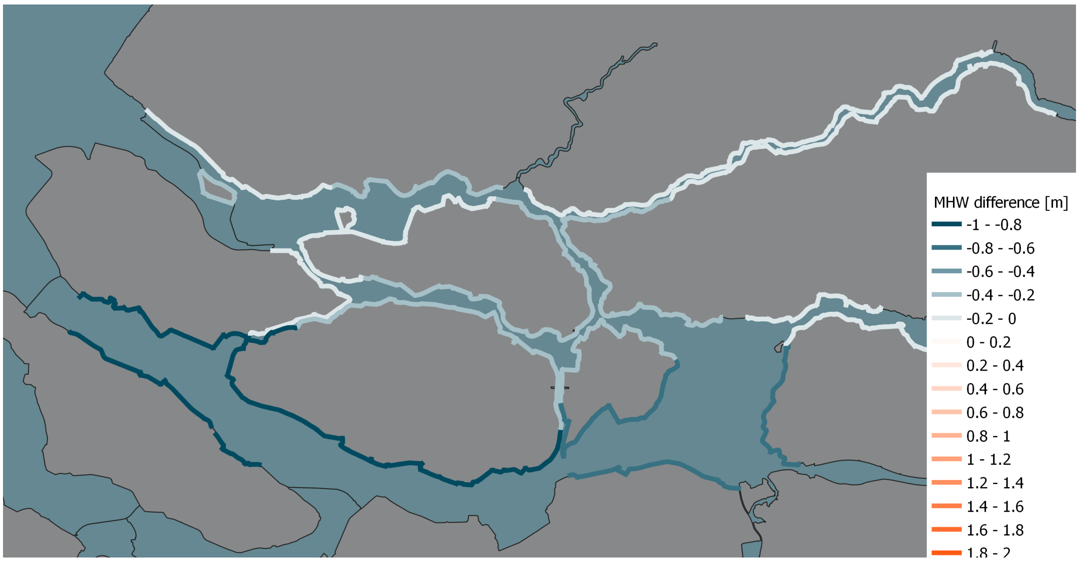


(b) Delta21, failure probability of Europoort barrier of 1/100 per closure and 1 m sea level rise.

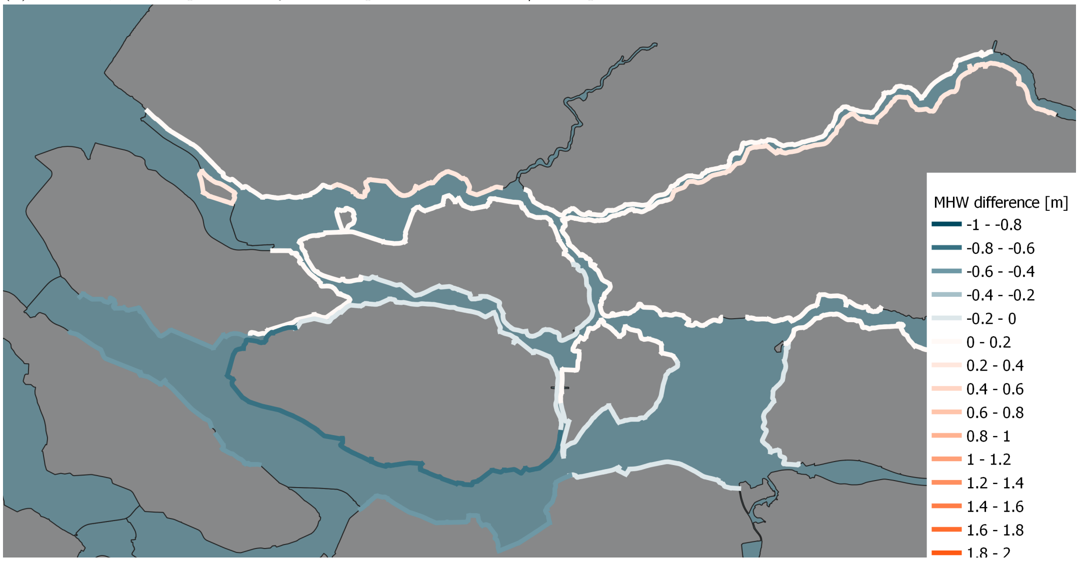


(c) Delta21, failure probability of Europoort barrier of 1/100 per closure and 2 m sea level rise.

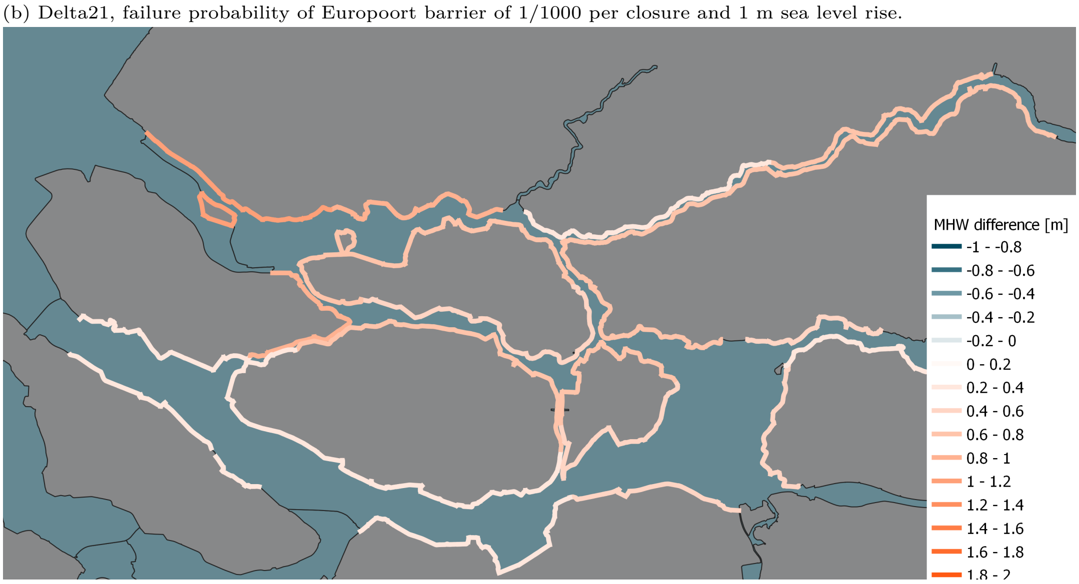
Figure 5.13: Difference of Delta21 with a failure probability of the Europoort barrier of 1/100 per closure. Under a range of sea level rises the configuration is compared to the reference scenario. Orange indicates that the MHW is higher than the reference, blue indicates that the MHW is lower.



(a) Delta21, failure probability of Europoort barrier of 1/1000 per closure and 0 m sea level rise.



(b) Delta21, failure probability of Europoort barrier of 1/1000 per closure and 1 m sea level rise.

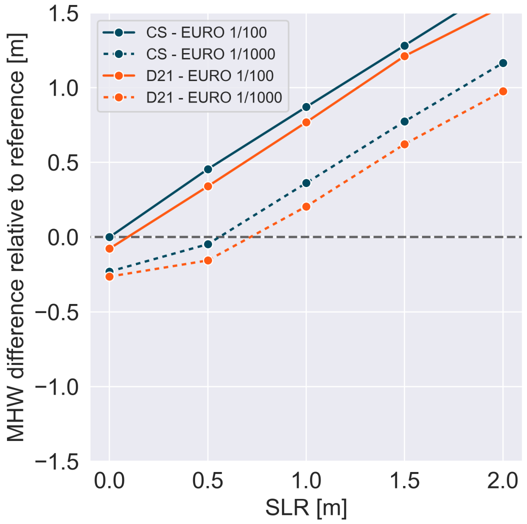


(c) Delta21, failure probability of Europoort barrier of 1/1000 per closure and 2 m sea level rise.

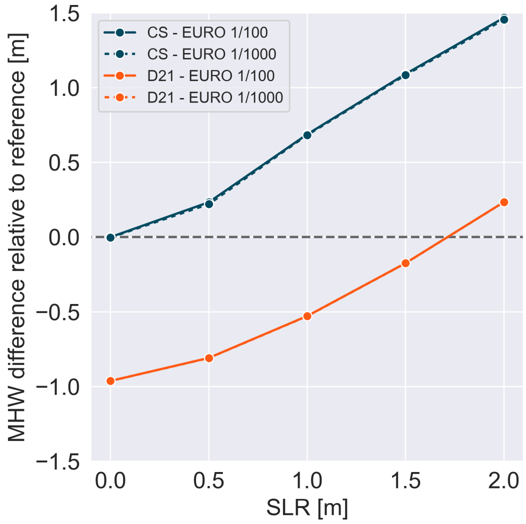
Figure 5.14: Difference of Delta21 with an improved failure probability of the Europoort barrier of 1/1000 per closure. Under a range of sea level rises the configuration is compared to the reference scenario. Orange indicates that the MHW is higher than the reference, blue indicates that the MHW is lower.

5.2.2 Influence of improved Europoort barrier on governing water levels

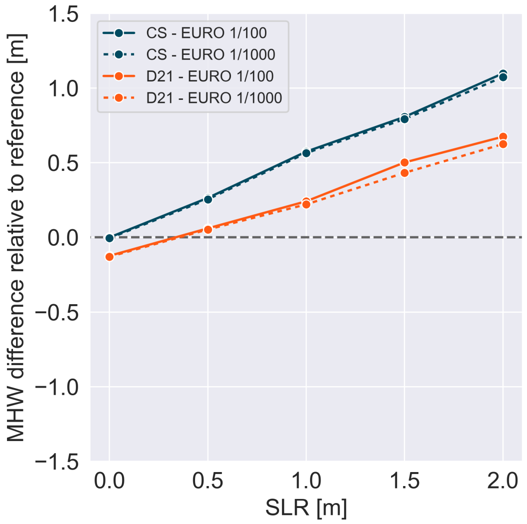
It is also interesting to investigate a combination of Delta21 with an improved Europoort barrier. As denoted before, the effect of Delta21 is limited for the storm surge area, which can be ascribed to the failure probability of the Europoort barrier. For the storm surge dominant area, the performance of the Europoort barrier is significant (Figure 5.15a). The solid and dashed lines are very distinct for the location of Rotterdam. In this case, the improved Europoort barrier leads to about 0.5 m reduction in governing water levels. The amount of reduction does not change that much for increasing sea level rise. In Figure 5.15, the vertical distance between the dashed lines is larger than the distance between the two solid lines. This means that an improved Europoort barrier has a positive effect on the effectiveness of Delta21 for the storm surge area. Furthermore, the difference in slope indicates that not every area is evenly affected by sea level rise. As the slope of the line at Schoonhoven is smaller, this region is less affected by sea level rise.



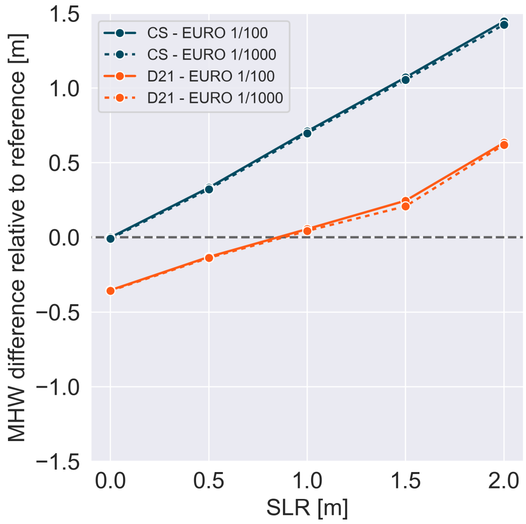
(a) Rotterdam (storm surge area).



(b) Hellevoetsluis (flood storage dominant area).



(c) Schoonhoven (discharge dominant area).



(d) Dordrecht (transition area).

Figure 5.15: MHW plotted against sea level rise for the current system and Delta21 for different Europoort failure probabilities. The current system is depicted in blue and Delta21 is depicted in orange. For both systems, the solid line represents a failure probability of the Europoort barrier of 1/100 per closure and the dashed line represents an improved failure probability of 1/1000 per closure. Four different locations are used to illustrate the effect for the storm surge dominant, flood storage dominant, discharge dominant and transition area.

5.2.3 Relation between sea level rise and governing water levels

Delta21 aims to lower the hydraulic loads to increase the flood risk safety in the Rhine-Meuse estuary. For various locations in the domain, it has been determined to what degree this configuration of Delta21 succeeds in mitigating the effects of sea level rise. In other words; how much sea level rise can Delta21 mitigate for different locations? In Figure 5.16, the amount of sea level rise is shown for which the governing water level in case of Delta21 is equal to the governing water level for the current situation. For the storm surge dominant area is the mean sea level rise that can be mitigated is 0.09 m (95% confidence interval: 0.05 m and 0.14 m), for the flood storage dominant area is the mean 1.25 m (95% confidence interval: 0.91 m and 1.59 m), discharge dominant area is the mean 0.48 m (95% confidence interval: 0.05 m and 0.92 m) and transition is the mean 0.57 m (95% confidence interval: 0.13 m and 1.01 m). The 95% interval indicates the dispersion in return period factors for locations within one sub-area (e.g. storm surge dominant area).

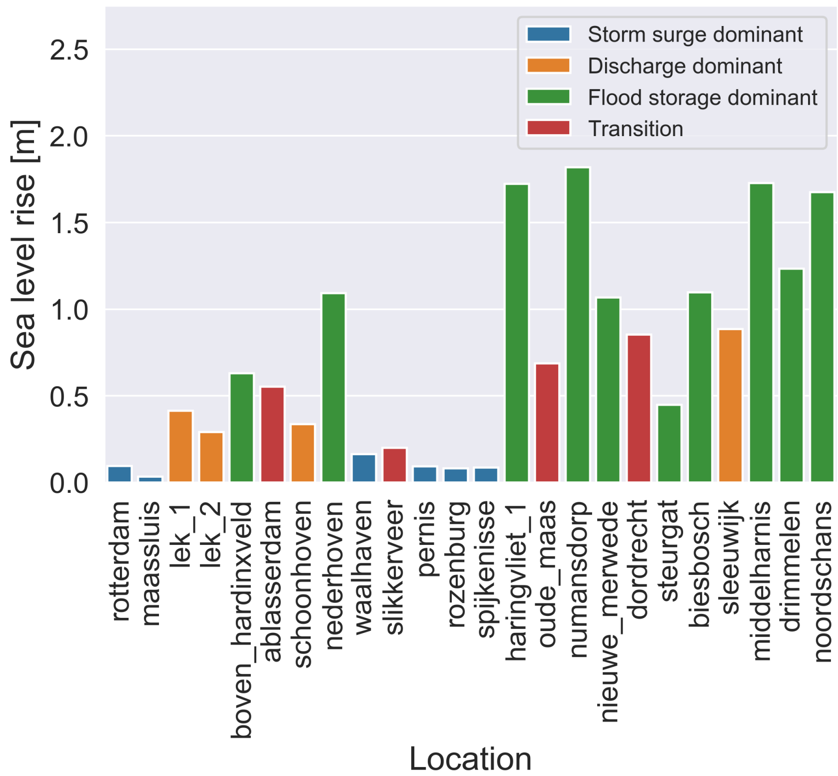


Figure 5.16: Amount of sea level rise mitigated by Delta21. For various locations throughout the current governing high water level without Delta21 and without sea level rise is compared to a situation with Delta21. The amount of sea level rise indicated up to which Delta21 succeeds in keeping the governing water level lower or equal to the current governing high water level.

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Delta21 succeeds in reducing the water levels throughout the entire domain. At the same time, these reductions differ considerably per area depending on the processes that are dominant. For the storm surge dominant area, the reduction for various steps of sea level rise is 10-20 cm, for the discharge dominant area 10-40 cm, for the flood storage area 1-1.5 m and for the transition area 30-60 cm.

An improved storm surge barrier would influence the governing water level in the Rhine-Meuse estuary. This is mostly visible in the storm surge area and is almost negligible for the flood storage dominant, discharge dominant and transition area. This can be ascribed to the fact that outside the storm surge area, discharges are dominant in the water level for larger return periods (>1000 years). As governing water levels are computed for larger return periods as well, an improved Europoort barrier will have a limited effect in reducing the governing water levels.

Chapter 6

Influence of Delta21 on the failure probabilities of flood defences

From a flood risk management perspective, the aim of Delta21 is to enhance the flood risk safety by reducing the hydraulic loads in the Rhine-Meuse estuary. In the previous chapter, the hydraulic load reduction is elaborated. This reduction in hydraulic loads can not be directly projected on the current failure probabilities. In this section aims to answer the last sub-question of the physical perspective by making the translation from hydraulic loads to failure probabilities:

SQ-I.e How do the failure probabilities of flood defences change due to Delta21, taking into account the most important failure mechanisms?

First, the current situation regarding the failure probabilities is described (Section 6.1). Subsequently, the difference to the current situation is computed for both configurations and various steps of sea level rise (Section 6.2). To conclude, the first two sections are combined to provide insights into the assessment of flood defences under different scenarios (Section 6.3). Hence, this last section contains information about the expected flood defence reinforcements under various steps of sea level rise for the current system and a system with Delta21. The modelling approach that has been used to obtain the presented results can be found in (Section 3.3).

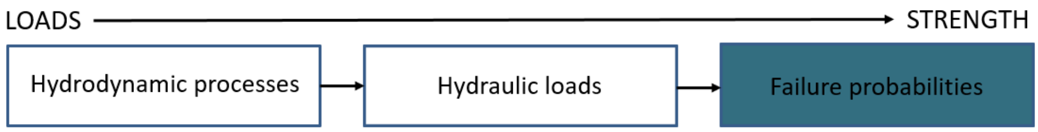


Figure 6.1: Schematic overview of the three parts within the results of the physical perspective. This chapter analyses the failure probabilities, rendered in blue.

6.1 Current failure probabilities

6.1.1 Total failure probability per dike section

The Veiligheid Nederland in Kaart (VNK2) project has mapped flood risk in the Netherlands (Vergouwe, 2015). This analysis included the quantification of failure probabilities on a dike section level. These results are taken as reference and are depicted below (Figure 6.2). The probabilities belong to separate dike sections in the Rhine-Meuse estuary and represent the total failure probability, which is the sum of failure probabilities belonging to different failure mechanisms.

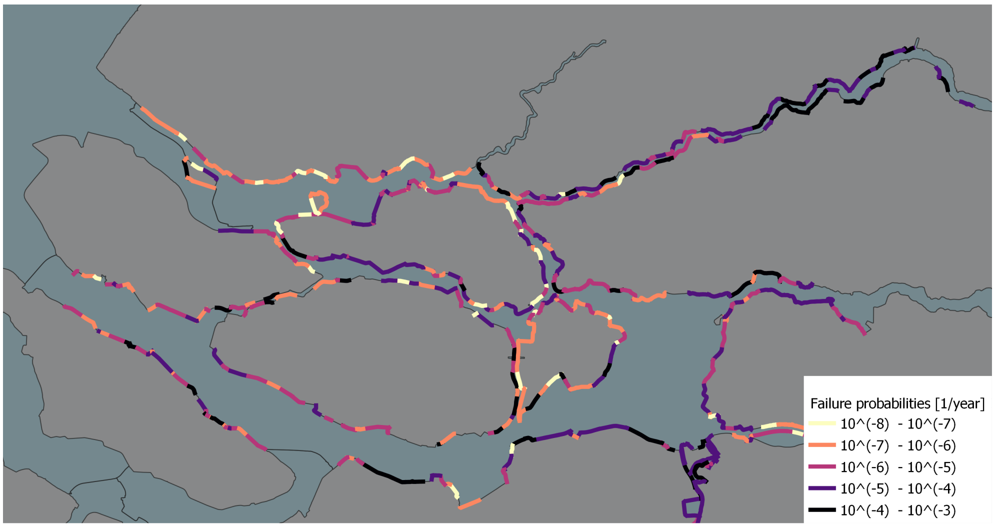


Figure 6.2: Failure probabilities for dike sections in the Rhine-Meuse estuary. Light coloured lines indicate a low failure probability, dark lines correspond to a higher failure probability. This map only provides information about the failure probability, not whether this probability meets the norm. Note that the interval of the classes is logarithmic (Based on data of Vergouwe (2015)).

6.1.2 Distribution of failure probability per failure mechanism

Not every failure mechanism is equally contributing to the total failure probability. The share of each failure mechanism in the total failure probability depends on the hydraulic loads, the shape of the profile and (geological) parameters. Per dike ring, the contribution for each failure mechanisms is determined based on VNK2 results (Figure 6.3). Overall, piping is currently the most dominant failure mechanism

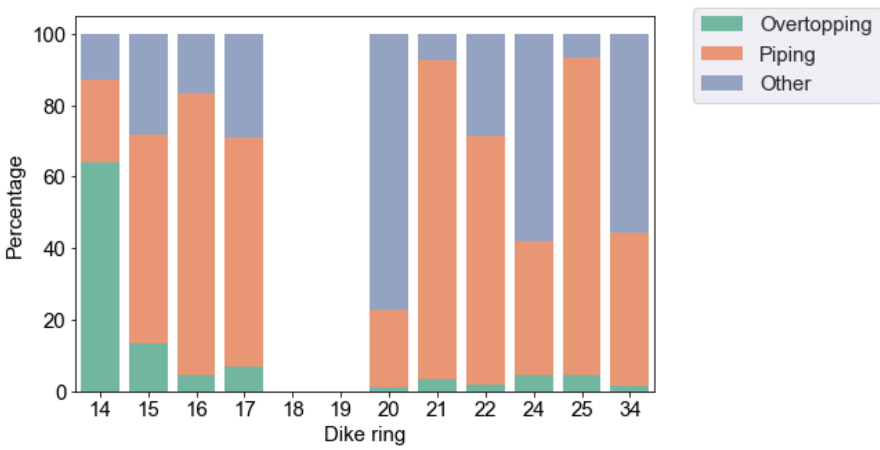


Figure 6.3: Contribution of failure mechanisms piping and height in total failure probability. Per dike ring, the share of the failure probability for piping and height is computed. The distribution belongs to the current situation without sea level rise (Based on data of Vergouwe (2015)).

in the Rhine-Meuse estuary. For most dike rings, the combined failure probability of height and piping has a share of more than 80 percent in the total failure probability. Dike ring 20, 24 and 34 form an exception as the failure mechanism related to stability is dominant. This means that these dike rings are less sensitive for the relative changes that are computed in the next section. At the same time, failure related to stability is also a geotechnical failure mechanism. This means that the approach to assess stability shows similarities with the methodology for piping.

6.2 Relative change in failure probabilities

For different sea level rises, the difference to the reference situation is computed. This is done for the failure probabilities belonging to two failure mechanisms, overtopping and overflow (height) and piping (Section 3.3). Important to note is that the reduction in failure probabilities belong to the evaluation of one section of a particular dike segment. The reductions in that dike section, are visualized on a dike segment level. The translation between a reduction in hydraulic loads to a relative change in failure probability is made with fragility curves. The fragility curves are tailored to the layout of the dike section, which means that variables have been altered depending on the geological lay out of the dike section (Table 3.4).

Due to sea level rise, the failure probabilities changed at 24 locations (Figure 6.4). As each location represents a particular dike segment, the relative increase or decrease can be determined. This change is a combination of the change in probability of exceedance of the water levels and the fragility curve, which contains information about the strength of a flood defence. The relative change in failure probability is computed for the mechanism height (Section 6.2.1) and piping (Section 6.2.2).

Figure 6.4: 24 locations throughout the domain for which the relative change in failure probability is computed. Each location represents a particular dike section, which in turn represents one of the segment in the Rhine-Meuse estuary (Table G.1).

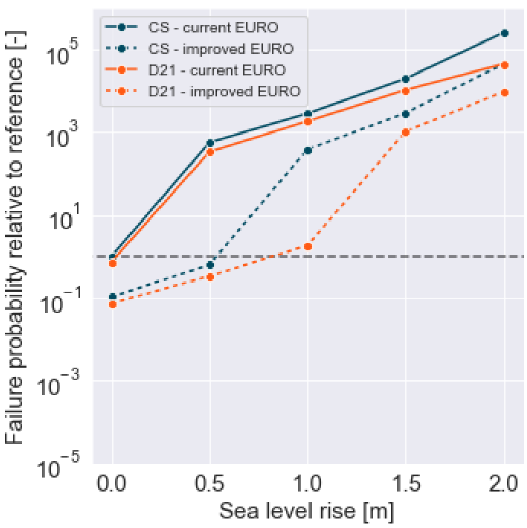
6.2.1 Relative change in failure probability for the mechanism height

Delta21 has an influence on the failure probability related to the failure mechanism height (Figure 6.5). For the location of Rotterdam, the failure probability related to height is in configuration with a current or improved failure probability of the Europoortbarrier are distinct (Figure 6.5a). The kinks in the curves have different causes. First of all, the failure probability for height is in order of magnitude of 10^{-9} for the current situation with 0 m sea level rise. Hence, a minor increase results in a relatively high step in failure probability ratio. First, the water level frequency lines shows a bend at the moment the failure probability of the Maeslant barrier becomes dominant (Section 5.1.1). This is also reflected in the failure probability. This sensitivity is further enhanced by the fact that the fragility curve is very steep around the water level corresponding to the crest height. The failure probability can be divided into two contributions: one where the Europoort barrier operates correctly and one where the Europoort barrier fails to close. This is interesting to investigate for the following two configurations:

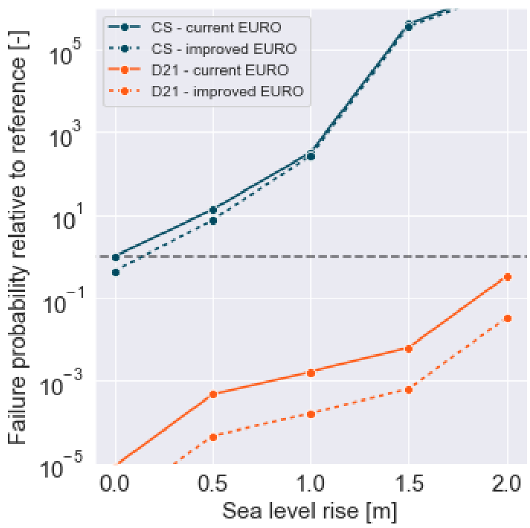
1. Current system with improved Europoort barrier. Up to 0.5 m sea level rise, the contribution of a closed Europoort barrier is limited compared to the contribution of an open barrier. For a sea level rise of 1 m, the contribution of a closed barrier becomes more important, which is reflected by the steeper slope between 0.5 and 1.0 m;

2. Delta21 with improved Europoort barrier. This situation is entirely dependent on the closure level of the Europoort barrier. The contribution of a closed Europoort barrier is 0 percent. This means that when the Europoort barrier succeeds to close, Delta21 can flatten the slope of the water level which strains the probability that overtopping and overflow occur (Section). This also explains the kink at a sea level rise of 1 m. The closure levels for the Europoort barrier for 1.5 meter sea level rise are larger, which makes that the probability of exceedance of water levels is increased.

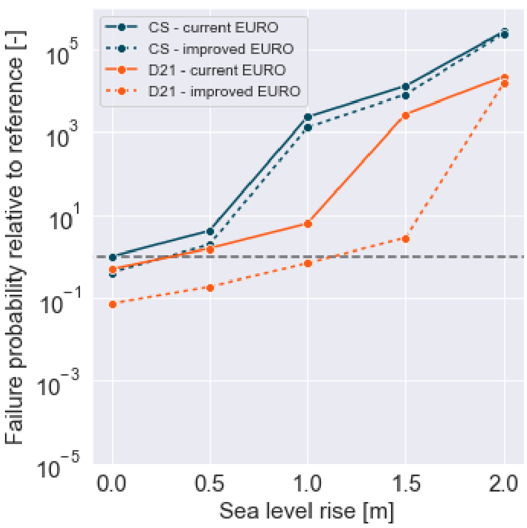
In the flood storage area, Delta21 succeeds in lowering the failure probability of height by a order of magnitude of more than $10^{(5)}$ for a sea level rise of 0 m. This reduction is strained as sea level rise



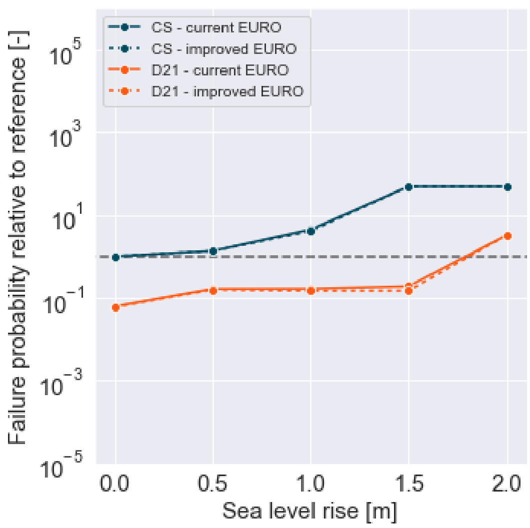
(a) Rotterdam (storm surge area).



(b) Hellevoetsluis (flood storage dominant area).



(c) Schoonhoven (discharge dominant area).



(d) Dordrecht (transition area).

Figure 6.5: Semi-logarithmic plot of relative change in failure probability for the failure mechanism height. The failure probability for height computed for various steps of sea level rise. The ratio - failure probability divided by the reference failure probability is presented on a log scale for four different locations. The current system is depicted in blue and Delta21 is depicted in orange. For both systems, the solid line represents a failure probability of the Europoort barrier of 1/100 per closure and the dashed line represents an improved failure probability of 1/1000 per closure.

increases, but achieves an reduction for a sea level rise of 2 m.

In the discharge dominant area, the lines in case of Delta21 for an improved or current failure probability of the Europoort barrier are distinct. The difference becomes larger for a sea level rise of 1.5 m. For the current system, the lines converge at a sea level rise of 0.5 m. This is because the contribution of a closed Europoort barrier increases at this sea level rise. For Delta21, this phenomenon occurs at a sea level rise of 1.5 m.

For the transition area, the failure probability is already large in the reference situation. The failure probability for height reaches 1 per year for a sea level rise of 1.5 m. As 1 is equal to the maximum failure probability in the computation method, the failure probability does not continue to increase after 1.5 m of sea level rise and the ration remains at 49. The failure probability for height is not governed so much by the failure probability of the Europoort barrier. This is due to the fact that a closed Europoort barrier is governing in all configurations.

6.2.2 Relative change in failure probability for the mechanism piping

Fragility curves for piping are based on the parameters for seepage length, permeability and grain size among others. Those fragility curves, together with the information about the probability of exceedance of water level, result in failure probabilities for the current configuration and a configuration with Delta21 (Figure 6.6) . The development of the failure probability for piping is shown in the next figures. In the graphs, the y-axis gives information about the reduction factor. For example, a factor of 10^-1 indicates that the order of magnitude of the reduction is, while an 10^3 implies that the failure probability is increased with an order of magnitude of 1000.

The slope of the graphs for the storm surge dominant area and flood storage dominant area showed a steeper slope than the discharge dominant and transition area. This is due to two reasons; 1) the first two areas are more susceptible to sea level rise and 2) the latter two sub-areas are represented by sections that have a failure probability in case of zero sea level rise. This means that the failure probability factor at 1.5 m sea level rise corresponds to a (maximum) failure probability of 1.

6.2.3 Comparison of relative change for the mechanisms piping and height

To what degree a water level reduction results in a failure probability reduction depends on the character of the fragility curves. For piping, the fragility curve is entirely depended on the occurring water level at the location of the flood defence. For height, the fragility curve is also affected by wave loads. Wave loads are more complex and dependent on the water level, wind speed and orientation of the flood defence. This introduces more stochastic variables to the fragility curve. For instance, in the failure probability for height only has contributions for the wind directions from the west, south-west and north-west.

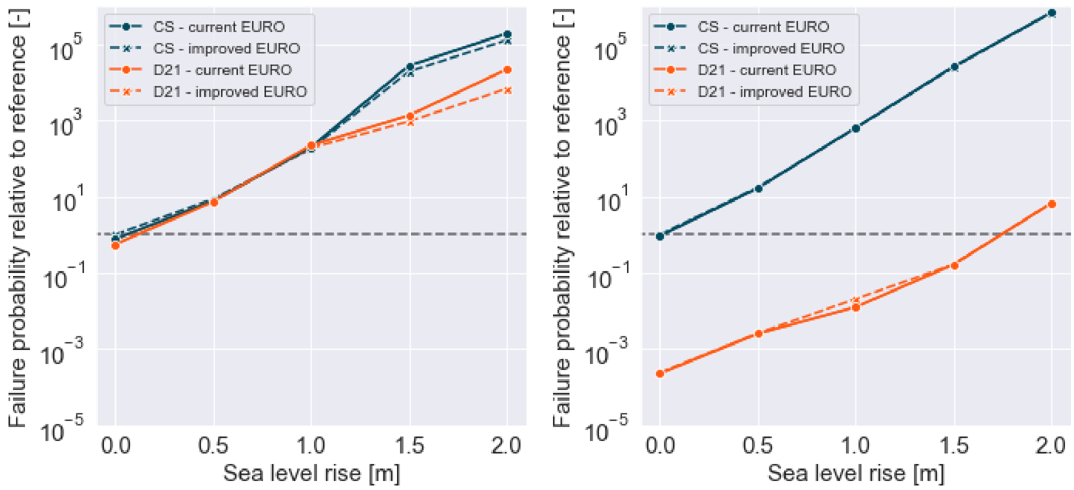
The fragility curves for piping are less steep compared to the fragility curves for height. This means that the failure mechanism of piping is more sensitive to lower water levels. As Delta21 is most effective in reducing water levels corresponding to more extreme events (e.g. joint occurrence of high discharge and storm surge), the failure probabilities are more reduced for the failure mechanism height than for piping.

CONCLUDING REMARKS

The changes in failure probability for two failure mechanisms - height and piping - have been computed at 24 locations belonging to different dike segments in the domain. The current failure probability, based on VNK2 data, served as a reference. Subsequently, the relative change to this reference is computed for both height and piping. Similarly to the reduction in hydraulic loads, the failure probability reduction achieved by Delta21 differed throughout the domain. The reductions for the failure mechanism height were larger than the reduction for the failure mechanism piping.

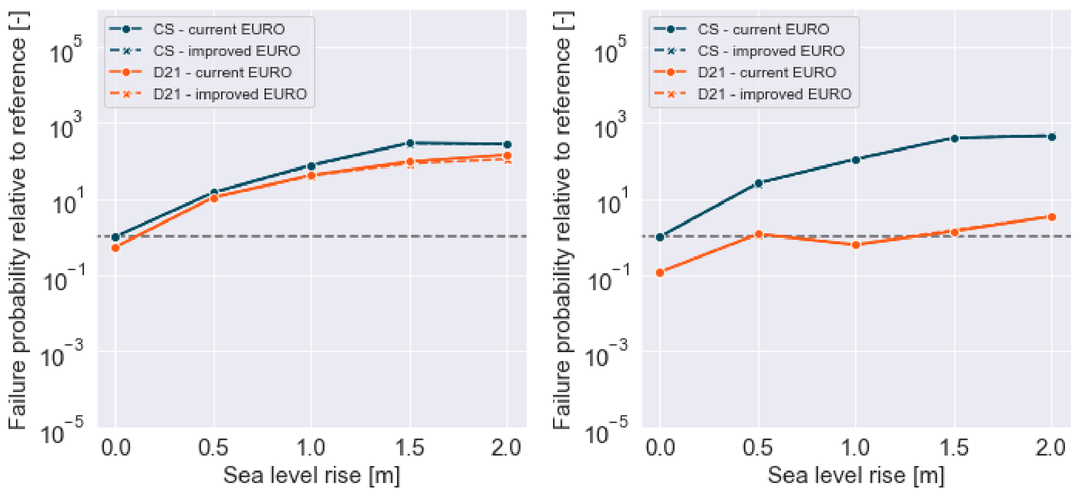
6.3 Assessment of flood defences under sea level rise

The failure probabilities of the dike sections can be assessed based on flood safety requirements. The requirements depend on the traject norm and the particular failure mechanism that is assessed. Each failure mechanism must adhere to a specific failure budget, which represents a share in the total failure probability. The failure probabilities for a certain sea level rise and configuration (current system or Delta21) change along with the hydraulic loads. This failure probability is a combination of the current failure probability (Section 6.1) and the relative change (Section 6.2). Following the methodology of the WBI, a class can be assigned based on the failure probability and the norm (Table 6.1). The classes IV and V indicate that the failure probability is larger than the lower limit, which means that the resistance of the flood defence is not sufficient. In the following two sections the failure mechanisms height and piping are discussed, followed by a combined assessment of both failure mechanism. About 420 dike sections in the Rhine-Meuse estuary are included in the analysis. The total length of evaluated flood defences is equal to 484 km.



(a) Rotterdam (storm surge dominant area).

(b) Hellevoetsluis (flood storage dominant area).



(c) Schoonhoven (discharge dominant area).

(d) Dordrecht (transition area).

Figure 6.6: Semi-logarithmic plot of relative change in failure probability for the failure mechanism piping. The failure probability for piping computed for various steps of sea level rise. The ratio - failure probability divided by the reference failure probability is presented on a log scale for four different locations. The current system is depicted in blue and Delta21 is depicted in orange. For both systems, the solid line represents a failure probability of the Europoort barrier of 1/100 per closure and the dashed line represents an improved failure probability of 1/1000 per closure.

Table 6.1: WBI classes for assessment on section level for a particular failure mechanism. Depending on the norm, a signaling value and lower limit are assigned for each dike traject. The failure probability for each failure mechanism on a section level can be compared to the lower limit and signaling value. Based on this comparison, different classed are assigned.

Description	Class	Requirement
Failure proability is much smaller than signaling value	I	$P_{mech,section} < 1/30 P_{mech,sign}$
Failure proability is smaller than signaling value	II	$1/30 P_{mech,sign} < P_{mech,section} < P_{mech,sign}$
Failure proability is larger than signaling value, but smaller than lower limit	III	$P_{mech,sign} < P_{mech,section} < P_{mech,lower}$
Failure probability is larger than signaling value and lower limit	IV	$P_{mech,lower} < P_{mech,section} < 30 P_{mech,lower}$
Failure probability is much larger than signaling value and lower limit	V	$30 P_{mech,lower} < P_{mech,section}$

6.3.1 Assessment for the failure mechanism height

For each section, the segment norm is translated into a norm per section for the failure mechanism height. With the current failure probability per section and the relative change in failure probability per dike segment a revised failure probability for each step of sea level rise is computed. An example is given in Table 6.3. For the current system with the current failure probability 31, 66 and 72 percent does not meet the requirements when the water system is subjected to 0, 1 or 2 meter sea level rise respectively.

Table 6.2: Assessment for the failure mechanism height. Comparison of current system and configuration of Delta21. The failure probabilities are assessed based on the requirement for the prevailing dike section (lower limit). The failure probability depends on the configuration Delta21 or current system, and the subjected sea level rise. This failure probability is compared to the lower limit and results in a particular class (Table 6.2). Two examples are given, in total 526 sections are evaluated for five steps of sea level rise (0, 0.5, 1.0, 1.5 and 2.0).

Section	Low. limit	SLR 0 m				SLR 0.5 m				SLR 1 m	
		CS	Cl.	D21	Cl.	CS	Cl.	D21	Cl.	CS	Cl.
14001001	$4.00\ 10^{-6}$	$2.79\ 10^{-7}$	II	$2.05 * 10^{-8}$	II	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	..	..	..
16001001	$8.00\ 10^{-6}$	$2.49\ 10^{-2}$	V	$1.24\ 10^{-2}$	V	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	..	..	..

6.3.2 Assessment for the failure mechanism piping

For each section, the segment norm is translated into a norm per section for the failure mechanism piping. With the current failure probability per section and the relative change in failure probability per dike segment a revised failure probability for each step of sea level rise is computed. For the current system with the current failure probability 45, 77 and 81 percent does not meet the requirements when the water system is subjected to 0, 1 or 2 meter sea level rise respectively.

Table 6.3: Assessment for the failure mechanism height. Comparison of current system and configuration of Delta21. The failure probabilities are assessed based on the requirement for the prevailing dike section (lower limit). The failure probability depends on the configuration Delta21 or current system, and the subjected sea level rise. This failure probability is compared to the lower limit and results in a particular class (Table 6.2). Two examples are given, in total 526 sections are evaluated for five steps of sea level rise (0, 0.5, 1.0, 1.5 and 2.0).

Section	Low. limit	SLR 0m				SLR 0.5m				SLR 1m	
		CS	Cl.	D21	Cl.	CS	Cl.	D21	Cl.	CS	Cl.
14001001	$7.29\ 10^{-6}$	$1.00\ 10^{-7}$	II	$7.36\ 10^{-8}$	II	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	..	..	..
16001001	$7.33\ 10^{-5}$	$2.49\ 10^{-2}$	V	$1.24\ 10^{-2}$	V	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	..	..	..

6.3.3 Combined assessment

The combined assessment provides insight into the question whether dike reinforcement is required for different configurations. In the following figures, an combined assessment of the failure mechanisms height and piping is shown (Figure 6.8, 6.9 and 6.10). The first three figures belong to the configuration of the current system with the current failure probability of the Europoort barrier, the following three figures belong to the Delta21 with the current failure probability and the remaining three figures to Delta21 with an improved failure probability.

As expected, the failure probabilities show similar behaviour as the governing water levels (Section 5.2). For a sea level rise of 0 m, 45 percent of the dike sections fail in the current situation and 30 percent of the dike sections fail in the case of Delta21. This profit in sufficient dike sections is gained throughout the domain. In case of 1 meter sea level rise, 77 percent of the section do not meet the norm for the current situation and 52 percent for Delta21. This difference is most clearly visible in the flood storage dominant area. For a sea level rise of 2 m, 82 percent of the dike section do not meet the norm for the current situation against 65 percent for Delta21 (Figure 6.7).

When Delta21 is combined with an improved failure probability of the Europoort barrier some improvement can be made for very limited sea level rise. The percentage of sufficient dike sections is raised by 3 percent.

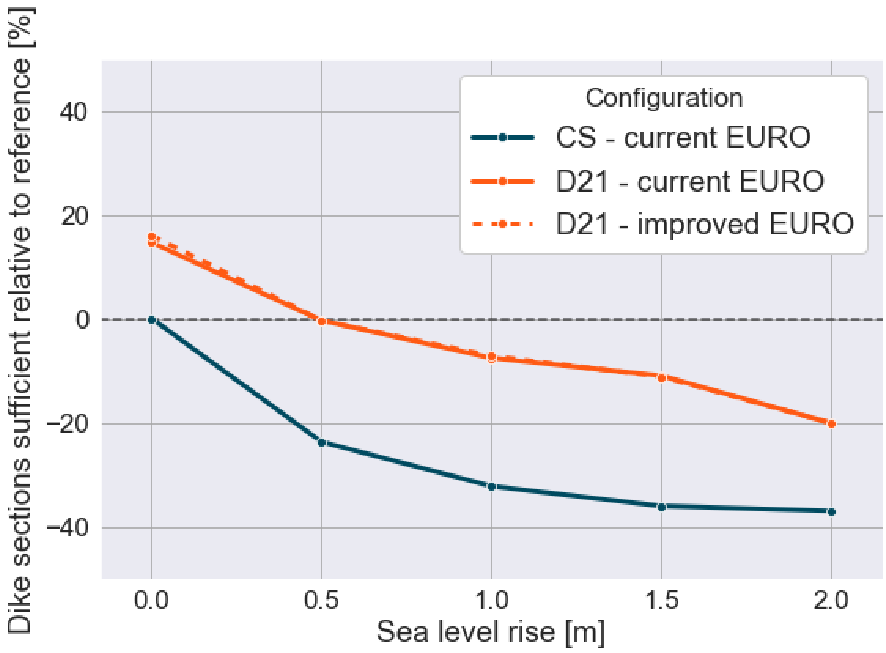
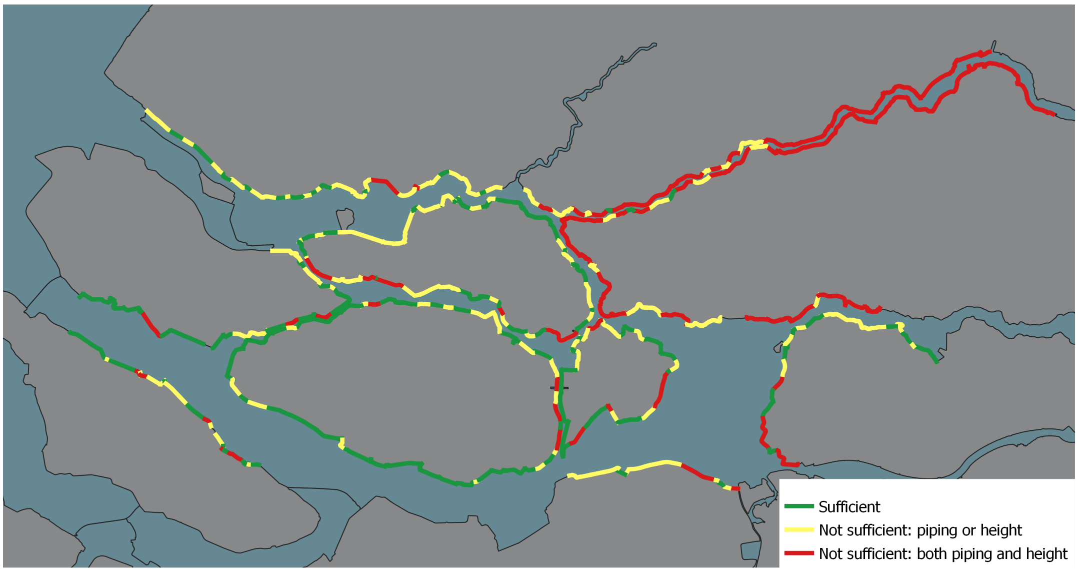
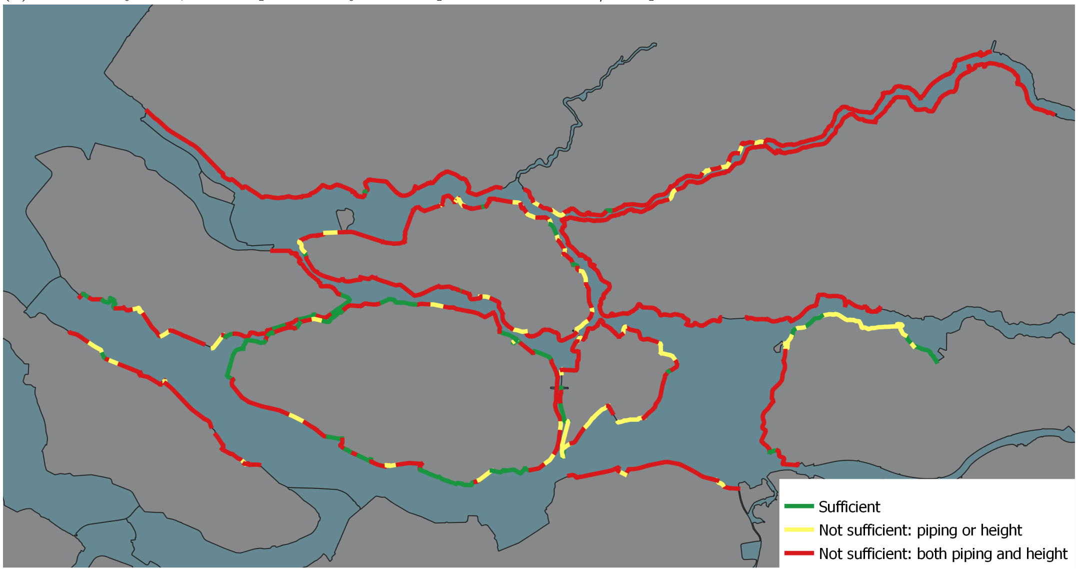


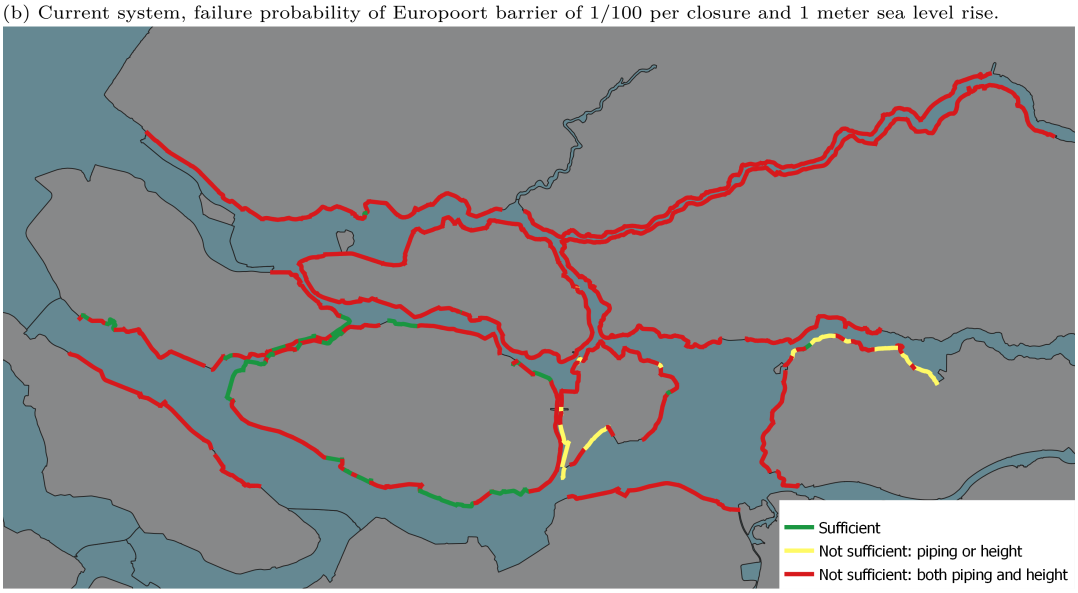
Figure 6.7: Percentage dike sections that meets the norm for three different configurations relative to the reference. For the reference scenario - current system without sea level rise - 45 percent of dike sections do not meet the norm for piping or height. The reference scenario is depicted with a horizontal dashed black line (0%), the current system is depicted in blue and Delta21 is depicted in orange. For Delta21, a distinction is made between the current failure probability (1/100 per closure) and an improved failure probability (1/1000 per closure) of the Europoort barrier. Due to sea level rise, the percentage of dike sections that meets the norm decreases, indicated by a negative percentage. In case of Delta21 and a sea level rise of 0.5 m, the percentage of dike sections that does not meet the norm is equal to 45 percent, which is in turn equal to the percentage in the reference scenario. The total number of dikes sections in the domain is 526.



(a) Current system, failure probability of Europoort barrier of 1/100 per closure and 0 meter sea level rise.

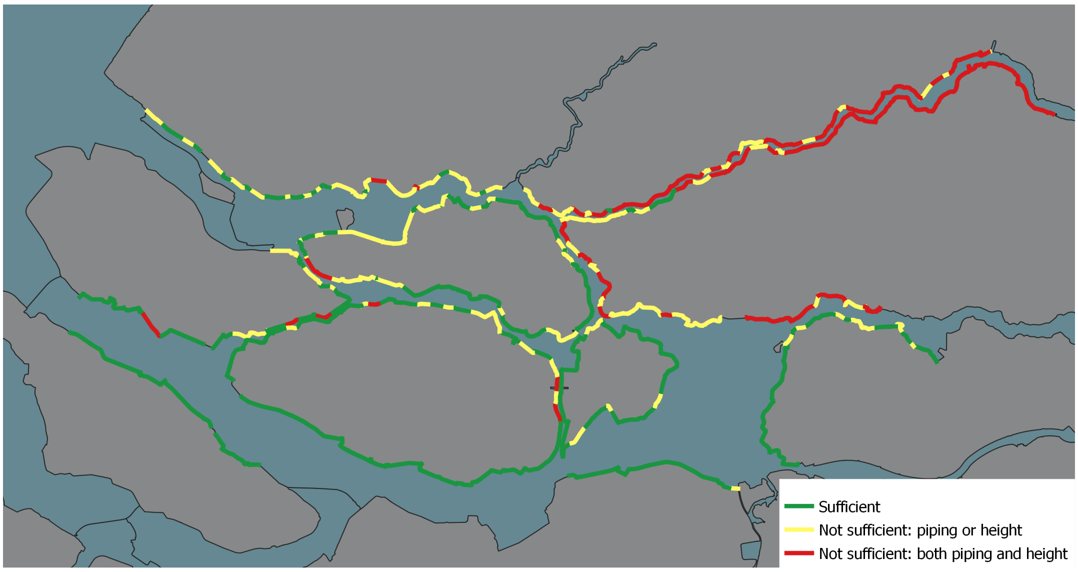


(b) Current system, failure probability of Europoort barrier of 1/100 per closure and 1 meter sea level rise.

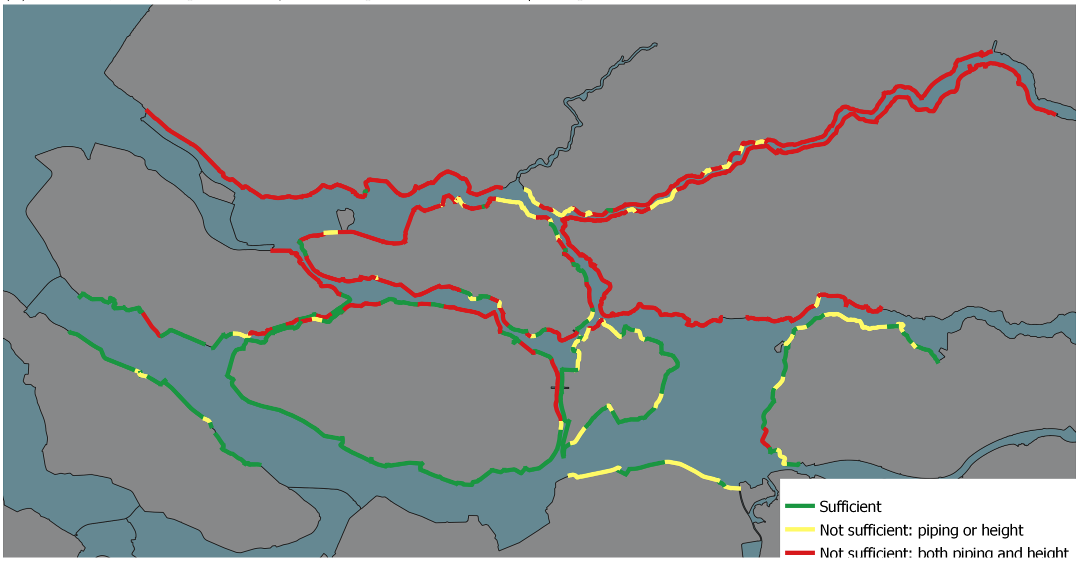


(c) Current system, failure probability of Europoort barrier of 1/100 per closure and 2 meter sea level rise.

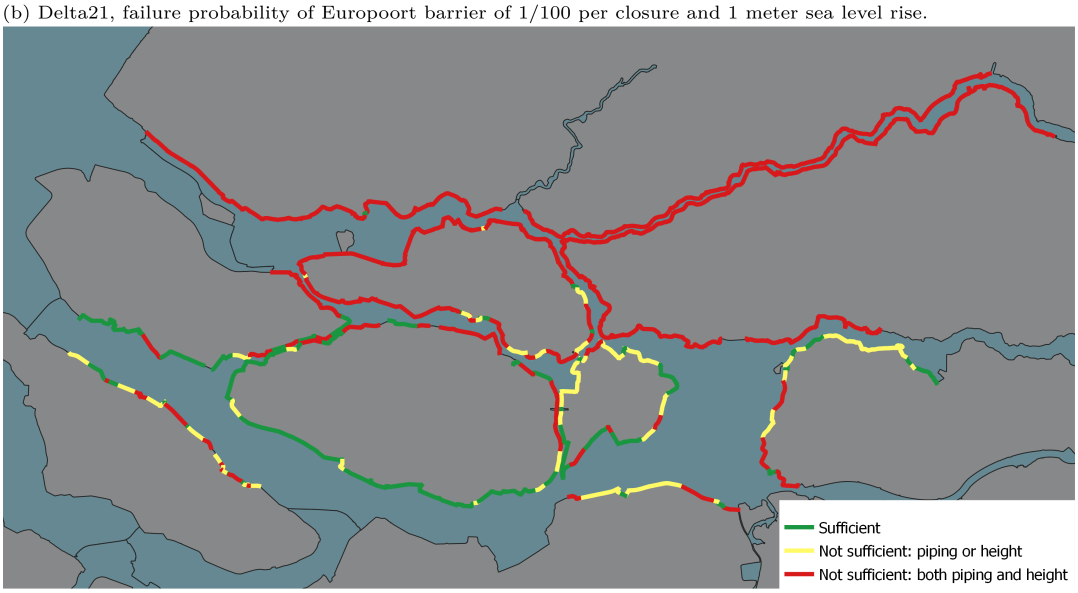
Figure 6.8: Assessment for the current system with the current failure probability of the Europoort barrier. Green lines indicate that the dike sections comply to the norms for both piping and height, yellow lines indicate that the resistance for piping or height is not sufficient and red lines indicate that the sections fail to meet the requirements for both piping and height.



(a) Delta21, failure probability of Europoort barrier of 1/100 per closure and 0 meter sea level rise.

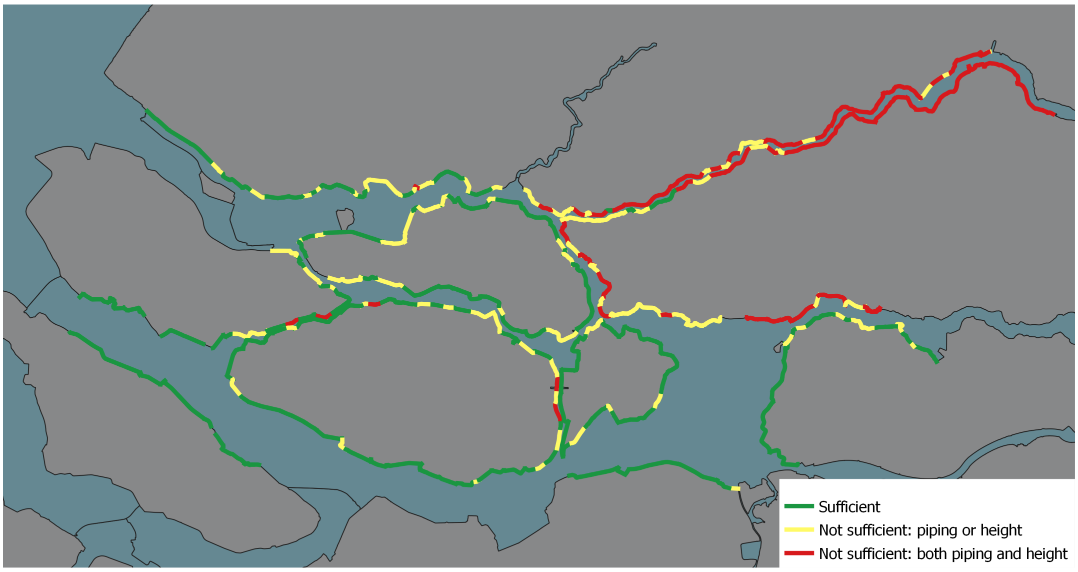


(b) Delta21, failure probability of Europoort barrier of 1/100 per closure and 1 meter sea level rise.

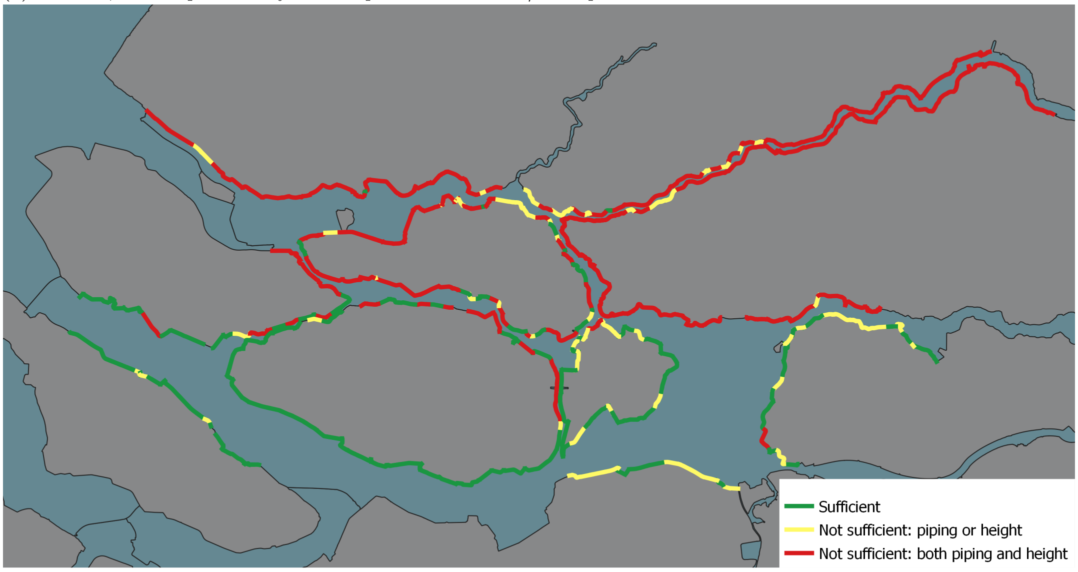


(c) Delta21, failure probability of Europoort barrier of 1/100 per closure and 2 meter sea level rise.

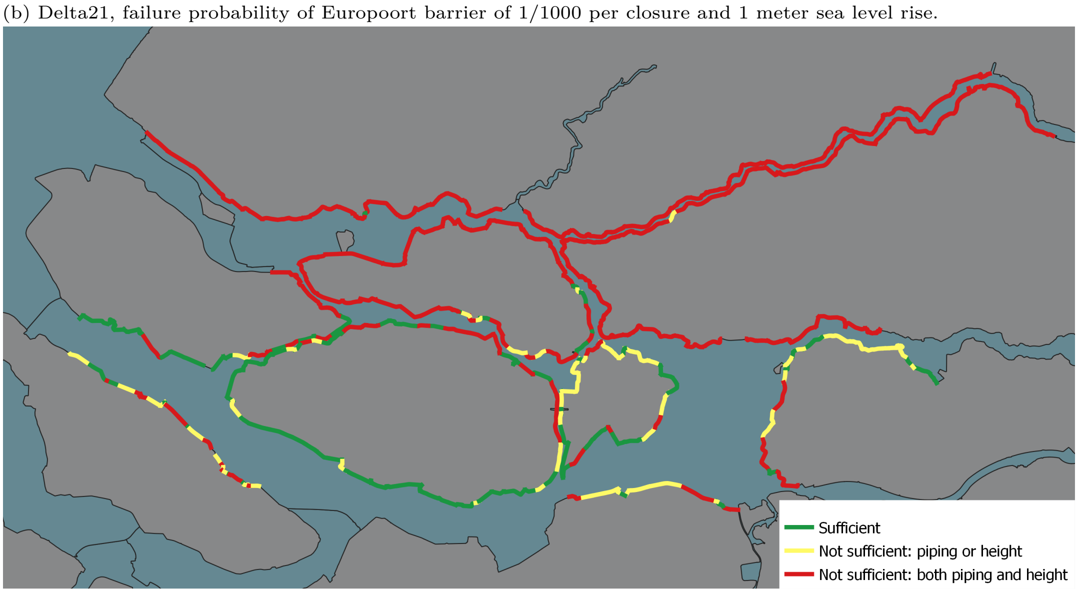
Figure 6.9: Assessment for the configuration with Delta21 and the current failure probability of the Europoort barrier. Green lines indicate that the dike sections comply to the norms for both piping and height, yellow lines indicate that the resistance for piping or height is not sufficient and red lines indicate that the sections fail to meet the requirements for both piping and height.



(a) Delta21, failure probability of Europoort barrier of 1/1000 per closure and 0 meter sea level rise.



(b) Delta21, failure probability of Europoort barrier of 1/1000 per closure and 1 meter sea level rise.



(c) Delta21, failure probability of Europoort barrier of 1/1000 per closure and 2 meter sea level rise.

Figure 6.10: Assessment for the configuration with Delta21 and an improved failure probability of the Europoort barrier. Green lines indicate that the dike sections comply to the norms for both piping and height, yellow lines indicate that the resistance for piping or height is not sufficient and red lines indicate that the sections fail to meet the requirements for both piping and height.

6.3.4 Effect of Delta21 on dike reinforcement strategies

Pump capacity and extra storage reduces the hydraulic loads and failure probabilities in the Rhine-Meuse estuary. At the same time, this adaptation comes with high costs. Hence, it is interesting to provide a first overview of how many kilometers of dike reinforcement can be delayed or even prevented (Figure 6.11). From a sea level rise of 0.5 m onwards, Delta21 saves about 100 km of dike reinforcement, which is 20 percent of the investigated flood defence length in the Rhine-Meuse estuary. The largest reduction is achieved for a sea level rise of 1.5 m. Moreover, an improved failure probability in combination with Delta21 does not have a large influence and is most apparent for a sea level rise of 0.5 m.

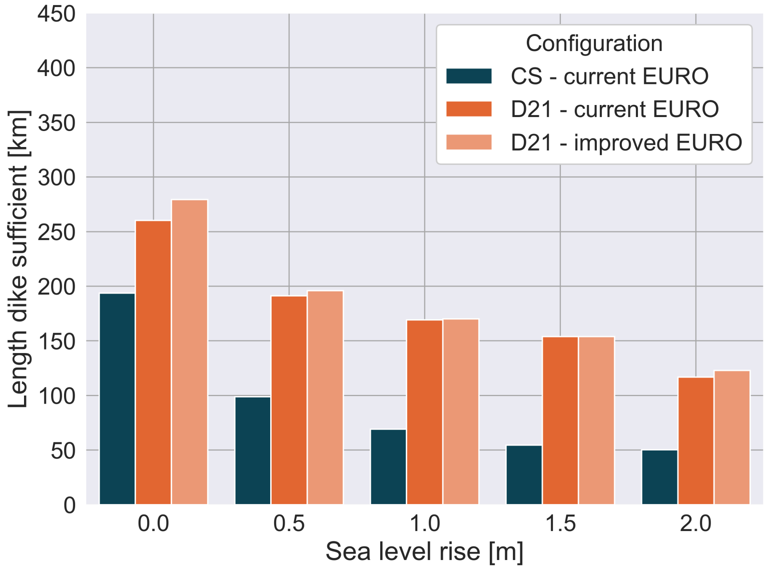


Figure 6.11: Kilometers dike that meet the norm for three different configurations. For different steps of sea level rise, the length of dikes that meet the norms for piping or height are depicted. The current system is depicted in blue and Delta21 is rendered in orange. For Delta21, a distinction is made between the current failure probability (1/100 per closure) and an improved failure probability (1/1000 per closure) of the Europoort barrier. The total length of dikes in the domain is 484 km.

CONCLUDING REMARKS

Based on the reference and the relative change per dike segment and sea level rise scenario, failure probabilities are computed for the failure mechanisms height and piping. This analysed for both the current system and Delta21. Subsequently, the failure probabilities for each system and step of step of sea level rise, are assessed according to the WBI methodology. This gave an overview which dike sections did meet the norm for configurations: 1) the current system with the current failure probability (1/100 per closure) of the Europoort barrier, 2) Delta21 in combination with the current failure probability (1/100 per closure) of the Europoort barrier and 3) Delta21 with an improved failure probability (1/1000 per closure) of the Europoort barrier.

The percentage of sufficient dike sections is compared for the current system and a system with Delta21. For 0, 1 and 2 m sea level rise, the difference is 15%, 25% and 17% respectively (Table 7.1). An improved Europoort barrier increases the number of sufficient section by 3 percent, but only in case of limited sea level rise (0 - 0.25 m).

Table 6.4: Percentage of dike sections that suffices the norm for different steps of sea level rise.

System	Sea level rise [m]		
	0	1	2
Current system	45 %	77 %	82 %
Delta21	30 %	52 %	65 %

Chapter 7

Closure of physical perspective

This chapter provides the discussion and conclusion that are especially relevant to the physical perspective. First, the limitations are elaborated (Section 7.1). The limitations are the characteristics of the followed approach and hydrodynamic model that impacted the application and the interpretations of the results. Afterwards, the conclusions are drawn related to the sub-questions of the physical perspective (Section 7.2). Finally, partly related to the limitations, recommendations are made for both improving the methodology as promising directions that help to prevent the Rhine-Meuse estuary from flooding (Section 7.3).

7.1 Limitations

7.1.1 Morphological developments disregarded

So far the response to climate change, and possible interventions, has been judged based on hydrodynamic simulations. The impact of sea level rise on current erosion trends in branches is not clear. Various inter-dependencies, such as between the morphodynamic development and baroclinic processes controlling salt intrusion and mud dynamics have largely remained unexplored. These developments can have an indirect effect on the water flows of the system.

7.1.2 Simplifications in modelling

In this report, one possible configuration of Delta21 is researched. In order to include Delta21 in the hydrodynamic model, several simplifications are made. The pumps capacity of the artificial lake is placed directly on the Haringvliet sluices. Hence, water can be directly discharged from the Haringvliet to the North Sea. In the conceptual plan of Delta21, a basin is located between the Haringvliet and the North Sea.

Throughout this research, it has been found that significant improvement can be made in the operation. Currently, the pumps are controlled depending on the water level in the Haringvliet. However, the Haringvliet is not the most critical location in terms of flood risk. Once the real-time control is tailored more to the water level at Dordrecht or Rotterdam, the potential to lower the water levels could be increased.

The failure probability of the barriers is kept constant in this research. In other words, the failure probability is not adjusted for changes in loading. In reality, the design water level is more frequently exceeded in the case of increasing sea level rise.

7.1.3 Fragility curves

For the fragility curves, only the seepage length, grain size and permeability have been altered per dike section. Although these parameters are important in determining the failure probability for a particular water level, there are many more parameters that have a role in computing failure probabilities. Moreover, to accurately determine the failure probability of a dike section, more detailed schematisations are needed. The fragility curves account for a fully probabilistic analysis in which lower water levels are also pivotal. Generally, the seepage length is larger for lower water levels. In this research a conservative approach with one single seepage length is chosen. Several seepage lengths for different water levels would yield better results.

In the case of more than 1.5 meters sea level rise, flood defences started to approach a failure probability of 1 for the failure mechanisms height and piping. As fragility curves are derived and calibrated to work with failure probabilities around the norm, the reliability tends to decrease for extreme sea level rise scenarios.

7.1.4 Model uncertainty

Inherent uncertainties related to the natural variability are included in this research. These are uncertainties that arises from pure randomness, which cannot be reduced by further analysis and lead to fluctuations in time and space. The inherent uncertainties are related to the physical processes e.g. discharge and storm surge. At the same time, the used model approach introduces new uncertainties. These model uncertainties occur due to inaccurate parameterized models, model simplifications and wrong mathematical equations. As this research is mainly about comparing two configurations to a reference, not much effort is put in the quantification of model uncertainties. However, it would be interesting to see what the effect would be of model uncertainties on the performance of Delta21. In the WBI-approach, it is mandatory to include model uncertainties for the computation of hydraulic loads.

7.2 Conclusions

SQ-I.a What are the present and future boundary conditions for the Rhine-Meuse estuary?
The most important phenomena that affect the present and future boundary conditions of the system are the storm surge, discharge and (rate of) sea level rise. These three phenomena are all affected by climate change. The storm surge is described with the seven points WBI schematisation with a storm duration of 35 hours. The peak discharge of the Rhine and Meuse is expected to increase in the future. For this research, the current discharge distribution is used. This choice has been made to quantify the influence of pump capacity and extra storm surge capacity on mitigating sea level rise. Currently, the rate of sea level rise is about 2 mm/year along the Dutch coast. At the same time, large uncertainty exists about the rate of sea level rise in the future. As no time horizon is assigned in this research, sea level rise up to 2 meters is investigated, which is in line with scenarios used by the Delta Program.

SQ-I.b How can the hydrodynamic behaviour of the current system, and the system with Delta21, be modelled with a computationally efficient model?
Several different programs and python applications have been used to determine the influence of pump capacity and extra storage capacity on the hydraulic loads and flood risk probabilities in the Rhine-Meuse estuary. For the hydrodynamic computations, the 1D model SOBEK-3 is used including six hydraulic structures: Maeslant barrier, Volkerak barrier, Haringvliet sluices, Hollandse IJssel barrier and Heusdensch Canal barrier. The model has been adjusted to implement the pump capacity and extra storage in the case of Delta21. The barriers are controlled with the real-time control of SOBEK-3 and an external python script - SingleRunner. With the SingleRunner, barriers can be controlled based on predictions of water levels which corresponds to the control in reality. All the simulations are supported by MHWp5. The results of SOBEK-3 are processed with Hydra-NL, to connect statistical information of the exceedance probabilities of boundary conditions to the hydrodynamic computations. Fragility curves are used to translate the hydraulic loads to failure probabilities of flood defences.

SQ-I.c What is the influence of Delta21 on the water flows in the Rhine-Meuse estuary?
The influence on the water flows is investigated by analysing one realisation. The used realisation corresponds to the illustration point, which is the combination that just failure occurs, and the probability of occurrence belonging to this combination is the highest compared to other combinations that lead to just failure. The used realisation had a storm surge level of 3.54 m, discharge of 10.000 m^3/s and a correct functioning Europoort barrier. In general, Delta21 did not have a drastic (adverse) effect on the hydrodynamic processes. The effects on water level, discharge and velocity were not equal for every location in the Rhine-Meuse estuary. For the investigated realisation, the maximum water level in the storm surge area is reduced with 1.5 m, in the flood storage dominant area with 1 m, in the transition area with 60 cm and in the discharge dominant area 20 cm.

Because of the lowering in the Haringvliet and Hollands Diep, the storage area for the Volkerak Zoommeer is not utilized when Delta21 is operating. The water level at Rotterdam, and the water level reductions due to Delta21, are considered in more detail. The sensitivity of those reductions is investigated for various discharges and steps of sea level rise. In case of correct functioning Europoort barrier and a discharge of 10 000 m ^{3} /s at the Boven-Rijn, Delta21 succeeds to keep the slope of the water level during a storm surge to lower than 1 cm/h. The maximum reduction in water level between the current situation and Delta21 is achieved for the combination with a discharge of 13 000 m^3/s and a storm surge of 5.59 m. For larger discharges than 13 000 m^3/s, the effect of Delta21 on the maximum water level is less profound. For discharges lower than 10 000 m^3/s, the closure duration for the current situation is shorter compared to the configuration including Delta21. This is due to the lowering of the water level which delays the moment when the inside and outside water level are equal around the Maeslant barrier. This equal water level is required to open the barrier. Delta21 enables shorter closure of the Maeslant barrier for discharges larger than 13 000 m^3/s.

SQ-I.d What is the influence of Delta21 on the hydraulic loads in the Rhine-Meuse estuary?
Delta21 succeeds in reducing the water levels throughout the entire domain. At the same time, these reductions differ considerably depending on the processes that are dominant. For the storm surge dominant area, the reduction for various amounts of sea level rise are 10-20 cm, for the discharge dominant area 10-40 cm, for the flood storage area 1-1.5 m and for the transition area 30-60 cm.

The return period for a particular water level is increased due to Delta21. The order of magnitude of the return period factor - return period in the case of Delta21 divided over the return period for the current system - differs between 1 and 100. For the storm surge dominant area and the discharge dominant area the order of magnitude is 1, for the transitions area it is ranging between 1 and 10 and for the flood storage dominant area it is ranging between 10 and 100 for most locations.

SQ-I.e How do the failure probabilities of flood defences change due to Delta21, taking into account the most important failure mechanisms?
The changes in failure probability for two failure mechanisms - height and piping - have been computed at 24 locations belonging to different dike segments in the domain. The current failure probability, based on VNK2 data, served as a reference. Subsequently, the relative change to this reference is computed for both height and piping. Similarly to the reduction in hydraulic loads, the failure probability reduction achieved by Delta21 differed throughout the domain. The reductions for the failure mechanism height were larger than the reduction for the failure mechanism piping.

Based on the reference and the relative change per dike segment and sea level rise scenario, failure probabilities are computed for the failure mechanisms height and piping. This analysed for both the current system and Delta21. Subsequently, the failure probabilities for each system and step of step of sea level rise, are assessed according to the WBI methodology. This gave an overview which dike sections did meet the norm for configurations: 1) the current system with the current failure probability (1/100 per closure) of the Europoort barrier, 2) Delta21 in combination with the current failure probability (1/100 per closure) of the Europoort barrier and 3) Delta21 with an improved failure probability (1/1000 per closure) of the Europoort barrier.

The percentage of sufficient dike sections is compared for the current system and a system with Delta21. For 0, 1 and 2 m sea level rise, the difference is 15%, 25% and 17% respectively (Table 7.1). An improved Europoort barrier increases the number of sufficient section by 3 percent, but only in case of limited sea level rise (0 - 0.25 m).

Table 7.1: Percentage of dike sections that suffices the norm for different steps of sea level rise.

System	Sea level rise [m]		
	0	1	2
Current system	45 %	77 %	82 %
Delta21	30 %	52 %	65 %

7.3 Recommendations

As the Rhine-Meuse estuary is a fascinating area with many interdependencies, it provides a host of opportunities for further research. Some of the recommendations in these sections follow from the limitations of this research, other present other interesting design and computation directions for flood risk management.

7.3.1 More computations at more locations

A limited amount of representative locations is used in this research. In further research, it is recommended to use more locations and cluster dike sections within one segment into different groups with similar parameters. In this way, the relative change in failure probabilities would become more accurate as well while still preserving the computational efficiency. Next, it is advised to include more failure mechanisms than height and piping. In this way, a combined fragility curve can be used which approaches reality more closely. Moreover, it is expected that other failure mechanisms become more prominent in the future as current dike reinforcements are tailored to limit the failure probability due to piping.

Discrete values have been used to represent the stochastic variables in both the hydrodynamic computations as the fragility curves. A discretization is always an approximation of a continuous distribution. In this approximation, certain information is lost which can be reflected in the results. For example, the fragility curves show a steep curve around the crest height. More discrete values would lead to more accurate fragility curves leading to more accurate failure probabilities. Moreover, it is recommended to research the influence of sea level rise in combination with changing storm surges and increasing peak discharges of rivers.

Throughout this research, a set with 9 discharges and 6 storm surges is used. This set is derived to cover the critical combination that leads to governing water levels in the Rhine-Meuse estuary. When large sea level rises are modelled, it remains to be seen whether this particular set of discharges and storm surges still cover governing situations. In other words, research is needed to investigate whether the set of boundary conditions need to be adjusted to deliver more reliable results for large sea level rise scenarios.

7.3.2 Explore other configurations of pumping stations

The focus in this research is on the influence of pump capacity on the flood risk safety in the Rhine-Meuse estuary. This pump capacity is deployed with a control scheme that is triggered by the water levels in the Haringlviet and the North sea. To fully assess the potential of pump stations, it is recommended to explore other real-time control schemes. The conceptual plan of Delta21 offers many opportunities to fine tune the real-time control. It is expected that a more advanced real-time control scheme can result in more hydraulic load reductions. Delta21 consists of many different elements such as pumps, storage and siphons. The sequence, closure and opening levels can be simulated and fine tuned by simulating different locations. Furthermore, the real-time control can be adjusted to the real-time control of other hydraulic structures, such as the Europoort barrier and Volkerrak sluices. Moreover, the geometry of Delta21 could be investigated in more detail, especially regarding local flow dynamics around the inlet and outlet of the structures.

Delta21 is mainly effective for the flood storage dominant areas. To further analyse the potential of pumps in reducing the hydraulic loads, it would be interesting to investigate the effect of pumps when these are placed at the Nieuwe Waterweg. Also a combination between pumps at the Haringvliet, pumps at the Hartelkanaal and pumps at the Nieuwe Waterweg bould be interesting to investigate. Moreover, further research to smaller pumps stations - 500 to 1000 m^3/s - would be interesting as well. These plans might be easier to implement and do more justification for the complex interactions in the water system than a pump station on a single location.

7.3.3 Investigate failure probability of hydraulic structures subjected to sea level rise

In this thesis, the hydraulic loads on the flood defences of the hinterland are investigated. The failure probability of the storm surge barriers and other hydraulic structures is kept constant for different steps of sea level rise. The design water level of the Maeslant barrier, Haringvliet sluices and Hollandsche IJssel barrier is equal to NAP+ 5 m, NAP+ 5 m and NAP+ 4,4 m. A preliminary analysis based on model simulations indicates that the return periods, for which these design water levels are reached, increases with an order of magnitude of 100 for a sea level rise of 2 meters. Hence, it is advised to research the failure probability hydraulic structures in the Rhine-Meuse estuary related to sea level rise. Moreover, the current failure probability of hydraulic structures is already uncertain as the current failure probability of 1 in 100 per closure is related to outdated research.

II

Socio-political perspective

Chapter 8

Decision-making and learning in the Rhine-Meuse estuary

This chapter provides an introduction to the socio-political perspective. The focus in on how delta management works in practice and how technologies are embedded in a network of social routines to achieve overall management objectives. In other words, how do decisions come about in water management and in what way can learning activities contribute to taking into account the true complexity of water systems at different scales and large uncertainties. In this chapter, it becomes clear why the focus of the socio-political perspective is on the interaction between decision-making and learning processes. This is one of the missing links in delta management.

First, the societal and political changes in delta management in the Rhine-Meuse estuary are discussed (Section 8.1). Subsequently, the characteristics of decision-making in network structures are discussed (Section 8.2). This provides information about the socio-technical system and the need for collaboration in networks. This chapter provides a more general background about the interaction between decision-making and learning in networks. A more detailed actor analysis can be found in Chapter 10).

8.1 Societal and political changes in delta management

8.1.1 From the origin of flood risk governance to the flood of 1952

The water system interferes since early times with the spatial planning of the inhabitants of the low delta. This interference grew as economic activity and population increased. Inhabitants had to deal with regular floods that compromised their prosperity in the estuary. Hence, inhabitants started cooperating to mitigate (the consequence of) floods and manage the water system. From the twelfth century onwards, water boards were established which carried out interventions in the water system which they financed by means of taxation (Mostert, 2017).

Over time, more water boards came into being and managed particular parts of the water system in the Netherlands. In the fourteenth century, most Dutch rivers were lined with dikes, yet the hinterland was frequently plagued by flooding. Nonetheless, the battle against water was the result of good organisation at the local level. Every community took care of its own drainage and protection systems without overburdening others'. With a high degree of involvement on the part of local inhabitants whose knowledge of the local water system was excellent, an incredibly complicated institutional system arose (Lintsen, 2002). In this context, larger water boards and provinces played an important role in the Netherlands. At the same time, complex problems arose that proved difficult to be solved in a decentralised system. This resulted in the establishment of a central governmental body, Rijkswaterstaat. The changing political circumstances further fostered the founding of Rijkswaterstaat in 1798. In the nineteenth century, the parliamentary democracy and separation of powers were introduced leading to important changes in water management. Water boards lost their judicial powers and direct elections were introduced. Although there was a tendency to organise water management in a more centralised way, 2670 existed on the eve of the 1953 flood (Mostert et al., 2007).

8.1.2 From the flood of 1953 to the second Delta Committee

On the night of 21 January to 1 February, a heavy storm swept across the North Sea. In the South-West of the Netherlands, dykes breached at about 150 locations and inundated 136 000 ha of land. More than 72 000 individuals had to be evacuated, 1836 individuals perished and the economic losses amounted about 1.5 billion guilders in the Netherlands (Voorendt, 2017).

8.1.3 Current affairs of flood risk governance

Two institutions are primarily responsible for flood risk management. At the national level, the minister for Infrastructure and Water Management (in Dutch: Ministerie van Infrastructuur en Waterstaat; I&W) is formally responsible for setting norms and standards, strategic planning and reports to the Parliament. Rijkswaterstaat is the executive body at the national level and is manages public works and water management of the larger waters (North Sea, Wadden Sea, rivers and canals). At sub-river basin level, 23 Dutch water boards (hereafter called 'water authorities') are responsible for integrated water management, which includes flood protection. These water authorities have legislative power and make decisions with respect, to the budget, taxes, water level and water management plans (Wiering et al., 2015).

Dutch water management is based on integrated long-term strategic planning which is translated into mid-term strategic and operational planning. The Legal Assessment Tool (in Dutch: Wettelijk Beoordelingsintrumentarium; WBI) provides the format in which managers should assess the safety standards that are elaborated in the Water Act. This system has a 12-year monitoring cycle and reporting to the Parliament. The Dutch water management is characterised by high flood safety standards which correspond with a focus on prevention. In the RMD, 1:10,000 years flood risk standards are applied because of the high social and economic consequences and the problematic possibilities for evacuation.

8.2 Characteristics of decision-making in a network structure

8.2.1 Decentralised water management

Water management in the Netherlands is increasingly characterized by a network structure. This means that knowledge and decisions do not belong to one single actor or group of actors, but those decisions come about during interactions between various groups of actors. Although there are no crucial changes in actor coalitions in the Rhine-Meuse estuary, there is a move towards decentralizing responsibilities and empowering regional authorities (Wiering and Arts, 2006). Hence, it is important to take characteristics of networks into account (de Bruijn and ten Heuvelhof, 2008):

1. Pluriformity; many different actors, interests and resources;
2. Mutual dependencies; actors are dependent on one another to meet their own objectives;
3. Closed for hierarchical signals; actors do not recognize steering of other actors or do resist against this;
4. Dynamics; actors and their positions continually change.

These characteristics govern the interactions related to delta management in the Rhine-Meuse estuary and form the setting in which learning takes place. Over time, the interactions between different layers of actors have been intensified and are heading towards more co-operative and horizontal interrelations. As the network of delta management in the Rhine-Meuse estuary is stretched over various (governmental) layers, accountability is also diffuse and spread throughout the network. The Dutch constitution consists of three general administrative levels: 1) national, 2) provincial and 3) municipal. The issue of water management has an additional fourth layer: the water boards. Hence, it is not always clear who is accountable for the participatory process, how feedback in the process between accountable actors is arranged and who is accountable for making the final decisions in water management interventions.

Finally, networks are systems and these systems are recursive. It can be divided into subsystems and is at the same time part of a larger system; 'system of systems'. Boundaries are thus choices, such as geographical boundaries, water system boundaries or political boundaries. These choices need to be made by decision-makers and might be controversial for other actors. The different scales are also apparent in the Rhine-Meuse estuary. Research and decisions are made on different levels including various system boundaries. These boundaries are vital for decision-making in delta management as they are important in framing problems and solutions.

8.2.2 The need for multi-actor collaboration

The variety of actors and dimensions make a collaborative approach necessary in reaching decisions. This collaborative approach is also deemed necessary because of the focus on adaptive water management, which is build upon the idea of stakeholder involvement. In this context, the legitimacy for water management interventions is not solely dependent on scientific evidence but needs to be earned in a deliberative process with all relevant actors. This means that the ways in which delta management interventions are legitimized also changes over time (Gearey and Jeffrey, 2006). The different dimensions also host various points-of-departure for learning processes. Research with a long time horizon has different aims and outcomes than short term oriented research. Hence, one can expect that knowledge development takes place in a decentralized manner with different learning preferences.

Water managers in the Rhine-Meuse estuary need to deal with an important challenge. On the one hand, they need to comply with the norms for flood safety and other functions. On the other hand, for a collaborative approach, many different parties need to be involved, which implies a potential decrease of decisiveness for planning and implementation force of the government. In that sense, hierarchical and horizontal notions of legitimacy need to be combined in order to deliver solutions that are both supported and in-time to respond to changing circumstances.

8.2.3 Towards adaptive social learning

Adaptive delta management requires that not only the decisions or interventions themselves are adaptive, but that the process in reaching decisions is adaptive as well. As denoted before, a collaborative approach is vital in decentralized decision-making systems. To turn the collaborative approach to success, learning from and with other actors is required. Explicit notions about the role of learning in decision-making remain unclear in delta management in the Rhine Meuse estuary. This hinders the development of adaptive solutions for changing circumstances. Hence, one of the aims of this research is to make learning explicit in delta management in the Rhine-Meuse estuary and provide suggestions on how learning activities themselves can be designed and used in an adaptive manner.

Table 8.1: Three dimensions in water management, including aspects and sub-aspects.

Dimensions	Aspects	Sub-aspects
Sector	Actors	Organisations
		Staff
	Resources	Authority
		Knowledge
		Budgets
	Policies	Problem definitions
		Solution strategies
		Process management
Scale	Geographical	Water basin
	Administrative	National
		Provincial
		Municipality
Temporal	Time	Timing
		Time horizon
	Change	Speed
		Time pressure

Chapter 9

Approach and methodology

The research addresses the tension between decision-making and learning in delta management. The intersection between those two fields is investigated in two case studies: the Delta Program and Knowledge Program Sea Level Rise. This chapter elaborates upon the approach and methodology used for the socio-political perspective. It describes how the research is set up, how theory and practice interfere, how the case studies are used and which methods are used to generate the desired input for answering the research questions.

9.1 Research design

The aim of this study is to create an approach that enables decision-makers to apply adaptive social learning. This research is of an exploratory nature as little is known about the intersection of decision-making and social learning in delta management. Exploratory research offers flexibility and adaptability to change, which is a great advantage. The cross-cased approach with two case studies has resulted in more insights and perspectives to address learning processes. Furthermore, the research is case-oriented as the analysis aims to understand several cases by looking closely to the details of each (Babbie, 2013). Data were collected from various sources to obtain diverse evidence and cross-check causal inferences.

The cases of the Delta Program and the Knowledge Program Sea Level Rise are selected to investigate the processes that play a major role in adaptive social learning. As the Knowledge Program Sea Level Rise is part of the Delta Program, the cases are closely interrelated. The data related to the Delta Program is used to deepen the conceptual model and get a better understanding of the decision-making context and processes related to adaptive learning. Since the Knowledge Program Sea Level Rise is smaller and more tangible, it enables me to translate theoretical and more abstract notions related to adaptive social learning into concrete recommendations. Both cases illustrate the value of the developed conceptual model.

9.2 Methods

A range of methods has been used throughout this research. This section describes why and how these methods are used and how they did connect to one another. An overview of the methods is given in Figure 9.1.

9.2.1 Literature review

A systematic literature reviews was performed to provide a solid base of frameworks and theories that are related to decision-making and learning. As, decision-making and social learning are connected to broad strands of literature, this systematic literature review is followed by a snowball sampling strategy. Based on different angles, different snowballs have been rolled. Crucial point of departures in the literature review were the book of Marchau et al. (2019), the article of (Pot et al., 2018) and Wenger (2000) among others. A more detailed method for the literature review can be found in Appendix C.

9.2.2 Document analysis

Different kinds of documents are published describing the case studies: policy documents, advisory reports and scientific literature. These documents are analysed to assess the goals of different actors, how the Delta Program and Knowledge Program Sea Level Rise work and intermediate process evaluations. For the Delta Program case, primary documents are the Delta Programs that have been published yearly along with background documents (Appendix D).

Documents were collected through a systematic search of the database of the Delta Commissioner. Additional documents have been selected through snowball sampling. Decisions do not come into place suddenly, decision rounds provide the basis for decisions and it would be interesting to see the nature of those rounds. In other words, policy documents that provided insight into the information that decision-makers have been using and whether they have been more focused (or biased) towards one stream of the conceptual model.

9.2.3 Actor analysis

An actor analysis is carried to get understanding of the roles of actors in the network, and the influence they have on the unfolding of the erratic decision-making process in the Rhine-Meuse estuary. This research is about the interaction between learning and decision-making. Both processes are intertwined and so are the collaborations between actors. Hence, an actor analysis has been conducted to make the relations between actors more explicit and define key-stakeholders in adaptive delta management.

9.2.4 Conceptual model

Although the theoretical framework provides crucial insights about the decision-making process, it is not necessarily equipped to analyse and improve the current situation. Hence, the afore-mentioned theories and concepts have been merged into one theoretical framework. The notions in the theoretical framework are converted to a model which is more practically applicable. The aim of the model is to provide a tool to bridge the theory-to-practice gap. The tool should serve both understanding and improving of the decision-making process. Furthermore, it would provide a clear and traceable basis for the construction of code trees.

9.2.5 Semi-structured interviews

Eight interviews with key actors were conducted, recorded and transcribed. Interviewees were selected through background documents and snowball sampling. All interviewees were involved in the Knowledge Program Sea Level Rise, some more direct than others. Furthermore, interviewees were associated with the Ministry of Infrastructure and Water management (n=1), Rijkswaterstaat (n=2), Water Board Hollandse Delta (n=1), Rotterdam Port Authority (n=1), Municipality of Rotterdam (n=1), Province of South Holland (n=1) and staff Delta Program (n=1).

For the interviews, a semi-structured interview guide was designed to elaborate on pre-defined topics while being open to other relevant information about the decision-making context. Several recurring topics were discussed during the interviews, as denoted in Appendix F. The interviews were transcribed verbatim. In this style, every word on the recording is transcribed as is including grammatical errors. However, extra details like stutters and repetitions are removed.

9.2.6 Participant observation

In the context of this research, I attended one work session about 'accelerated sea level rise' on January 14th, 2020. Participant observation allows for more explanation, context and confirmation which makes it a useful element in mix-method studies (Babbie, 2013). The meeting took place at an early stage in the research and is solely used to gain some general understanding of the subject and way of collaboration. Furthermore, this meeting helped in selecting potential interview candidates. Although participant observation provides many insights in the behaviour of participants, it is known for its low degree of reliability and representativeness.

9.2.7 Data analysis

The interviews were coded in two subsequent rounds. First, paragraphs were coded for the absence of presence of sub-codes. Second, I described the coded paragraphs in more detail to account for their specific formulation and their relation to other coded paragraphs and important mechanisms. The basis of the code network is deductive. Interesting concepts in literature are operationalised in codes.

These deductive codes are expanded with a constant comparison method that consisted of the following methods:

- Open coding allowed to capture the exploratory character of the research. This inductive approach resulted in a general narrative of events and codes for key-themes;
- Axial coding further elaborates on the core concepts of the study. This approach is also inductive and particularly supported the exploration of dilemmas and meaning that interviewees assigned to particular topics.
- Constant comparison is used to distinguish conditions from strategies and consequences, and relate recurrent patterns to each other.
- Selective coding is more an abductive method and primarily allowed to switch between theoretical, conceptual and practical notions. This iterative process created new plausible links between existing theory and empirical data (Wolf and Baehler, 2018).

I iterated between theoretical concepts and empirical manifestations to identify (causal) mechanisms that are important for adaptive social learning. These mechanisms explain how certain processes and activities contributed - or frustrated - adaptive learning in delta management of the Rhine-Meuse estuary. The used approach shows major similarities to what scholars call theory-building process tracing (Beach and Pedersen, 2016).

Table 9.1: Overview of sub research questions and associated methods.

	Literature review	Document analysis	Stakeholder analysis	Conceptual model	Semi-structured interviews	Participant observation
SQ-II a How can decision-making be characterized in delta management of the Rhine-Meuse estuary? (Chapter 9)		✓	✓		✓	
SQ-II b What theories and frameworks are important in social learning and decision making in delta management? (Chapter 11)	✓					
SQ-II c How can the insights from these theories and frameworks be combined in a conceptual model? (Chapter 12)	✓	✓		✓		
SQ-II d How is the concept of learning defined and used by the Delta Program? (Chapter 13)		✓	✓			✓
SQ-II e How can the conceptual model be used to enhance adaptive social learning in the Knowledge Program Sea Level Rise? (Chapter 14)		✓	✓	✓	✓	✓

Chapter 10

Actors in the Rhine-Meuse estuary

The introduction to this report briefly mentioned the Delta Program and the Knowledge Program Sea Level Rise. The current chapter describes the decision-making process in more detail and identifies important mechanisms that are key in improving this process. As such, it answers the following sub-questions:

SQ-II.a How can decision-making be characterized in decision-making of delta management in the Rhine-Meuse estuary?

In the following sections, attention is paid to institutional context and collaborations in which actors operate, and the aspects of decision-making that are important for learning processes. First, the most important actors are described (Section 10.1). Next, the governance structure in the Rhine-Meuse estuary is discussed (Section 10.2). In Section 10.3 and 10.4, the Delta Program and Knowledge Program Sea Level Rise are discussed. To conclude, the interactions between the actors and programs are elaborated (Section 10.5).

10.1 Description of actors

This section mentions the most important actors that carry responsibility in delta management of the Rhine-Meuse estuary. These actors could be seen as key players that carry responsibility regarding the functions of the water system (Table 10.1). At the same time, these parties governmental bodies use the information and are advised by other parties. This surrounding knowledge system of Dutch water management is dominated by specialized governmental services, knowledge institutes, private parties and universities.

Table 10.1: Main actors present in the Rhine-Meuse estuary including area of responsibility and policy activities (Adjusted from Werners et al. (2009).

Player	Level	Area of responsibility	Policy activities
Rijkswaterstaat	National	Flood protection and water management of main river system	Drawing up national water policy and legislation.
Ministry of Infrastructure and Water management	National	Regulation of drinking water supply	Determination of drinking water quality standards.
Waterboards; Delfland, Hollandse Delta, Schieland en Krimpenerwaard	Regional	Water quantity management of main canal and polder systems, Water quality management, including wastewater treatment, Flood protection	Drawing up policy plans, Executing water assessments, Operation and maintenance of flood defense infrastructure.
Province of South Holland	Regional	Spatial planning, Land management, including coastal management, Emergency response coordination	Water quantity management of main canal and polder systems, Water quality management, Flood protection, Drawing up policy plans, Operation and maintenance of flood defense infrastructure.
Municipality of Rotterdam, Department of Municipal Works	Municipal	Drainage system, Public space, Urban infrastructure, Groundwater management	Drawing up Waterplan Rotterdam, Operation and maintenance of sewer system and other infrastructure and public space, Collecting and transporting excess groundwater from allotment boundary.

10.2 Governance structures in the Rhine-Meuse estuary

The Rhine-Meuse estuary is affiliated with two regional programs; Rijnmond-Drechtsteden andZuid-westelijke Delta. The governance structure is complex due to interests, (legal) responsibilities and actor coalitions. The structure between both regions is similar (Figure 10.1) and consist of the following elements (Veraart et al., 2016):

1. The area consultation can be considered to be the most important body and is responsible for 1) monitoring progress of plans in Delta Program, 2) collaboration with the national government, 3) coordination of projects and 4) inspire actors.

    - For Rijnmond-Drechsteden, the following organisations are affiliated: Ministry of Infrastruc-ture and Water Management, Province of South-Holland, Municipality of Krimpenerwaard, Municipality of Molenlanden, Municipality of Hoeksche Waard, Municipality of Rotterdam, Municipality of Dordrecht, Municipality of Brielle, Municipality of Rotterdam, Water Board Hollandse Delta, Water Board Schieland and Krimpenerwaard.

- For the Zuidwestelijke Delta, the following actors are involved: Province of Noord-Brabant, Provinve of Zeeland, Province of Zuid-Holland, Water Board Brabantse Delta, Water Board Hollandse Delta, Water Board Scheldestromen, Ministry of Infrastructure and Water Management and Rijkswaterstaat.

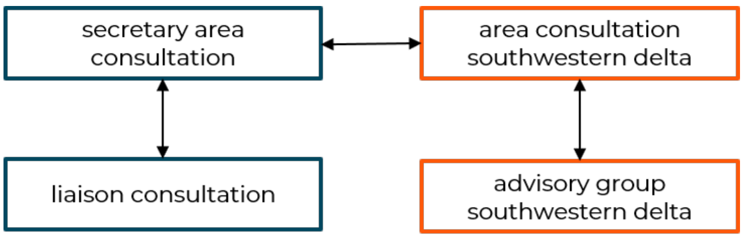
2. Programme team Rijnmond-Drechtsteden has members from Rijkswaterstaat, veiligheidsregio Zuid-Holland Zuid, water board Delfland, water board Hollandse Delta, Port of Rotterdam, Municipality of Rotterdam, Water Board Schieland and Krimpenerwaard, Municipality of Dordrecht, Ministry of Infrastructure and Water Management, Province Zuid-Holland.

3. Advisory groups are often a combination of governmental bodies and interests groups:

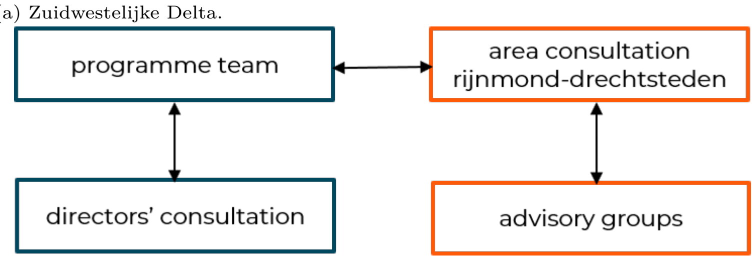
   - It is not entirely clear which organisations are involved in the advisory groups in Rijnmond-Drechtsteden, probably actors related to the following themes: ecology, private parties, fresh water, shipping, environment and landscape.
   - Zuidwestelijke Delta has members from Municipality of Noord-Brabant, Municipality of Zuid-Holland, Municipalities regio Oosterschelde, munciipalities region Zeeuws-Vlaanderen, munipalities region Walcheren, LTO Noord, ZLTO, Brabantse Milieufederatie, Delta overleg, Staatsbosbeheer, Natuurmonumenten, ANWB, Konkinklijke Schuttevaer, EVIDES, HISWA and Blueport.

4. Director's consultation is only applicable to Rijnmond-Drechtsteden. Its aim is to consult the programme team and has members from the Water Board Schieland and Krimpenerwaard, Province of Zuid-Holland, Municipality Dordrecht, Municipality Rotterdam, Ministry of Instructure and Water management, Rijkswaterstaat and Veiligheidsregio Zuid-Holland Zuid.

5. Liaison consultation. It is not entirely clear who is connected to this consultation, but probably people from municipalities, provinces, water boards, Rijkswaterstaat and the ministry of Infrastructure and Water management.



(a) Zuidwestelijke Delta.



(b) Rijnmond-Drechtsteden.

Figure 10.1: Governance structure of regional collaboration of Zuidwestelijke Delta and Rijnmond-Drechtsteden. The boxes with an orange outline depict administrative (In Dutch: bestuurlijke) and the boxes with a blue outline depict official (in Dutch: ambtelijke) consultations.

10.3 Delta Program

The national government, provinces, municipalities and water boards are working together in the Delta Program. The Delta Program performs various projects: implementation programs for strengthening dikes and protecting the coast, making room for rivers and sub-programs investigating what needs to be done on the long-term (Table 10.2). From a network structure perspective, the Delta Program serves as a bridging organization. Bridging organisations act as intermediaries to support networking and cooperation (Gonzales-Iwanciw et al., 2020). The role of bridging organisations is stressed for its facilitation and mediation role to connect local, regional and national collaboratives in multi-level water management (Reed et al., 2010; Johannessen and Hahn, 2013).

On 1 January 2012, the Delta Act went into force. This act stipulates that an annual Delta Program is to be drawn up to ensure that the Netherlands is well protected against flooding and to ensure sufficient freshwater supply. The Delta Fund is connected to the Delta Act and contains resources that are earmarked for flood safety, freshwater supply and other water-related management. The fund aims to institutionally bridge the usual four-year policy cycles and guarantee the long term character of the climate change adaptation measures. From 2020, this fund will be fed by an amount of at least 1 billion euros.
The Delta Commissioner was installed in 2010 and is responsible that the annual report of the Delta Program is drawn up and ensuring that progress is achieved. The commissioner serves as a liaison between (local) authorities, civil society organisation and the private sector. Moreover, the commissioner secures the cohesion between different components of the Delta Program and makes sure that decisions are made at the right time.

Table 10.2: Main programmes and sub programmes of the Delta Program. Sub-programs can be focussed on a particular geographic location or evolve around a particular theme. In this table, the three national programs are depicted along with five regional programs.

Generic subprograms	Objective	Responsible executive
Delta Act (Deltawet)	Provide the legal foundation for the Delta Program, set out the financing plan for the interventions to be taken in the Delta Program	State Secretary IenW
Flood safety	Develop policy to maintain flood safety on a societal and political accepted risk level	State Secretary IenW
Freshwater supply	Guarantee long term freshwater supply including controlling salt intrusion	State Secretary IenW
Regional subprograms		
Coast	Explore boundary conditions for maintaining long-term coastal safety	State Secretary IenW
Rijnmond Drechtsteden	Guaranteeing long-term flood safety and creating boundary conditions for water supply and contribute to sustainable spatial development	State Secretary I en W
Wadden Sea	Sustain long-term flood safety of the islands and the coast	Minister LNV
Zuidwestelijke Delta	Securing climate-proof the long-term flood risk and the freshwater supply	Minister LNV
Rivers	Long-term analysis for the major rivers including strategic alternatives and decisions	State Secretary IenW

10.4 Knowledge Program Sea Level Rise

The Knowledge Program Sea Level Rise is a joint research program of the minister of IenW and the Delta Commissioner. Together with other partners, the program aims to deliver insight on the rate of sea level rise, the consequences for water related challenges and spatial adaptation. The knowledge program is organised in different tracks (Table 10.3). Each track has its own objective and own responsible organization.

Table 10.3: Different tracks of Knowledge Program Sea Level Rise including objectives (Hallie et al., 2020).

Track	Objective
Track I - Antartica research	Reduce uncertainty about the rate of sea level rise.
Track II - System explorations	Determine the resilience of the current strategies and decisions
Track III - Monitoring system	Design a monitoring system to detect signals to adapt to uncertain sea level rise
Track IV - Long-term alternatives	Explore long-term alternatives for climate change adaptation.
Track V - Implementation, participation and communication	Ensure effective communication with involved parties

The Knowledge Program Sea Level Rise has close ties with the Delta Program since the developed knowledge serves as input for the review moment (in Dutch: Herijkingsmoment) in 2026 (Figure 10.2). Moreover, many actors take place in multiple committees and programmes at the same time. In the appendix, a preliminary planning of the knowledge program is included (Figure E.1).

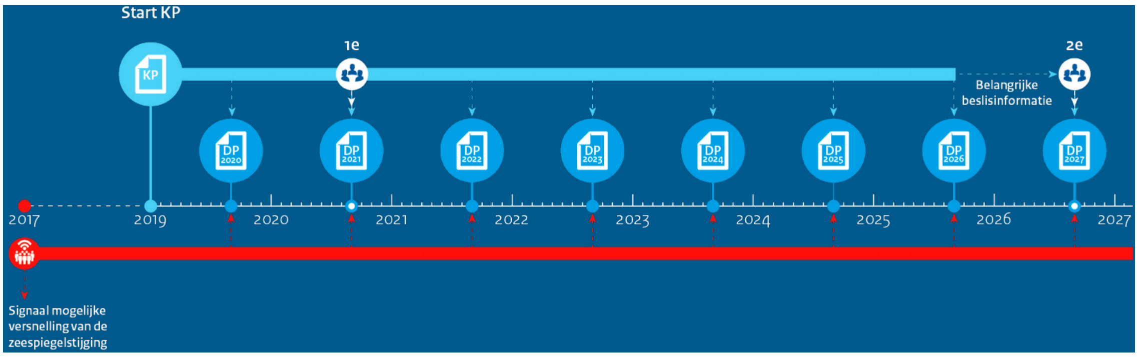


Figure 10.2: Relation between the Knowledge Program Sea Level Rise and the Delta Program. Every six years, a review moment (in Dutch: Herrijkingsmoment) takes place (Ministerie van Infrastructuur en Waterstaat, 2019).

10.5 Interactions between actors and programmes

In Figure 10.3, the relation is shown between politics, sub programmes, regional actors and other involved actors. This overview can be seen as a summary of this chapter and denotes the interactions between actors. In decision-making for coastal adaptation, it is vital to connect disparate knowledge system each pertaining to different actor groups (O'Toole and Coffey, 2013). As can be seen in the figure, the various actors in Dutch delta management are connected to one another. At the same time, this overview does not provide any insight in the quality of those interactions. The factors that are important for increasing the learning potential and decision-making quality are discussed in the remainder of the report.

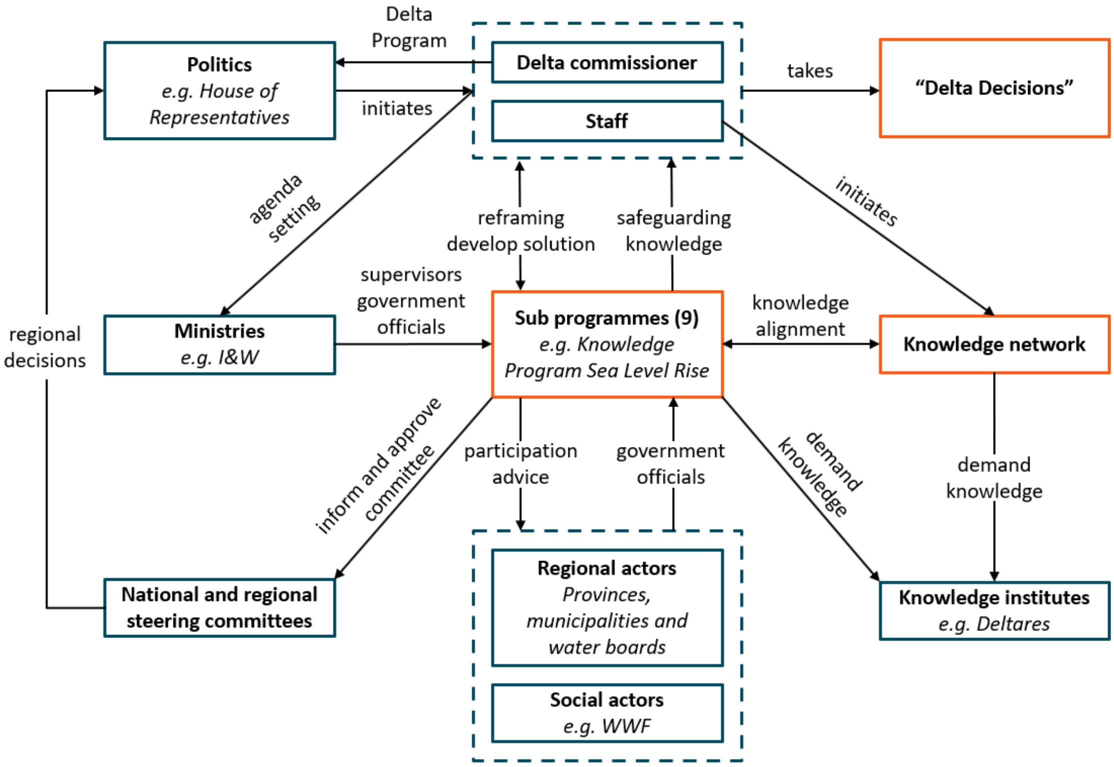


Figure 10.3: Structure of Delta Program and relations to other organisations. Actors and organisations are depicted with a blue outline, while the programs and decisions have a orange outline.

CONCLUDING REMARKS

Many actors are active in the Rhine-Meuse estuary. Those actors carry a wide range of responsibilities. The most import actors from a flood risk management perspective are the water boards, provinces, municipalities, Rijkswaterstaat and Ministry of Infrastructure and Water Management.
The Delta Program plays an essential role in connecting variety of actors and providing funds to finance interventions. The Delta Program consists of three parts: implementation programs for strengthening dikes and protecting the coast as well as making room for rivers as several sub-programs investigating what needs to be done on the long-term. From a network perspective, the Delta Program fulfils the role of a bridging organisation.

Specifically for the Rhine-Meuse estuary, three sub-programmes of the Delta Program are important. The first two are regional sub-programmes: Rijnmond-Drechtsteden and Zuidwestelijke Delta. These sub-programmes play an important role in mobilizing actors in the Rhine-Meuse estuary and realizing consensus about the preferential strategy. The third sub-programme, the Knowledge Program Sea Level Rise, is a national joint research program and aims to deliver insight on the rate of sea level rise, the consequences for water related challenges and spatial adaptation. This program is also one of the case studies and consists of five different tracks that have their own objective and responsible organization.

Chapter 11

Theoretical framework

> Reductionism is the most natural thing to grasp. It's simply the belief that a whole can be understood completely if you understand its parts, and the nature of their 'sum'. No one in her left brain could reject reductionism.
>
> Douglas Hofstadter, Gödel, Escher, Bach: an Eternal Golden Braid., 1979

This chapter aims to gain the necessary theoretical understanding of learning in the context of adaptive delta management. Different strands of literature are combined into a theoretical framework, which answers the following sub-question:

SQ-II.b What theories and frameworks are important in adaptive social learning for delta management?

Recently, the theory of adaptive delta management gained prominence in flood risk management in the Netherlands. This is motivated by two key concerns; 1) society can no longer afford to manage floods and droughts in a reactive manner and 2) existing scenario-planning can not support the dynamic adaptation over time in response to unknown future developments. Although this approach introduces some new features, it must be noted that flood risk management has always had an adaptive character. However, as the rate of change is increasing, the socio-political system in the Rhine-Meuse estuary needs to be able to change faster to remain adaptive. As also denoted by other scholars, learning is key for adaptive delta management (Gersonius et al., 2010; Haasnoot et al., 2015, 2013a; Zevenbergen et al., 2015). So, learning in itself must be adaptive as well, which is the reason why the concept of adaptive learning is coined. Adaptive learning stresses the point that an organization - or group of actors - learns in a continuous and aggregate way.

In building the theoretical framework, concepts from different strands of literature are used. In this way, concepts of (social) learning are connected to the context of decision-making in delta management. The core idea is that adaptive learning should be based on both literature related to decision-making and social learning (Figure 11.1). Additionally, adopting a framing perspective on policy translation enables researchers to uncover how policy actors make sense of policy problems and ambiguous realities, and strategically choose to present particular policy solutions for addressing problems in their own countries and beyond. Hence, literature about framing is included as well.

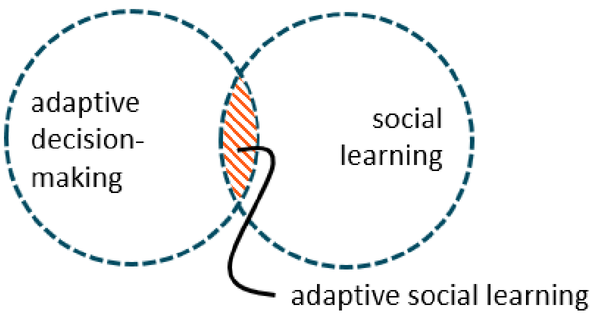


Figure 11.1: Venn diagram illustrating the position of adaptive learning.

Climate change in general and uncertainties in climate change in particular are is a difficult message to communicate to water managers (Tang and Dessai, 2012; Tribbia and Moser, 2008). Consequently, the communication (of uncertainties) from science and policy plays an essential role. This communication takes place on science-policy interfaces (SPI's), which play a central role in this research. Policies about delta management rely heavily on scientific knowledge to provide a basis for decisions, as experts are not only involved in the design and monitoring of flood deference, but also in determining the economic effects of interventions (Turnhout et al., 2008). Although there is a general consensus and empirical evidence that decision-making and social learning are closely linked (Raymond and Cleary, 2013; Yuen et al., 2013), the knowledge about the nature and interplay between adaptive decision-making and social learning is fragmented in literature (Stagl, 2007; Thi Hong Phuong et al., 2017). Hence, this theoretical framework is tailored to examine the interplay between those strands of literature in the context of delta management.

First, decision-making frameworks and theories are discussed related to delta management (Section 11.1). Second, theories about social learning are elaborated (Section 11.2. In the last section, literature related to framing is discussed (Section 11.3). The theoretical notions in this chapter provide a basis for the development of the conceptual model (Chapter 12). The most important notions are summarised throughout this chapter in design briefs (gray text boxes).

11.1 Adaptive decision-making in delta management

Policy-oriented literature mainly had its roots in two perspectives; 1) agenda setting theory, researching the ability to influence the importance placed on the topics of the public agenda and 2) decision making under deep uncertainty – entailing a spectrum of different decision-making under uncertainty frameworks designed for spatial planning in deltas. This strand of literature has close ties to environmental policy making, urban planning and water management. A combination is made between different theories to provide a balance between different aspects of decision-making. Decision-making under deep uncertainty often assume a rational decision-making process with structured actions by decision-maker which makes this literature more prescriptive. On the other hand, agenda-setting theory has a more descriptive character since it takes the chaotic processes in decision-making as a point of departure. The premise is that the integration of both exposes important factors critical for communication.

11.1.1 Agenda setting theory

Kingdon and Thurber (1984) adapted the "garbage can model" of organizational choice to explain the agenda-setting process in the making of public policy. The garbage can model portrays decision opportunities as a garbage can into which problems and solutions are dumped by actors, and where a problem sticks to a solution from time to time (Cohen et al., 1972). Elaborating upon the Garbage can model, the Multiple Streams Framework arose which aims to explain why certain problems (or solutions) receive the attention of policy makers and other problems, or solutions, do not (Kingdon and Thurber, 1984; Howlett et al., 2016). The Multiple Streams Framework considers four streams:

- The first stream - problem stream - consists of the various problem definitions that exist among actors. A crucial mechanism in this stream is framing (Section ??). In this stream actors frame the problem and determine if something needs to be done to change the current situation. It also refers to the evolving public opinion about the relevance or urgency of some issue. In the context of flood risk management in the Netherlands, the majority of the Dutch population considers that the risks are under control. The latest dike reinforcement plans met little resistance. In case resistance became apparent, it is mostly disbelief in new approaches to water management or a clear issue of diverging interests, such as farmers that demand fresh water or people being unwilling to move their house or farm.
- The second stream; the solution stream entails the (technical) solutions developed by experts and highlighted by specific actors. Certain actors bring solutions to the table, in search of a suitable problem frame (Pot et al., 2018). An example would be the Delta21 plan. This plan is developed by experts in the field and currently, the initiators are busy with connecting the solution to the right problem frame. Strategies and technical measures that are generated may circulate for years

without anything being done with them. This stream is typically dominated by technical experts and planners that are often strongly guided by their specific discipline (Lawrence et al., 2015). According to Kingdon and Thurber (1984), ideas that are taken seriously meet three criteria: 1) technical feasibility, 2) fit the national political mood and 3) fit to dominant values within society.

- The third stream - political stream is the collection of political processes and consists of elections, coalition changes and pressure from groups outside of the government. This is apparent in the political will for investment decisions, but also in more awareness and changing perspectives of actors.
- The final stream is the choice opportunity stream which consists of the occasions when organisations are expected to make decisions. These occasions are governed by rules, procedures and norms that guide the decisions. For example, dike trajectories need to be evaluated in certain cycles. This stream has close ties with the rounds model (Teisman and van Buuren, 2000) and dictates the pace of decisions.

Table 11.1: Key-references of agenda-setting theory and garbage can related models.

Model	Key-references
Garbage Can Model	Cohen et al. (1972)
Rounds Model	Teisman and van Buuren (2000)
Multiple Streams Framework	Kingdon and Thurber (1984); Howlett et al. (2016)

11.1.2 Decision-making under deep uncertainty

Actors confront and navigate a world filled with many uncertainties. A number of examples can be found in this thesis, e.g. the rate of sea level rise and technological developments. Scholars in decision-making under deep uncertainty literature state that existing mechanisms do not provide appropriate responses in the presence of deep uncertainty which may yield collectively poor decisions. Several approaches have been developed to cope with deep uncertainty. Since there is a vast amount of approaches within decision-making under uncertainty, only approaches that have overlap with climate adaptation in deltas have been selected:

- Decision scaling researches the best approaches to process and use climate change projections for adaptation planning. As we have seen in Section 2.2.1, numerous projections about the rate of sea level rise have been developed and many more will follow. In practice, adaptation planners are often overwhelmed by the number of climate projections, including emission scenarios, downscaling methods, biases, model selections and corrections. Decision scaling aims to characterize uncertainties in terms of its implications for decisions instead of solely attempting to reduce future uncertainty (Brown et al., 2012). A distinctive attribute of this approach is that it makes use of climate stress testing, which produces an unbiased estimation of the response of the system of interest to climate change. Moreover, it can be incorporated into collaborative processes (Poff et al., 2016).
- Dynamic Adaptive Policy Pathways conceptualizes a plan as a series of actions over time, resulting in a pathway. The premise is that political decisions have a design life and might fail when operating conditions change (Kwadijk et al., 2010). In Haasnoot et al. (2013b), the seven steps of this model can be found. The key advantage of this approach is the framing of pathways which challenges to make the connections between interventions explicit. Similarly, adaptation time is included in a direct way, including thinking about actions that may need to be taken now to keep long-term options open. Moreover, it facilitates decision-making by offering intuitively understandable visualisations of policy options. Dynamic Adaptive Policy Pathways (and other adaptive approaches) are particularly useful when the implementation time is really short compared to the rate of change, when alternative decisions or interventions are possible and when there is flexibility in solutions (Maier et al., 2016).

Adaptation pathway approaches implicitly require tipping points. However, in practice, it is very challenging to determine tipping points, especially for intrinsically flexible strategies and in the absence of precise policy goals (Haasnoot et al., 2017; Bloemen et al., 2019). Furthermore, modelling different alternatives under a wide range of scenarios is computationally expensive. Hence, it remains a difficult task to define (or predict) social tipping points because of the feedback following changes in the technical, economic and ecological systems. Moreover, the greater the uncertainty of the infrastructural project, the greater the value of the opportunity, and the greater incentive to wait and keep options open rather than implement it at once.

- Info-Gap Theory provides a decision theory for prioritising alternatives and making decisions when deep uncertainty exist. Info-Gap Theory states that the planner, decision-maker or designer is confronted with an unavoidable info-gap: the discrepancy between what needs to be known for a responsible decision and what is currently known (Ben-Haim, 2006). It builds upon the idea of satisfycing (Simon, 1956) - when deep uncertainties exist, it is better to achieve a satisfactory or acceptable outcome, rather than trying to reach an optimal solution. A key characteristic of this theory are trade-offs between robustness and outcome requirements; in quantitative approaches, this results in an assessment of cost in terms of reduced robustness. Info-Gap Theory has been applied to many areas. For this research, especially the applications for engineering (Chinnappen-Rimer and Hancke, 2011; Harp and Vesselinov, 2013) and public policy (Hall et al., 2012) is interesting. A challenge is the gap between mathematics and the meaning - or between quantitative and qualitative analysis. Although mathematics is a powerful tool in exploration of reality, incorporation in decisions is difficult when knowledge is predominantly verbal (Ben-Haim, 2006).

- Robust Decision Making represents deep uncertainty by considering system performance under a wide range of futures. Four key elements of robust decision making are: 1) consider multiple plausible and diverse futures, and collect them in an ensemble. The ensemble of futures can also facilitate group processes in exploring different groups' world views. 2) seek robust strategies, rather than optimal strategies. 3) Employ adaptive strategies that are designed to respond to new information. Such strategies can be designed around near-term actions and monitoring actions. 4) Use quantitative models to foster human deliberation over options, actions and policies, not as ranking device for available strategies (Lempert et al., 2013). Robust Decision Making uses a trigger system, a system is modified when a certain threshold is surpassed, which delivers the adaptive. However, it does not provide guidance on how triggers are to be specified (Kwakkel et al., 2016).

- Real options analysis encourages appropriate climate change adaptation and mitigation of investment decisions (Woodward et al., 2011). It allows a decision-maker to change investments when new information comes to the table. In flood risk management, it can be used to address two challenges; 1) what is the most appropriate set of interventions to make in a flood system and when is the best time to make these interventions (Woodward et al., 2014). The approach is applicable to all urbanizing deltas where dikes or other flood protection measures are being planned (Kind et al., 2018). However, real options analysis requires difficult assumptions, a pile of information and considerable effort, and has never been used to support a real decision on flood risk management in the Netherlands (Bos and Zwaneveld, 2017; Kwakkel, 2020).

Table 11.2: Key-references of relevant decision-making under uncertainty models with close ties to adaptive delta management.

Model	Key-references
Decision-Scaling	Brown et al. (2012); Poff et al. (2016)
Dynamic Adaptive Policy Pathways	?Haasnoot et al. (2013b); Kwakkel et al. (2016)
Info-Gap Theory	Ben-Haim (2006)
Robust Decision Making	Lempert et al. (2013); Watson and Kasprzyk (2017)
Real Options Analysis	Woodward et al. (2014)

Decision-making under deep uncertainty prescribes that decision support should move away from trying to define what is the right choice and instead aim at enabling deliberation and joint sense-making among the various parties to a decision (Marchau et al., 2019). Several governance capabilities are required to have the ability to respond to the wicked problem of climate change adaptation. The following capabilities are key in observing and understanding the problem (problem stream), develop strategies to cope with it (solution stream) and institutional conditions to facilitate these observations and strategies (political stream) (Dewulf and Termeer, 2015):

- Reflexivity is the capability to deal with different and conflicting frames (see Section ??) (Termeer et al., 2015). Delta management presents itself as a mess of interrelated problems with different causes, triggers and priorities. Without consensus, it is critical to be able to deal with a variety of frames.
- Resilience is the capability to adapt to unpredictable changing circumstances (Walker et al., 2013). Resilience is a complex concept that is derived from ecological theories and applied to socio-technical systems for the purpose of adaptivity (Folke et al., 2003; Pahl-Wostl, 2007). In a flood risk management setting, it means that strategies have to be functional under a range of different scenarios (robustness), or flexible to be able to adjust strategies as needed (Brugnach et al., 2008).
- Responsiveness is the capability of decision-makers to observe and respond effectively and in a timely fashion (Termeer et al., 2015). This capability is closely related to the agenda-setting theories mentioned before as it deals with linking policy attention to changes in policy.
- Revitalization is the capability to overcome barriers and deadlocked policy processes (Dewulf and Termeer, 2015). The uncertainties and endlessness sea filled with factors and interconnections can be overwhelming. This may lead to frustrating and ineffective decision-making.
- Rescaling is the capability to deal with the multi-scale character of delta management and innovation management (Termeer and Dewulf, 2014; Geels, 2002). Especially the temporal scale mismatch between the temporal scale of sea level rise and governance processses are relevant for this research (Cumming et al., 2006).

DESIGN BRIEF

The combination of agenda-setting theory and decision-making under uncertainty has both descriptive and prescriptive power. The following descriptive elements can be identified:

- It is valuable to assess the chaotic behaviour of decision-makers with the Multiple Streams Framework, consisting of: 1) a problem stream, 2) a solution stream, 3) a political stream and 4) a choice opportunity stream. Hence, this multiple streams framework will form the blueprint of the conceptual model.

The prescriptive elements, according to literature, are mentioned below:

- Adaptive delta management demands: 1) connection between short-, medium and long term objectives 2) embrace uncertainty by taking into account an ensemble of scenarios, 3) explicit addressing of time periods for implementation and construction and 4) integrate the diverse knowledge of the actors involved.
- Adaptive delta management should enhance five governance capabilities that are required to deal with wicked problems: 1) reflexivity, 2) responsiveness, 3) resilience, 4) revitalization and 5) rescaling.

One of the aims of this research is to stimulate adaptive social learning in delta management. Hence, this design brief distilled the ”ingredients” that are necessary to make decision-making process adaptive. The descriptive elements can be used to observe the current decision-making process in the Delta Program and Knowledge Program Sea Level Rise, where the prescriptive elements guide learning processes.

11.2 Social learning and other forms of learning

Literature of learning processes mainly refers to social learning, and to policy and institutional learning. In adaptive systems, continuous learning is required to adapt to changing situations with many uncertainties, complexities, and unknowns (Pahl-Wostl, 2007). McCrum et al. (2009) showed that social learning emerges from knowledge exchange and recognise that knowledge is contested, socially constructed, and used in specific contexts. Social learning can foster the development of innovative solutions by providing opportunities to explore new ideas and testing policy, especially when it is applied in informal settings (Gunderson, 2001; Olsson et al., 2006; van Herk et al., 2011; Jeffrey and Seaton, 2004). This supports the claim that science-policy interfaces are vital in the exchange of knowledge in a network. Social learning can be defined in three ways (Steyaert and Jiggins, 2007):

- Convergence of goals, criteria and knowledge which leads to more accurate and mutual expectations and the building of relational capital. The premise is that when social learning is at work, convergence and relational capital may lead to agreement of concerted action;
- Process of co-creation of knowledge is about providing insight into the causes of, and the means to, transform the situation.
- Change in behaviours and actions resulting from understanding something through action.

So, social learning refers to collective learning in different communities (Folke et al., 2003; Pahl-Wostl, 2007), referred to as social learning systems. Key characteristics of those social learning systems are modes of belonging (Wenger, 2000). The demands and effects of these modes can be both conflicting and complementary, which means that balancing between these modes lead to drastically different social learning systems. The modes are:

- Engagement discusses how people within a system interact and shapes the experience and reactions to interactions;
- Imagination is about forming an image of the social system and the actors' position in it;
- Alignment concern to the extent with which local actions are aligned so that they are effective beyond someone's own engagement. This is closely related to multiple frames, as it is about mutual coordination of actions, perspectives and interpretation of long term goals.

Different communities of practice can be distinguished. Wenger (2000) defines communities of practice as containers of the following competences:

- Joint enterprise concerns enough understanding of the enterprise as a whole to enable members to contribute to it;
- Mutuality is the capability to engage with the community as trusted partner;
- Shared repertoire is about the shared stories, language and resources which have been produced by the community.

Learning happens at boundaries - borders between different communities - and can be bridged in multiple ways:

- Boundary brokers who facilitate the interaction of communities by switching between communities;
- Boundary objects are artefacts, discourses and shared processes;
- Boundary interactions are encounters and events that take place on boundaries;
- Cross-disciplinary projects are about processes and strategies that require and involve actors with different backgrounds.

For learning, it is important that communities are able to understand each other while there is still tension between diverging parties. The effectiveness of learning at policy interfaces can be described by three criteria (Cash et al., 2003; Haasnoot et al., 2018b):

- Salience refers to the extent to which information and knowledge are deemed relevant for the actor. This means that the actors involved find the information and knowledge meaningful;
- Credibility is about technical and scientific believability. Information and knowledge should be convincing to gain the necessary trust of actors. It also connected to the multiple streams framework as it relates to political sensitivity (Bosomworth et al., 2017) and windows of opportunity (Kingdon and Thurber, 1984);
- Legitimacy concerns the perceived fairness of information and knowledge by actors. It is about taking into account all the concerns, expectations and interests in the decision context. Gearey and Jeffrey (2006) argues that legitimacy is pivotal within the context of adaptive water management strategies.

However, stakeholders generally have different perceptions of what makes credible, legitimate, and salient information (Cash et al., 2003; Lemos and Morehouse, 2005; Lemos and Rood, 2010; Dilling and Lemos, 2011).

Boundary organizations play a critical role in bridging different communities by performing four critical functions (Cash et al., 2006). The first function - convening - fosters mutual understanding and trust building by bringing parties together for face-to-face contact. This is the foundation of effective information production, transfer and ultimate use. The second function is translating; making information comprehensible for other organisation and individuals. The third function - collaboration - enables a constructive and transparent dialogue important for developing scientific credible knowledge and for applying this knowledge in reality. The fourth function is mediation; which assures that various interests of actors are fairly represented.

It must be noted that social learning is time intensive and requires the involvement of many stakeholders. In formal settings, actors may feel limited by their position in organisations and agencies. This could limit the potential of learning from each other (Gunderson, 2001). Mostert et al. (2007) conclude that individuals with high technical competence acting as facilitators of the process is one of the most important mechanisms to foster social learning. When applied in informal settings, social learning can facilitate the development of innovative solutions to existing problems by providing opportunities to explore new ideas, devising alternative designs, and testing policy. As such, it plays an important role in connecting actors from different network communities (Olsson et al., 2006) and increases trust, shared norms and values (Rijke et al., 2012). Nevertheless, there is no unified agreement on how to operationalize learning in the publications reviewed.

DESIGN BRIEF

Social learning emerges from knowledge exchange and recognises that knowledge is contested, socially constructed, and used in specific contexts. It describes how information, which is the basis for decision-making, is developed networks of actors. The following insights are important to improve learning processes:

- Modes of belonging: 1) engagement, 2) imagination and alignment;
- Competences in communities of practise: 1) joint enterprise, 2) mutuality and shared repertoire;
- Bridging boundaries between communities of practice can be done via one of the following ways: 1) boundary brokers, 2) boundary objects, 3) boundary interactions and 4) cross-disciplinary projects. Boundary organisation can facilitate bridging and thus play a critical role in learning processes;
- In effective knowledge exchange, information is 1) credible, 2) legitimate and 3) salient.

Social learning governs the knowledge and information that is used to make decisions. Hence, social learning has a large influence on both the content of decisions and how decisions come about. For the conceptual model, the aspects of social learning are included to improve learning processes.

11.3 Framing

Actors' perceptions are based on frames or frames of reference. Frames function as filters through which information is interpreted. They encompass ideas of actors about facts, norms and values regarding their surroundings and the problems and opportunities within it (Van Buuren, 2006). Actors' perceptions possess certain stability since they are formed gradually through experiences. Actors' basic assumptions about reality - deep core beliefs - rarely change (Hommes, 2008). The concepts of frames and framing have been extensively studied in many different fields and from a different point of departure. In this research frames are understood as sense-making devices that mediate the interpretation of reality by adding meaning to a situation (Brugnach et al., 2008). Situations can be framed in various and equally valid ways. An example would be that one actor frames a problem as "insufficient water supply", while another actor states that "excessive water consumption" is the problem. In framing, certain aspects will be highlighted while others are downplayed to get grip on a complex reality. This relates framing to the multiple streams framework discussed in agenda setting theory (Section 11.1.1). Framing provides insight into how actors define problems, construct solutions and gain legitimacy for decisions.

There are two different approaches to frames and framing (Dewulf et al., 2009). The first - Frames as cognitive representations - considers framing as the process of applying cognitive frames to situations. In this approach, meaning to information is allocated by private understanding. The second - Frames as international co-construction - considers framing to be the dynamic shaping of meaning in ongoing interactions, which means that frames are communication structures. Meaning is located in discourses and depends on the reaction of others (Brugnach et al., 2008).

It is interesting to look into knowledge frames and corresponding uncertainty. As denoted before, uncertainties are at the very core of adaptive delta management. Brugnach et al. (2008) state that uncertainty cannot be understood in isolation, but only in relation to the socio-technical system in which it is identified. This relational conceptualisation of uncertainty involves three basic elements: 1) an object or knowledge, 2) one or more knowing actors for whom that object or knowledge is relevant and 3) a relationships between the two aforementioned elements. Based on the nature of uncertainty - ontological, epistemic or ambiguity (Renn et al., 2018; Brugnach et al., 2008) - three kinds of knowledge relationships can be distinguished.

- The first - Unpredictability - states that systems express non-linear and chaotic behaviour, and are sensitive to initial and boundary conditions. Moreover, (socio-technical) systems are constantly learning and adapting to new conditions. Following this reasoning, actors have to accept the unpredictability of the system as it is hard to reduce. Unpredictability is strongly related to ontological uncertainty (Walker et al., 2013).
- The second - Incomplete knowledge - involves the lack of data, lack of theoretical understanding or ignorance. In the case of predictability, uncertainty that comes from incomplete information can be reduced with enough time and means. However, it must be noted that more research and data can also introduce new uncertainties. Incomplete knowledge is related to epistemic uncertainty (Renn et al., 2018; Brugnach et al., 2008).
- The final relationship is called multiple knowledge frames and is characterised by different (and sometimes conflicting) views about how to understand and to manage the socio-technical system. Differences may arise from different (scientific) backgrounds, context-specific experiences, societal positions or ideologies of actors. Several strategies exist to cope with this kind of uncertainty (Brugnach et al., 2008):
  - Communicating uncertainties allows actors to judge the quality of technical expertise and raises awareness among actor;
  - Persuasive communication convinces other actors to adopt a particular perspective;
  - Dialogical learning is based on transparent dialogue. Scholars advocate this approach since it may lead to mutual understanding, trust and reduction of resistance against interventions;
  - Negotiation approach is about reaching an agreement that is beneficial for multiple parties;

- Oppositional modes of action includes avoiding each other or imposing and forcing your perspective on others.

This knowledge relationship is related to ambiguity since it addresses different meaning that is given to the same information (Renn et al., 2018). These relationship can result from multiple phenomena. Decision-makers may have strategic or political motives for adopting certain frames (van den Brink et al., 2010). For example, actors may argue that knowledge is incomplete to delay a decision. Framing can have an agenda-setting character. Moreover, the level of active participation of researchers and policy-makers in learning has varied depending on the framing (Wise et al., 2014).

DESIGN BRIEF

Frames provide insights in how actors perceive aspects in decision-making and how actors filter incoming information. Hence, framing literature is an important addition to decision-making and learning literature. In this research, an relational focus on framing is taken. Three kind of knowledge relationships - related to uncertainty and ambiguity - are distinguished: 1) unpredictability due to non-linear and chaotic behaviour of socio-technical systems, 2) incomplete knowledge comes from incomplete information which can be reduced with enough time and means and 3) multiple knowledge frames is characterised by different - and sometimes conflicting - views about how to understand and manage the socio-technical system. Those different relationships require a different approach to designing learning activities.

Framing literature provides the third building block for the conceptual model as it offers more depth on how decision-making and learning take place in practice. To just provide information to the decision-making arena is not enough to influence decisions. Information needs to be connected to existing knowledge frames in order to become meaningful to actors. Framing literature recognizes that actors have different perceptions about which information is meaningful.

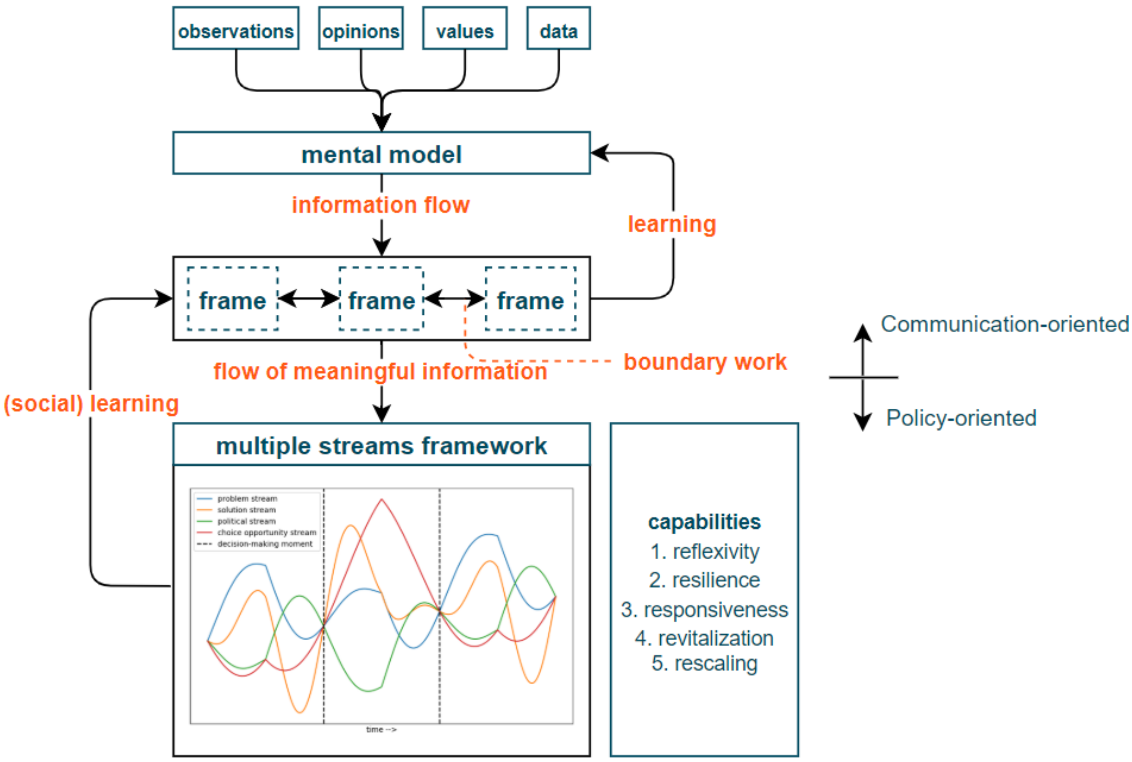


Figure 11.2: Full theoretical framework. This framework shows the communication-oriented processes about frames and framing in the upper part and the policy oriented literature about agenda setting in the lower part. The framework shows the concepts and processes that are involved in the interpretation of observations, opinions, values, data of the real world and translation to the decision-making arena, which is schematized in the multiple streams framework.

Chapter 12

Development of the conceptual model

> Science does not enter a chaotic society to put order into in anymore, to simplify its composition, and to put an end to controversies. It does enter it, but to add new uncertain ingredients [..] to all the other ingredients that make up the collective experiments. When scientists add their findings to the mix, they do not put an end to politics; they add new ingredients to the collective process.
>
> Bruno Latour, From the World of Science to the World of Research?, 2003

In the previous chapter, a theoretical framework is developed. In order to enhance the application, theories and concepts are collected in a conceptual model. This provides an answer to the following sub-question:

SQ-II.c How can the insights from these theories and frameworks be combined in a conceptual model?

The first section elaborates the aim, requirements and premises of the conceptual model. This provides the contextual boundaries of the model and provides a clear point of departure (Section 12.1). Subsequently, the development process towards the conceptual model is shared (Section 12.2). In this way, the choices that have been made along the way are transparent and some extra background to the central notions of the model are provided. This is followed by the lay-out of the conceptual model. Special attention is paid on which elements and processes are described by the model and provide insight in learning processes related to decision-making (Section 12.3). To conclude, some limitations are shared about both the development and application of the conceptual model (Section 12.4).

12.1 Aims, requirements and premises of conceptual model

In order to be useful and valuable, the conceptual model should have a number of properties. Generally, the model is meant to explore the tensions that exist in the decision-making arena and be able to respond to those tensions in such a way that the learning potential is maximized. The premise is that the role of science and expertise in water governance varies corresponding to the dominant framing that is used for the problem, solution and political stream. This means that the features of boundary work also change depending on the framing. Building on this premise, the aim of the model should be:

> **Make the interactions between decision-making and learning explicit within delta management of the Rhine-Meuse estuary.**

Explicit interactions provide clear points-of-departure about the ways learning processes and decision-making interact. Subsequently, the synergy between learning and decision-making can be improved to support adaptive delta management. This leads to the following requirements for the conceptual model:

1. Recognise different frames. The model should be able to describe the decision-making context, and the different (knowledge) frames that are present in the network. This provides the point of departure for selection of the boundary work features that are important for adaptive learning.
2. Sensitive to communication processes. In the end, communication shapes the decision-making process. Hence, the conceptual model should provide a natural connection to communication processes, and particularly to the role of boundary work. Only with this sensitivity, learning processes can be made adaptive. This relates both to the timing and the quality of learning activities.

3. Provide tools for analyzing the current collaboration and deliver guidance for the organizing future collaboration between different actors. The idea is that the model can be used by actors. When actors use the model, they can include their own experience and are flexible in switching between different learning strategies. It is important that those strategies are integrated into the existing planning.

The added value of the conceptual model is that it is both sensitive to aspects that are vital for decision-making as well as factors that are proven to foster learning processes. This is elaborated in the following premises:

- Science is not a separate institutional sphere for independent production of warranted and salient knowledge. Only from a rational perspective knowledge is value free and give decision-makers objective information to make decisions. However, decision-making develops erratic and is hard to predict (section 11.1.1). So, instead of that learning and decision-making are disconnected, the focus is on integrating both fields to provide insight in how and when decision-making and learning counteract or complement one another;
- Long-term science/policy interaction is about mutual knowledge exchange, hardly about uni-linear transfer. Also, more knowledge does not necessarily mean that contradictions are minimized. In other words, more insights and more knowledge lead not directly to consensus in the problem stream, solution stream and political stream. The next section discusses this premise in more detail.
- Both science and politics work to develop new expertise for dealing with new problems through the creation and maintenance of productive knowledge structures. So, different collaborations and actor coalitions are formed over the progress of a project and are subjected to continuous change.

12.2 From theoretical framework to conceptual model

The conceptual model can be seen as an extension of the Multiple Streams Framework presented in the theoretical framework (Figure 12.1). As the Multiple Stream Framework is originating from agenda-setting theory, it is argued that an extension is necessary to meet the requirements regarding communication and learning processes. The streams are defined for the entire network of actors. This means that the streams cannot be traced back to one actor, but rather are comprised of the different perspectives and frames connected to the network itself.

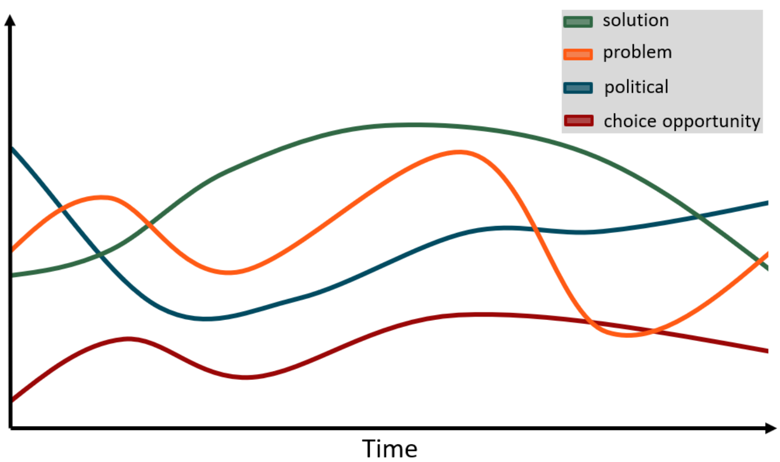


Figure 12.1: Multi Streams Framework. This model consists of multiple streams related to the problem, solution, political and choice opportunity stream. The x-axis represents time, while the vertical axis illustrates whether different streams use the same or complementary frames (small distance between lines), or if actors have disparate or conflicting frames (large distance between lines) (based on (Pot et al., 2019)). Ideally, the streams intersect when decisions have to made. This intersection illustrates that the problems and solutions are aligned, and guarantee sufficient political support.

The model is extended to acknowledge the fact that actors have different knowledge frames (Figure 12.2). This means that there is never one problem and one solution definition. The variety of perspectives on a problem, solution and political level is represented with the bandwidth (instead of a single line). For example, some actors might have a preference for dike reinforcement to adapt to sea level rise, while other actors have a preference for protecting the tidal influence in the Rhine-Meuse estuary. These different perspectives lead to different ideas about the problem and solution for the given situation. For the choice opportunity stream the same principle holds, some actors have a feeling of urgency and want to come up with immediate interventions, while other actors have a different time horizon in mind. Although the timing of some decisions is embedded in an institutional context, actors can still have diverging perspectives on when decisions should be made. A large bandwidth within one stream represents multiple phenomena: 1) one large abstract frame or 2) multiple - complementary or conflicting - frames that are present in one stream.

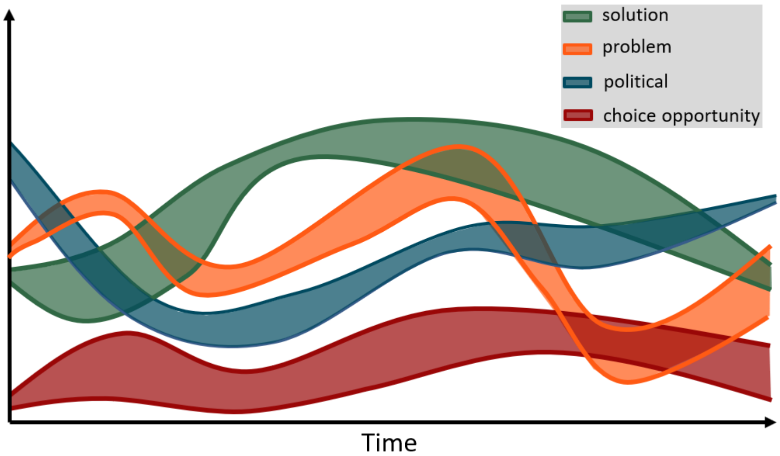


Figure 12.2: Extended Multiple Streams Framework. The difference is originating from the observations that actors - and actor coalitions - hold different knowledge frames and perception on the various streams. Hence, a bandwidth is assigned to the streams.

In time, snapshots can be made of the frames in the decision-making arena. These snapshots can be seen as cross-sections of the previous figure. The most interesting feature of the snapshots is that they illustrate the overlap between the different streams. The basic idea is that the overlap between the streams is a key characteristic in reaching consensus. The overlap illustrates that there is common ground to take decisions which agree with the frame of the problem, solution and political stream. This is elaborated in more detail in the remainder of this chapter.

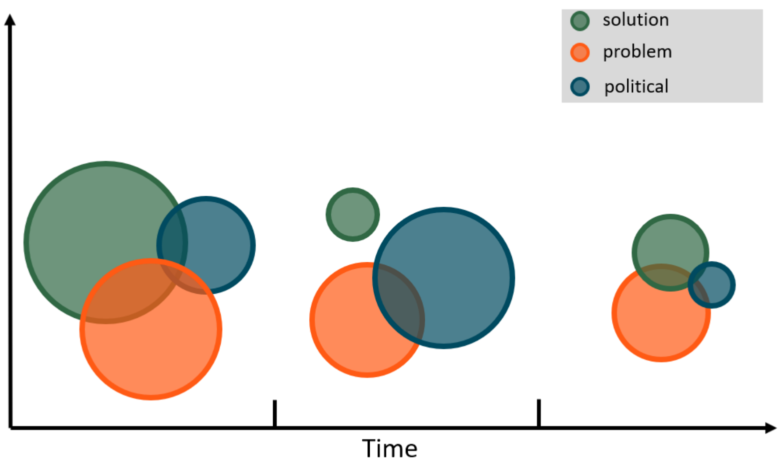


Figure 12.3: Illustration of snapshots. The snapshots are visualisation of cross sections in the multiple stream framework. An attentive reader will notice that the cross section of this plot are not corresponding to the location of the snapshot of Figure 12.2.

12.3 Lay-out of the conceptual model

As noted in the requirements (Section 12.1), the conceptual model should explore the interplay between framing, decision-making and learning. The conceptual model consist of three parts:

1. Framing. In the conceptual model is related to the frames that are imposed and communicated by actors. In other words, actors consciously or unconsciously share their frames with other actors. For example, the Delta Program frames the problem and solution direction in a particular way to support collaboration and to steer the learning processes.

2. Core. In the core, the cross-sections, indicated with bubbles, are formed. These bubbles are gathered frames that can be (arbitrarily) divided into different streams, corresponding to the problem, political and solution stream. As denoted, the (lack of) overlap provides insight in whether consensus exists among the stakeholders. Often, the overlap is guided by a particular narrative or line reasoning;

3. Decision rhythm. The bottom part indicates that decisions are made all the time, in an irregular and inferior manner. However, as noted before, the choice opportunity stream gives information about the expected rhythm by actors. In other words, decision-makers are obliged to make decisions according to certain procedures, policies and laws. The decision rhythm is important as it creates a sense of urgency and also challenges to define goals that need to be satisfied. For example, the yearly Delta Program stimulates to draw conclusions about the current activities and which steps are needed to satisfy the objectives of the Delta Program.

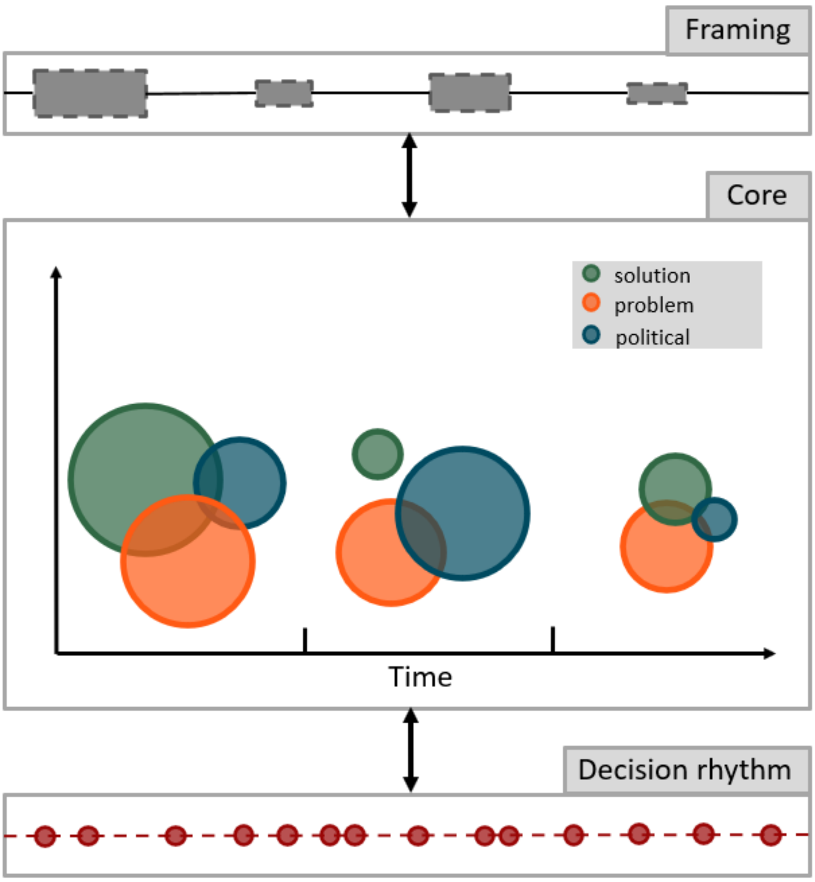


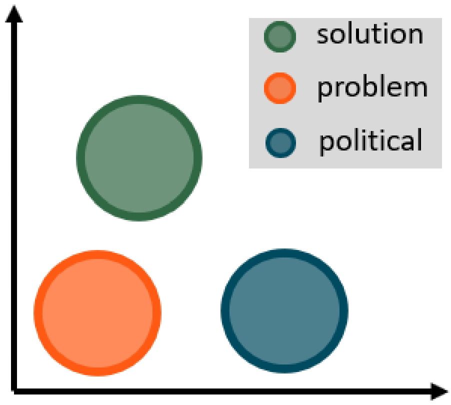
Figure 12.4: Conceptual model including the different streams of the multiple streams framework. The core of the conceptual model with the circles is originating from the extended multiple streams framework.

12.3.1 Characteristics and states of the conceptual model

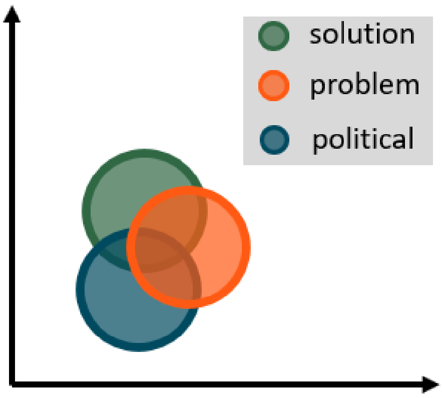
The core part is the most interesting and complex part of the conceptual model. In this section, the characteristics and behavior within the different streams is interesting. As stressed before, decision-making and learning are both very dynamic and erratic processes. Hence, the location and size of the circles will change over time resulting in overlap or more disparate frame collections.

- Location. The location of the circles determines the distance between the circles. When the circles are closer to each other, there is more chance for overlap between the circles. As noted before, the degree of overlap is corresponding with consensus.
- Size of circles. The size of the circles is corresponding to the degree of consensus within one stream. Multiple (conflicting) knowledge or value frames will lead to a large radius.

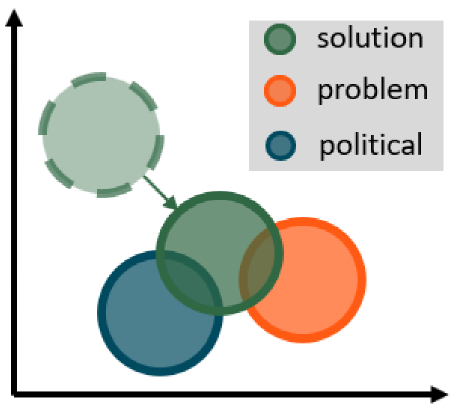
This results in many different states. A state can be seen as a snapshot of the frames in time. Interesting is that a variety of states can occur. In Figure 12.5, some states are illustrated. In Figure 12.5a a is described in which the solution, problem and political stream are far apart. This corresponds to a situation with little consensus between the streams. The opposite would be that the circles are completely overlapping. Although this presents a firm base for decisions, it is detrimental to learning as it rules out any tension between the streams.



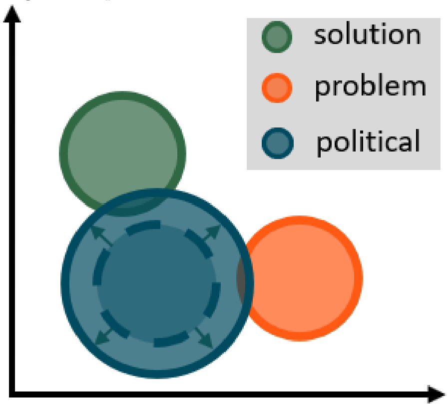
(a) No overlap between streams.



(b) Large overlap between streams.



(c) Searching for overlap by decreasing distance.



(d) Searching for overlap by increasing size. In this illustration, the size of the political stream is increasing leading to overlap with the problem en solution stream.

Figure 12.5: Different states and possibilities for change. The top figures represent a steady state both with and without overlap. The figures on the bottom indicate possibilities for movement.

12.3.2 Balancing the act of convergence and divergence

Streams are modelled with a certain bandwidth that develops over time. This bandwidth represents a variety of ideas, visions and discourses within a stream. A change in bandwidth indicates that learning has taken place; actors have changed their perceptions of the situation. Large consent refers to a small bandwidth, and vice versa. Over time, consent can change in the following ways. In essence, convergence and divergence explain something about the direction of learning within the network:

- Convergence. This means that the bandwidth decreases over time. It represents that the scope, within a stream, becomes smaller. This means that consensus within a stream is larger. An example of the solution stream could be that there is one plan that gains the support of the majority of actors involved. Note that a small bandwidth of one stream does not necessarily mean that there is overlap with the other streams. Convergence is about selecting. Van Der Wal et al. (2013) use changes in convergence of actors perspectives over time to describe and measure learning. This shows the connection of the conceptual model to the aspects of social learning mentioned in the theoretical framework (Section 11.2).
- Divergence. Contrary to narrowing, the bandwidth becomes larger over time. Widening is not necessarily negative; it allows more opportunity for overlap with other streams which can be beneficial for the decision-making process. For example, widening indicates that actors allow more ambiguity in the socio-technical system. This is not necessarily negative. On the contrary, ambiguity is an opportunity for change as it has the power to produce a shock among involved actors that motivates them to engage in joint sense-making. So, divergence is related to:
    1. Goal stretching; relating goals from a programme to other goals that an actor might have.
    2. Issue-linking; associate two existing issues to each other. Those issues are not necessarily within the same system, but could be part of different systems.

Alternating between diverging and converging leads to maximizing of the learning potential and reaching decisions that have a solid knowledge and political legitimate base. In the perspective of the conceptual model, divergence and convergence to complement each other. This is illustrated in Table 12.1. While divergence is good in relating different goals and foster an integral approach, its susceptible to indecisiveness and negotiated non-sense. Converging stimulates to select and determine the order of preference for different choices. At the same time, too much convergence leads to path-dependencies and lock-ins. When actors focus too much on realizing agreement without critically exploring other options and reflecting on former decisions, this could lead to grey compromises and postponed conflicts in the implementation phase.

Table 12.1: Summary of directions in conceptual model including susceptibilities.

Direction	Related to	Susceptible for
Divergence	Varying Goal-stretching Issue-linking	Indecisiveness Negotiated non-sense
Convergence	Selecting Negotiating Prioritising	Path-dependency Fact-fighting Controversies

12.3.3 Adaptive social learning

The idea of the conceptual model is that learning practises can be tailored to the decision-making situation at hand, resulting in adaptive social learning. Learning activities can be tailored to whether convergence or divergence is preferred. Furthermore, it can also be used to evaluate learning practises. It might turn out that learning leads to more different knowledge frames or that actors are not reaching common ground. These conflicting frames and strategies can be seen as a necessary complement of collaboration for actors who want to maximize the gains of a collaborative process. It also helps when actors hesitate to participate in a collaborative process as conflictive strategies can motivate them to participate in the collaborative process (Warner and Van Buuren, 2009). Adaptive social learning shapes the conditions and boundaries for conflictive frames which are contingent to the collaborative process.

12.4 Limitations of the conceptual model

The conceptual model provides a train-of-thought on how decision-making and learning interfere with delta management. It is tailored to describing the processes of divergence and convergence in designing strategies for delta management. At the same time, it still refers to a rather high abstract level which makes concrete application not easy on first sight. Moreover, as the model is originating from agenda-setting theory, the conceptual model is primarily tuned to describe decision-making processes. The conceptual model alone has limited predicting or prescribing qualities on what adjustments could be made to foster learning. Hence, it delivers limited guidance for actors on how future collaboration must be organized to enhance adaptive social learning. To be able to develop concrete recommendations, more knowledge about the circumstances and other case specific knowledge is required. In the remainder of this research, the conceptual model will serve as a lens to view the decision-making in the Rhine-Meuse estuary. With the observations about the Delta Program (Chapter)and Knowledge Program Sea Level Rise (Chapter 14). Although the conceptual model alone does not provide clear guidance on the design of learning activities, it is expected that the combination of the conceptual model with case-specific information about actors, interests and perspectives will provide insights that are valuable for adaptive social learning.

Chapter 13

Learning in the Delta Program

The conceptual model will be applied to the case study of the Delta Program. This case study research should be seen as a preliminary case study that aims to explore the usefulness of a relatively untested framework. This case study type shows many similarities with a plausibility probe case study (George and Bennet, 2005). This type of study serves as a test to explore whether a model can provide meaningful explanations of the phenomenon under study. Theoretical notions are compared with empirical analysis and answers the following question:

SQ-II.d How is the concept of learning defined and used by the Delta Program?

13.1 Longitudinal analysis: frames over time

The objectives, preferred solution directions and discussions at the tables of the Delta Program change over time. In the light of the conceptual model, the frames in the problem, solution and political stream alter. In this section, the frames that are applied in the Delta Program are analysed and grouped in different phases. These phases correspond to the rhythm of the choice opportunity stream (Figure 13.1, 13.2 and 13.3). As noted before, the choice opportunity stream guides when it is expected from organisations to take decisions. To analyse this process, a chronological narrative of events and decisions was developed. The narrative described what happened when, with what content, and with whom to reveal the entire decision-making process. Based on the perennial revision of the Delta Program, four phases can be distinguished. Those phases are analysed subsequently. The main aim of this analysis is to analyse the interplay of learning and decision-making. The interactions in framing assist in understanding some of the relations between learning and decision-making. Furthermore, this longitudinal analysis provides an extended background for inducement of the second case study; the Knowledge Program Sea Level Rise.

13.1.1 Phase 1: Initiation (2007-2011)

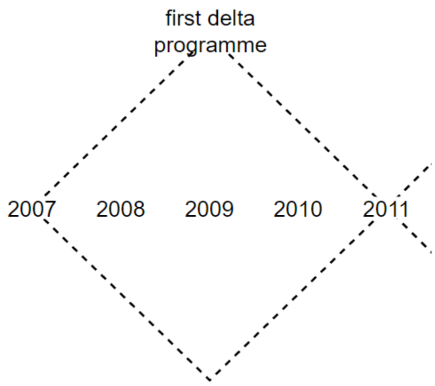


Figure 13.1: Rhytm of Delta Program in phase 1 (2007-2011). One major revision - in 2011 - took place in this phase.

Although the every-day risk of flooding was limited, new challenges arose that compromised the feeling of control. Especially, soil subsidence and climate change were recognised as important long term challenges for water management. Actors from both the private and public sector had the feeling that something should be done, but there was not yet a consensus of what interventions were needed. The idea that a new vision had to be developed gained attention. Some stressed the need for renewal of existing flood defenses, while others questioned the focus on prevention and argued that controlled flooding should be an option as well.

In this phase, the political stream is clearly dominant. Hurricane Katrina, which flooded New Orleans (USA) created a renewed sense of urgency. As the safety norms are embedded in the law, this discussion had a large political component. Eventually, the Dutch Senate (In Dutch: Eerste Kamer) accepted a resolution that the government should revise and strengthen its vision on long-term flood risk management and explicitly take climate change into account. This ”Water Vision” advised to establish a committee to investigate coastal flood protection, in the view of the changing climate. The committee got the following assignment based on four subjects (Cabinet Balkenede IV, 2007; van der Steen et al., 2016):

- The interaction between increasing expected sea level rise and discharge of the large Dutch rivers, and the social developments until 2200;
- The implication of those developments for the Dutch coast;
- Possible strategies for a coherent approach;
- Indicate the social value and flood risk reduction of these strategies for the short and long term.

The (political) framing of the assignment is rather wide. This both reflected in the time horizon of 2200 and the inclusion of social development. The political character is furthermore reflected in the appointment of the chair, Cees Veerman. This former minister and professor was known for his skill to reach consensus between a variety of actors in both the public and private sector. The committee consisted of prominent members from different sectors such as spatial planning, investment theory, system science and coastal engineering. This is in line with principles of boundary management, that state that it is important to recruit members from all sides of the boundary is important (Guston, 2001).

The committee started with a redefinition of their own assignment. They revised the assignment along three lines:

1. The time horizon of 2200 was too long to come up with projections and make a sensible claim about uncertainties. So to be foster the frame in the problem stream, the committee considered that 2100 would be a more appropriate time horizon;
2. Furthermore, the committee thought that a shorter time horizon would benefit the societal and political urgency. In other words, a shorter time period would help to keep the attention on the political stream;
3. The original assignment was focused on the coasts. However, it became clear that climate change will induce problems along the river as well, hence the committee extended the geographical scope;

One of the main frames that is adopted by the Deltacommittee is the crisis narrative. The crisis narrative is stressing that the floods that happened in the past: ”The disastrous floods of 1953 are still etched into our collective memory;” and ”Our Committee’s mandate is, therefore, unusual: we have been asked to come up with recommendations, not because a disaster has occurred, but rather to avoid one.” This crisis narrative is urging to take action (Delta Committee (2008b), p. 10):

> ”Implementation of the recommendations is a matter of urgency. The Netherlands must accelerate its efforts because at present, even the current standards of flood protection are not being met everywhere. Moreover, the current standards are out of date and must be raised, the climate is changing rapidly, the sea level is probably rising faster than has been assumed, and more extreme variations in river discharge are expected. The economic, societal and physical stakes in the Netherlands are great and growing still; a breach in a dike has seriously disruptive consequences for the entire country. ”

This crisis narrative was successful as it creates more room for decisive action of politicians. Once an issue or situation is framed as a crisis, resistance can be easily neutralised by arguing that crises ask for robust interventions. This can also be observed in this case. Critics argued that the committee exaggerated the predictions and neglected uncertainties surrounding the predictions. This discussion mainly centred around the financing of the Delta Fund (Verduijn et al., 2012). However, the frame presented by the committee is relatively easily accepted, including the problem definition, diagnosed causes and suggested remedies.

In other words, it can be observed that particular political framing can benefit reaching consensus in the problem or solution stream. Besides the crisis narrative, also a adaptation narrative becomes apparent. In this narrative, the logic is that climate is changing and that the Netherlands should adapt to this change (Delta Committee (2008b), p.5):

> ”Climate change is now forcing itself upon us: a new reality that cannot be ignored. The predicted sea level rise and greater fluctuations in river discharge compel us to look far into the future, to widen our scope and to anticipate developments further ahead.”

Over history, the crisis narrative is mainly apparent in cases of disaster. No disaster has happened in this case, making it additionally hard to establish a crisis narrative (Delta Committee (2008b), p. 77).

> ”The Committee realises that its message is a difficult one: after a disaster, there tends to be a widespread feeling of urgency that something must be done to prevent a repetition of events. (...) The general public takes it for granted that the government guarantees its protection against flooding, but the public does not see the matter as urgent, or of high political priority. The people of the Netherlands are not apprehensive of a natural catastrophe; the risks of climate change are only gradually becoming manifest and there is a general feeling that effects will only be felt in the distant future.”

Similar to the crisis narrative it calls for action. However, it does so with a more neutral point of departure: ”The Dutch delta is safe, but preserving this safety over the long term involves action now” (Delta Committee, 2008a). The strength of this narrative is that it focuses on solutions. The logic is that discussion about the problem is unnecessary as it cannot be denied. Hence, in this narrative, the solution stream is in favour over the problem stream.

13.1.2 Phase 2: Towards the first Delta Decisions (2011-2015)

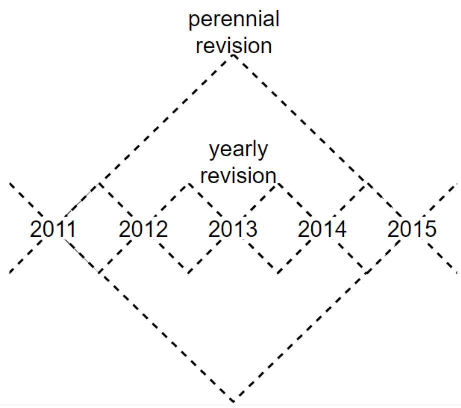


Figure 13.2: Rhytm of Delta Program in phase 2 (2011-2015). From 2011, each year a Delta Program is published which can be seen as a yearly updated or revision. In 2015, the Delta Decisions are published, which marks one of the most important publications of the Delta Program.

The second phase is working towards the Delta Decisions. The Delta Decisions are general agreements about the major changes that have to take place in the water system of the Netherlands in order to satisfy the objectives and flood risk norms. In 2015, five Delta Decisions have been taken (Delta Commissioner, 2015): 1) delta decision flood risk, 2) delta decision fresh water, 3) delta decision spatial adaptation, 4) delta decision Rhine-Meuse estuary and 5) delta decision Rhine-Meuse estuary. Together, the delta decisions present the answer to new future challenges. This analysis focusses not so much on the content of the decisions, but on the process towards reaching support. From the first programme onwards, an integral approach is advocated by the Delta Program. In the Delta Program, the integral approach is defined in the following way (Delta Commissioner (2012), p.70):

> ”Pro-actively seeking possibilities to link physical implementation of the Delta Program with tasking in other policy fields in the same area, e.g. spatial quality or the natural environment.”

Many sub-programmes of the Delta Program are aimed to foster an integral approach. Among others, this becomes apparent as inter connectivity between programmes is stressed throughout the Delta Programs (Delta Commissioner (2010), p.21):

> Considering the aforementioned relationships, it is essential that all measures and provisions for safety and availability of water be examined together. The Delta Program does this in a number of ways, such as with its Delta Decisions and the consistent direction from the Delta Commissioner.

It is commonly believed that this integral approach leads to more complete and effective solutions in water management. Although the integral approach is for many intuitively easy to understand, the integrality narrative can be considered to be a complex narrative that is used rightly and wrongly (Biesbroek et al., 2014). It is known to be an important vehicle to denote meaning to (policy) processes. Hence, the trap occurs that a solution resulting from a integral approach is necessary the best solution. It is hard to resist against an integral approach, which results in a consensus that is apparent. However, a more in-depth analysis learns that multiple conflicting frames about integrality are present among actors:

- Integrality as win-win. In some cases integrality is presented as a win-win approach. The interests of multiple actors on various scales can be merged into a win-win strategy. In this way, added value can be generated (Delta Commissioner (2012), p.80) :

  > ”Added value at lower cost can be achieved by combining functions. Well-known examples of cost-efficient function combinations include a flood defence system with a road on or next to it, or the combination of excavating and processing soil. Cost-efficient combinations with private functions are also conceivable. Looking for cost-efficient function combinations has high priority for the Delta Program and its administrative partners. It is also in line with the integral method of the Delta Program.”

- Integrality as a viscous and inefficient process. At the same time, some actors qualify integrality as a time-consuming process which is not effective. They associate integral approaches with the unnecessary involvement of more actors and ever increasing complexity of policy processes. This stream is mostly not surfaced, but more a underlying feeling of actors.

Both frames have the power to challenge the integral approach of the Delta Program. The Win-Win integrality by framing integral approaches as ideal for each and every situation. The other frame by resisting the tendency to adopt an integral approach, among others by fragmentation of budgets.

Knowledge seeking is key in problem framing. Knowledge could advocates for certain points of view and can support particular ways of reasoning. The Committee commissioned further research by the Dutch meteorological institute (KNMI) to come up with climate scenarios that were tailor made for the Dutch Delta. The Commitee based its argument on the KNMI scenarios, which stressed that the risk was higher than the original IPCC-scenarios (Attema et al., 2014). This further substantiated the need for urgency that was coined in Phase 1. However, employing scenarios with a particular frame in mind can lead to overestimating (Enserink et al., 2013). This further stresses the interaction between the different streams of the model. A converged problem stream (one-specific scenario) enhances a particular solution direction. Hence, the knowledge agenda that is presented along with the Delta Decisions is interesting (Delta Commissioner, 2015).

13.1.3 Phase 3: Adaptation to main the status quo? (2015-2021)

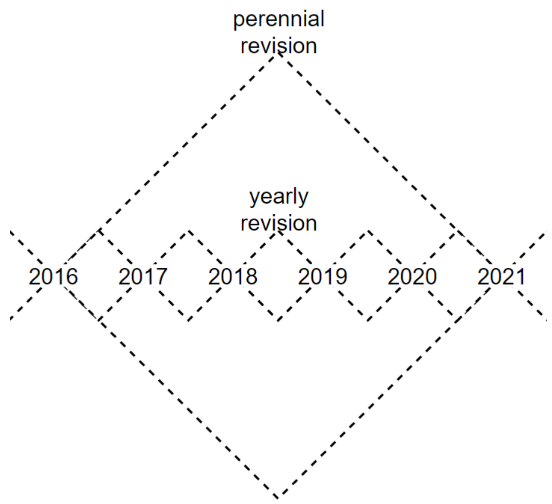


Figure 13.3: Rhytm of Delta Program in phase 3 (2015-2021). Besides the yearly revisions, the perennial revision is introduced.

Recent research on the rate of sea level rise (Section 2.2.1) and droughts in 2018 and 2019 raises the pressure on the preferential strategy which is stated in the Delta Decisions. At the same time, some interventions started such as the High Water Protection Program (In dutch: Hoogwater bescherming programmal; HWBP). For the first time, a moment is planned to evaluate if the strategy needs to be revised (in Dutch: Herijkingmoment). From now on, every six year an perennial revision is planned.

In previous phases, the delta program was mainly concerned with the collaboration between different parties and performing (or outsourcing) research to gain more understanding of the water system. The challenge in this phase is to put the principles of adaptive delta management - which is developed in the first phases - in practise (Delta Commissioner (2017), p.135):

> ”Within three years (by no later than 2020), the governments will have drawn up implementation and investment agendas for their regions, based on the adaptation strategy. These agendas set out the agreements regarding the efforts to be expended by each party, based on the dialogues.

Simultaneously, research is performed to determine the development of the main drivers such as sea level rise, socio-economic development and third-party actions. Adaptive delta management is currently translated into no-regret measures (Delta Commissioner (2017), p.135):

> ”And at locations at which bottlenecks have already been identified, the parties will take no-regret measures in anticipation of the vulnerabilities analysis and the dialogue.”

No-regret measures are interventions that are and remain beneficial no matter the development of drivers. These measures are attractive because it enables parties to make legitimate decisions. Nonetheless, it is not guaranteed that no-regret measures alone are sufficient to adapt to climate change. As mentioned in Chapter X, there are several adaptation options for the Rhine-Meuse estuary. To enable decision-makers to choose a particular option, they need to be informed. The complex character of the water system, as denoted in the physical perspective, makes it hard to define causal relations. Hence, more research is needed about the effects of different adaptation options.

Nonetheless, the focus of this phase is on the implementation of current interventions as major research reports are partly outdated. Hence, multiple parties find that more (fundamental) knowledge needs to be developed to be able to make a choice if the preferential strategy needs to be revised. In that light, it is very interesting to see what the Delta Program will publish in the Delta Program 2021. Form the first phase onwards, the story of the Delta Program was about preventing a crisis by adapting in time. Different measures have been proposed and implemented, but the main strategy remained unattached. Pelling et al. (2015) state that adaptive actions can be categorized by intended outcomes: some are resistant and reinforce existing pathways; some are incremental causing non-threatening adjustments; and some are transformational causing fundamental changes. Uptil now, the adaptive actions are mainly of a resistant or incremental character. Hence, the question might arise if the Delta Program is capable of taking transformational adaptive actions, or if the approach of the Delta Program only allows for small adaptation steps.

13.1.4 Comparative analysis

The long-term character of the Delta Program has been unique for its involvement of different (coalitions of) actors and its approach to create shared meaning. The three stages involved different actor configuration and expectations. The Delta Committee, later turned into the Delta Program, succeeded in achieving two things. First, the Committee managed to raise awareness for flood risk safety in the light of climate change. Although no actual flooding occurred, the Delta Committee gained attention by presenting a crisis narrative. The second conclusion is that the Committee, to a large extent, the frames posed by the Delta Committee were accepted by the water professionals and the public. This acceptance of frames is mainly set for the problem and politics stream, and not so much for the solutions streams. As the Delta Program increased in terms of involved actors and the number sub-programs, differences in narratives started to appear. Some actors stress the need to switch, at some time in the future, from incremental to transformational strategies but that there is little reflection on how this switch can be made.

CONCLUDING REMARKS

The frame and used narratives of the Delta Program changed over time. Three phases have been identified. The conclusion of first phase is that, even though no flooding event occurred, the committee succeed in achieving three things:

1. The report of the committee resulted in creating awareness and set the adaptation to climate change on the political agenda;
2. The committee managed to get their political frame accepted by other actors;
3. Along with the accepted political framing, the committee already gained some progress in converging the problem and solution stream.

The crisis narrative and climate adaptation narrative played a major role in Phase 1. These narratives played a major role in framing the problem and provided a general solution direction.

The second phase was about developing and gaining support for the Delta Decisions. The integrality narrative was key in this phase. This means that large actor coalitions are involved and the Delta Program looked for explicit interaction between different fields. However, the integrality narrative is also a complex narrative as multiple frames about integrality exist:

1. Integrality as win-win. Interests and ideas of multiple actors on various scales can be merged into a win-win strategy;
2. Integrality as a viscous and inefficient process; some actors qualify integrality as a time-consuming process which is not effective in finding solutions.

In the third phase the shift from plan formulation to implementation has been made. Major dike reinforcement programs have been launched and national agreeements are regionally implemented. At the same time, the first perennial revision is prepared, which is mainly focussed on the question whether the preferential strategy still suffices in reaching the objectives. To answer this question, it is argued that fundamental research about the water system should be intensified. Furthermore, although the adaptive management approach is internalised by the Delta Program, there are no signs that this approach leads to transformational changes in the preferential strategy.

13.2 Types of learning

Note: provide concrete examples of reports, sessions, activities etc that belong to a specific kind of learning. Moreover, include more details to make the results more tangible and attractive.

The term "learning" is used extensively in the context of the Delta Program. In this section, the use of the concept of learning is analysed by a extensive document analyses of the different Delta Programs, and related background documents (Appendix D. Four different frames of learning can be distinguished: 1) scientific learning frame, 2) the joint fact-finding frame, 3) the cross-project learning frame, 4) learning by doing frame and 5) system learning frame.

13.2.1 Scientific learning frame

In this approach the focus is on sound science, building an evidence base and doing (technical) studies and investigation to construct a firm foundation for decisions (Delta Committee, 2008b):

> "The Delta Committee sought scientific advice on a number of aspects, which form part of the present recommendations. In summary, these are the findings of a group of national and international experts, including those close to the IPCC and Dutch experts on flood protection and water management. This group of experts has supplemented the latest insights into climate scenarios, and come up with new estimates of extreme values."

This frame is mostly about increasing knowledge of the system at hand. Some actors find this frame pragmatic, as it has the tendency to focus on technical studies and quantitative analyses.

> "The pragmatic approach has yielded various lessons to be learnt: take an extra good look at the functions over which the government has authority."

The scientific frame is quite dominant in Phase 1 (2007-2011). In this phase the emphasis is on the performance of the water system under high-end sea level scenarios. The current phase of the Delta Program is more centred around the implementation of policies (e.g. the HWBP). This also resulted in a decrease of in-depth scientific studies about long term developments and possible solutions. Nonetheless, there are investigations about long term impact and solutions, but does investigation have a more preliminary approach (e.g. hackatons or quick scans).

13.2.2 Joint-fact finding frame

Uncertainties of rate of sea level rise, spatial developments and (fresh) water shortages are central in the Delta Program. The joint-fact finding frame is based on the idea that actors might have different perspectives on uncertainties. Hence, new knowledge has to be created together (Delta Commissioner (2010), p.44):

> "A collective approach to developing knowledge increases the quality and the support base of the solutions, which is why (...) considerable importance is attached to such methods as joint fact-finding."

The aim of joint fact-finding is defined as optimizing (DP2010, p.44):

> "The collection and use of knowledge from all stakeholders and to create a broad support base for newly generated knowledge."

Joint fact finding offers a mechanism to bring together actors and decision-making to build a common base of knowledge to inform delta amangement decisions. Joint fact finding promotes integration across various disciplines and organisations, as also reflected in the Delta Program (DP2014, p. 106):

> "Professionals from knowledge institutes, universities and research programmes can make their knowledge available on Deltaweb, whilst also learning about other colleagues' findings. This accelerates knowledge exchange and contributes to quality."

13.2.3 Cross-project learning frame

The logic in this frame is that learning should be based on best practices of other projects. Furthermore, obstacles that are encountered in projects should be connected to one another and approach in a more integral way. This is especially visible in the Flood Protection Program (In Dutch: Hoogwaterbeschermingsprogramma (HWBP); DP2016, p. 56):

> ”[..] using lessons learnt in programmes such as HWBP-2 and Room for the River.”

Cross-knowledge of all projects is beneficical in preventing similar problems to occur and to transfer experiences and knowledge from one project to another (DP2018, p.84):

> ”Lessons learnt in the Wadden Sea Dykes General Exploration are already being put to use in dyke improvements.”

Cross-project learning involves two basis steps; 1) first one needs to capture important lessons learned and 2) making effective use of them. Cross-project learning is complicated by discrepancy in projects and fragmentation of knowledge among others. The Delta Program is very fond of cross-project learning. However, it remains unclear in what way this is organized in practice and if all involved actors have access to lessons learned.

13.2.4 Learning by doing

The learning by doing frame stresses that learning takes place by undertaking activities. Learning is achieved through practice, self-perfections and a series of minor innovations. (DP2018, p.83)

> ”The pilot is intended to examine whether this method of providing the coast with the required volume of sand will cause less nuisance and disruption to the environment and nature than traditional sand replenishment.”

DP2020, p. 67

> ”This sum is supplementary to the ongoing incentive programme. It is intended for pilot studies [..] the knowledge acquired will be made available through the Knowledge Portal and the Climate-proof Together Platform.”

13.2.5 System learning

This is more about learning how to learn and is related to initiatives that are about reflection and focus on learning itself. In literature, this is often referred to as triple-loop learning. In the Delta Program, system learning often takes place in the form of evaluations, illustrated by the following quote (DP2017, p.59):

> ”To substantiate this process, the Delta Program is developing the “monitoring, analysing, acting” system. DP2016 has set down the outlines of this system and the past year saw an initial elaboration. The Netherlands Environmental Assessment Agency, the University of Amsterdam, and Delft University of Technology have jointly produced an advisory report* on the subject.”

Sometimes, spin-offs originate from those evaluations, such as ”Leergemeenschappen Water en Ruimte”.

13.2.6 Relation to conceptual model

From the conceptual model, it follows that the various learning types have a different influence on decision-making. Scientific learning is mainly reflective and can have both abstract or concrete properties. For instance, paper about adaptive delta management tend to make use of concepts in literature (abstract), while technical studies try to quantify particular phenomena (concrete). Joint-fact finding also makes use of abstract and concrete thinking, but is considered to be more active since focus is on the collaborative learning with multiple actors. Cross-project learning and learning by doing are placed in the bottom of the graph, those forms of learning are more concrete. Where learning-by doing is primarily active, cross project learning contains also reflective thinking.

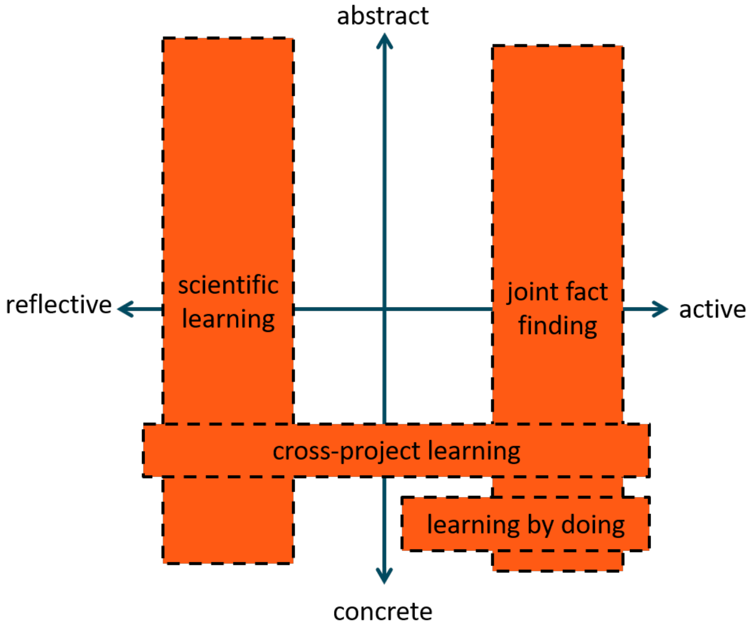


Figure 13.4: Relation between learning types and design thinking. The axes indicate whether the learning type is active or reflective and if it is more abstract or contrete.

CONCLUDING REMARKS

It is clear that actors did learn from and about the Delta Program. The Delta Program uses the concept of learning extensively in its reports. The frames on learning are different in both definition and occurrence over time. In this section, the learning activities are clustered in different learning types. This is important from the perspective of adaptive social learning, as each type of learning has its advantages and disadvantages. The main frames are: 1) scientific learning frame, 2) joint fact finding frame, 3) cross-project learning frame, 4) learning by doing and 5) system learning. Adaptive learning is closely related to the concept of system learning; learning how to learn.

However, there are also appeared to be an uneven basis for learning as explicit learning efforts were skewed towards flood risk management. This has enabled a larger knowledge base on this aspect, but also provided actors with an interest in flood risk management with more information in policy debates. Furthermore, learning is more described and used as a tool in the Delta Program, instead of as a natural endeavour.

Chapter 14

Towards adaptive learning in the Knowledge Program Sea Level Rise

Adaptive social learning improves decision-making in delta management. After the development of the conceptual model (Chapter 12) and the analysis of the Delta Program (Chapter 13), this chapter elaborates how adaptive social learning can be applied on the Knowledge Program Sea Level Rise. Hence, it answers the following sub-question:

SQ-II.e How can the conceptual model be used to enhance adaptive social learning in the Knowledge Program Sea Level Rise?

Background about the Knowledge Program Sea Level Rise can be found in Section 10.4. First, the main observations about the interactions both within the Knowledge Program Sea Level Rise and the interaction between other actors in the Rhine-Meuse estuary are discussed (Section ??). Subsequently, the main challenges for the Knowledge Program Sea Level Rise are identified from a communication and learning point of view (Section 14.2). The observations and challenges are used to develop concrete recommendations to improve the adaptive learning capacity of the Knowledge Program Sea Level Rise. Based on the insights of this chapter and previous chapters, a roadmap is designed including possible learning activities (Section 14.3).To conclude this chapter, the handbook for applying the conceptual model is developed (Section 14.4). This handbook is called DEALta learning. It must be noted that the Knowledge Program Sea Level Rise is still in the initiation phase. Hence, the observations and challenges mentioned in the following section do inevitably have a premature character.

14.1 Observations

Several interesting mechanisms can be observed in the Knowledge Program Sea Level Rise. Some observations are more rooted in the conducted interviews (Appendix F), while other observations can be traced back to the combination of policy documents (Section ??) the insights using the conceptual model (Chapter 12) . To relate the observations to the conducted interviews, quotes are used together with the operationalisation tables (Section F.3). Observations are linked to aspects found in literature (Figure 14.1). To support the observations, those aspects are classified as low or high. A distinction has been made between the level, local or system. This distinction is the result as observations tended to differ depending on the level that was observed (Figure 14.2).

Figure 14.1: Icons that are used in processing the interview transcripts. The icons reflect aspects found in literature. In the top row, aspects related to decision-making are depicted (Section 11.1). The icons on the bottom row refer to social-learning aspects (Section 11.2.)

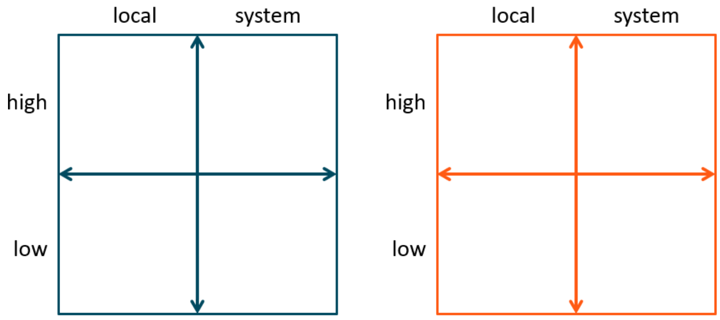


Figure 14.2: Graphs for classification of aspects for learning and decision-making. Aspects related to learning are classified in the blue graphs and decision-making aspects are depicted in the orange graphs. The four quadrants reflect whether the aspect is rated high and low, and on which level; local or system.

14.1.1 Actors do appreciate and have confidence in the Knowledge Program

All interviewees agreed that the knowledge program is useful and necessary. They appreciated the long term vision that is adopted by the knowledge program which invites actors to think about long term developments of the water system. Actors are very engaged with the Delta Program and Knowledge Program:

> ”Over the past, approaches of the Delta Program do work in facilitating collaboration and meeting objectives.”

The interest for track II - about the stretchability of the current system - stood out. This track is mentioned most by all interviewees. Furthermore, actors recognize the goals of the Knowledge Program, which indicates large alignment:

> ”The necessity and goals of the knowledge program are clear. The sea level will rise in the future, the questions are what is the rate of sea level rise and how can we respond to sea level rise.”

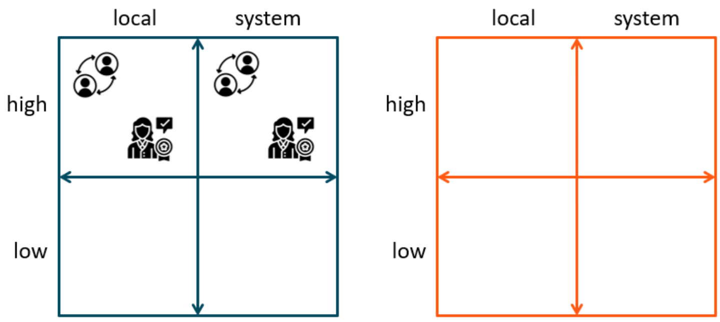


Figure 14.3: Empirical manifestations related to the observation that actors appreciate and have confidence in the Knowledge Program. Learning and decision-making aspects are depicted on the orange and blue graphs respectively.

14.1.2 Formulation of the preferential strategy takes place on a system level

Consensus about the preferential strategy (in Dutch: ”Voorkeursstrategie”) is found on the highest system level. This results in consensus that is quite abstract and can be interpreted in many different ways.

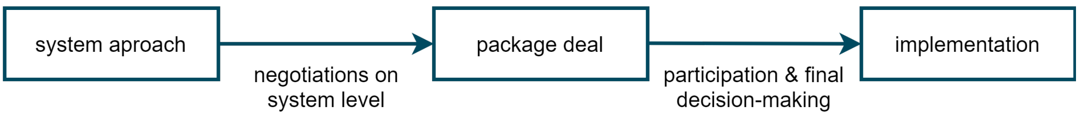


Figure 14.4: Course of developing consensus. Negotiations take place on a system level and the consensus is formed among national actors. This results in a package deal, such as a preferential strategy. The package deal forms the point of departure for implementation which have major regional consequences.

In a way, that is the purpose of the preferential strategy, it should be a vision which guides regional interventions in the Rhine-Meuse estuary. Although the preferential strategy is discussed and agreed upon by local partners, the abstract character of the preferential strategy makes the strategy specifiable for wishful thinking. Each actor can translate the abstract strategy towards their own objectives, making it questionable if there is really consensus, or whether it seems that there is consensus. This is illustrated in the figure below, on the system level negotiations take place about whether the preferential strategy needs to be revised. This leads to a "package deal". However, once the implementation of the preferential strategy leads to final decisions about interventions, the resistance of national or regional parties could become apparent. This can potentially undermine the legitimization of the preferential strategy.

> "[..] you don't want to interfere with future dike reinforcements, we are not posing general statement about spatial adaptation, it is really about custom made solutions."

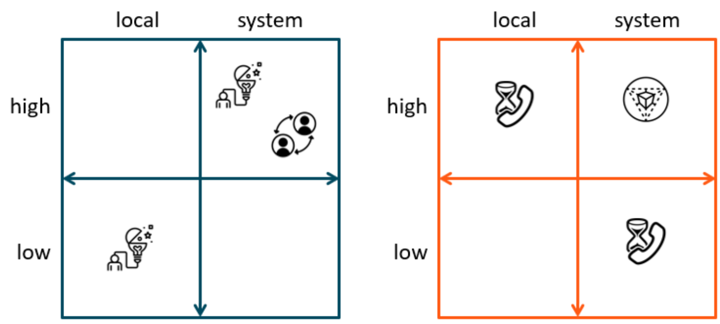


Figure 14.5: Empirical manifestations related to the observation that actors appreciate and have confidence in the Knowledge Program. Learning and decision-making aspects are depicted on the orange and blue graphs respectively.

14.1.3 The Knowledge Program is primarily about knowledge development

Interviewees stressed that the Knowledge Program is solely about gaining insight. They clearly separated the stage of knowledge development from the stage of decision-making.

> "We only explore the impact of different scenarios of sea level rise. That's it."

Regarding the frames of learning (Section 13.2), this observation shows that the scientific learning frame is dominant. Along with this observation, the knowledge program primarily focuses on gaining in-depth knowledge about the water system. In that sense, it counteracts the tendency of the Delta Program to move away from technical studies and tries to strengthen the knowledge base. However, this observation also implies that knowledge development and decision-making can be separated, which is impossible according to some of the theories presented in the theoretical framework (Chapter 11).

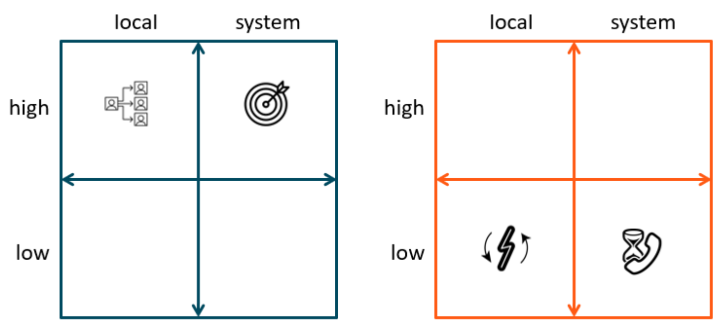


Figure 14.6: Empirical manifestations related to the observation that the Knowledge Program is primarily about knowledge development. Learning and decision-making aspects are depicted on the orange and blue graphs respectively.

14.1.4 The Knowledge Program uses a knowledge agenda

One of the first objectives of the Knowledge Program is to develop a knowledge agenda together with the involved actors. The knowledge agenda provides an excellent opportunity to explore the relations between the different streams. Also, it seems trivial to explore what the bottle necks are for the current situation. However, the Knowledge Program has limited capacity and resources. Hence, the knowledge agenda can secure that the right amount of attention is paid to the different tracks of knowledge program. As noted before, those tracks are strongly related to the problem, solution and political stream.

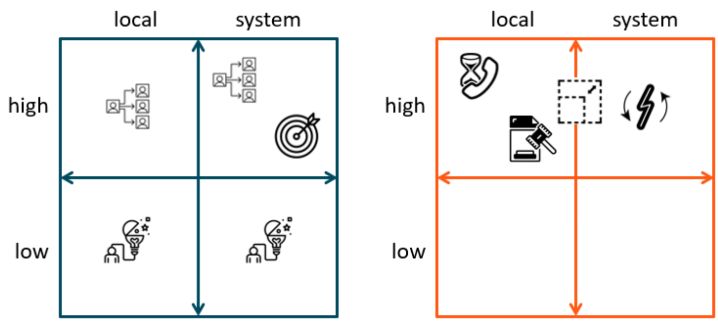


Figure 14.7: Empirical manifestations related to the potential of a knowledge agenda. Learning and decision-making aspects are depicted on the orange and blue graphs respectively.

14.1.5 Actors are not encouraged to learn from each other outside predefined activities

The knowledge program does not explicitly encourage actors to learn from each other. The Knowledge Program does interact with local parties per region. Nonetheless, it is unclear how local parties collaborate in the context of adaptive delta management other than the activities organised by the Delta Program. In social learning, it has been found that contact between parties outside of formal arrangements can have a beneficial influence on reaching consensus.

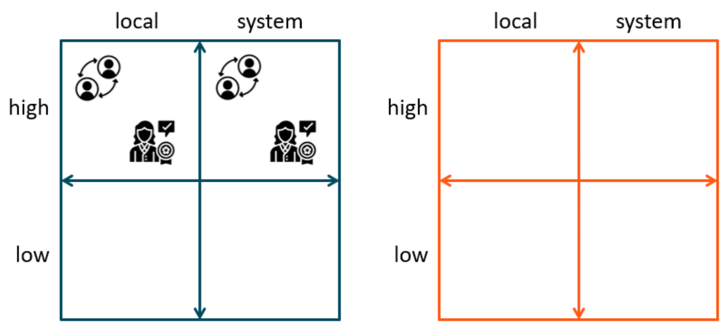


Figure 14.8: Empirical manifestations related to the observation that actors appreciate and have confidence in the Knowledge Program. Learning and decision-making aspects are depicted on the orange and blue graphs respectively.

14.1.6 Responsibilities are fluid

Many actors with different responsibilities are active in the Rhine-Meuse estuary (Chapter 10). The interviewees agreed that this challenges decision-making. Actors do need to make trade-offs while advantages and disadvantages do not belong to the same party. Moreover, in multiple cases the responsibilities are shared or not clear. In those cases, it is hard to come up with and maintain a long term vision and local short term interests often tend to take over.

> ”Only when push comes to shove (in Dutch: ”puntje bij het paaltje komt”), the relations are not so profound that you have to revise strategy based on an integral approach.”

This is also apparent in pseudo-converging, which is elaborated upon in the remainder of the observations (Section 14.1.9).

14.1.7 Track two is dominant

As denoted in the previous chapter, the knowledge program consists of five tracks. The majority of the interviewees spoke about track two, which is about the ”stretch” of the current configuration. Within this track, it is mainly about flood risk safety. This might seem obvious because track two is about the current system. However, from a perspective of adaptive learning, this is not desired. For adaptive learning, it is important to explore the links between solutions, problems and politics. Once more knowledge is developed for one particular stream without developing knowledge on the other streams, it can be hard to make use of the interaction between those streams.

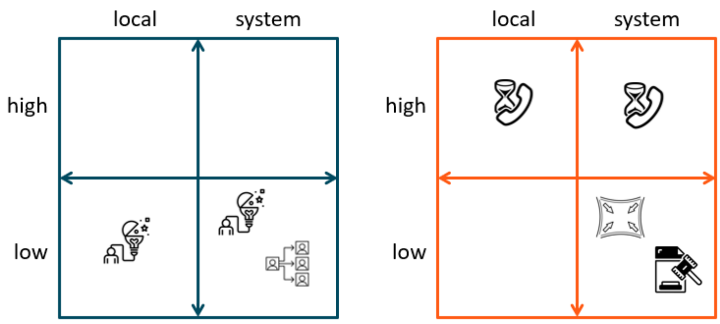


Figure 14.9: Empirical manifestations related to the observation that track two is dominant in the Knowledge Program. Learning and decision-making aspects are depicted on the orange and blue graphs respectively.

14.1.8 Water level follows function

Due to the integral approach among others, spatial planning is gaining more prominence in delta management. At the same time, flood safety still seems to be leading in the spatial domain. This can be partially assigned to the quantitative approach that is used. Flood risk management leans firmly on models of the water system of the Rhine-Meuse estuary. This means that interventions can be modelled that result in a reduction of hydraulic loads or an increase of the strength of flood defences. On the other hand, spatial adaptation uses more qualitative analyses that are rooted in smaller geographical scales (regional level). Due to the difference in scale, a different approach - quantitative vs qualitative - and different governance, follows water level the function. In other words, a sum of smaller spatial adaptation measures govern the allowable water level on a more national level.

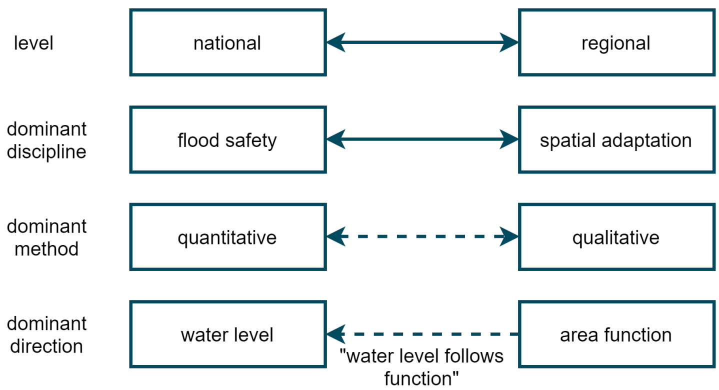


Figure 14.10: Interactions between levels, disciplines and methods. The main point of this illustration is that for an integral approach it is vital to have a good relationship on multiple levels based on two-way communication and responsibilities. On the lowest depicted level, however, ”function follows water level” resulting in an asymmetric relationship.

14.1.9 Relation to conceptual model

Overall, activities show converging behaviour. Activities are aimed at convegence of the solution and problem frames. The converging tendency does not mean that no diverging activities are taking place. Alternatives to the status-quo are discovered and new knowledge is applied, which corresponds to divergent thinking. However, following the above objectives, the (solution) space is not blank and open but shaded by preferences and interest of the actors in the network. The construction of alternatives is not so much part of a diverging moment, but part of a converging movement. It could be denoted as pseudo-divergence, as it seems that actors are coming up with alternatives for the status-quo, while in fact they are reducing the number of alternatives related to knowledge and perception of the early exploration of the situation. New solutions can be present and part of the alternatives, but then to complement or contrast existing solutions.

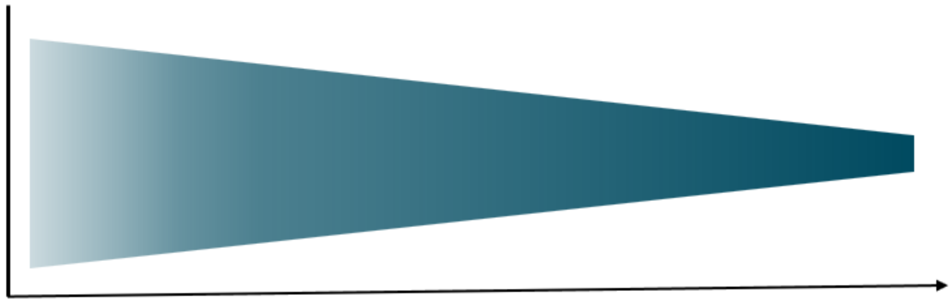


Figure 14.11: Illustration of converging behaviour. Currently, the activities are mainly focussed on converging. Some activities have a pseudo-diverging character.

CONCLUDING REMARKS

In this research, eight valuable observations have been made based on the conducted interviews and background documents. The observations show that actors have large confidence in the Knowledge Program, which reflects large engagement and is important for social learning. The Knowledge Program provides input for the preferential strategy. This information is mainly developed on the system level which puts pressure on the implementation of the preferential strategy. As the knowledge program is primarily about developing knowledge, interactions with decision-making are more implicit. Hence, decision-making and learning are not optimally aligned. As decision-making is complex due to many actors and interests, there exist ambiguity about the responsibilities of actors. Moreover, water level follows function appeared to be the dominant train-of-thought.

Overall, activities show converging behaviour. This means that the activities are aimed at convergence of the solution and problem stream. It is argued that although diverging activities take place, this divergence is not reflected in the development of actors' frames. This is denoted as pseudo-divergence, as it seems that actors are coming up with alternatives for the status-quo, while in fact, they are reducing the number of alternatives related to knowledge and perception of the early exploration of the situation.

14.2 Challenges

Following the observations and additional insights from the conceptual model, different challenges for the Knowledge Program can be identified. The challenges are related to important aspects in the interplay between learning and decision-making and provide a point of departure for the next section, in which more concrete recommendations are made to enhance adaptive social learning.

14.2.1 Communication in a polarized world

The debate about sea level rise can be considered to be polarized. Actors have different perceptions about the rate of sea level rise and the severity climate change consequences. This polarization could reflect on the output of the Knowledge Program and challenges whether the output is considered to be legitimate. This is a key focus point of adaptive learning. Learning should be tailored to actors that involved in a particular step of adaptive delta management. In this way, the learning activities can be made more inclusive.

14.2.2 Keep local parties involved

The interviewees stressed that it challenging to keep local parties involved. One of the main factors that complicate engagement are different geographical and timescales. This is related to the feature of rescaling, as discussed in Section 11.1. During the interviews, local actors mentioned that they want to be involved in the formulation of strategies. In practice, they are contributing to several area consultations (in Dutch: gebiedsoverleggen). Those area consultations cover the integration between flood risk management, economy and ecology on a local level.

The primary challenge is for the Knowledge Program is to provide knowledge that is relevant and credible on a local scale. As the Knowledge Program is a national program, knowledge about the system is developed. For adaptive learning, it is necessary to translate the knowledge from the national level to a local level. Once this translation is made, it is also easier to become adaptive for research and investigations that are performed on a local scale. This again could be beneficial for the formulation of strategies on the national level.

14.2.3 Unravel relations between parallel strategies

As can be seen in the Delta Programs, a whole set of parallel strategies and interventions are implemented. During the interviews, actors mentioned that it is a challenge to link those strategies to one another and frame it as a coherent story. The main challenge lies not so much in the connection between different actors. Over the years, the Delta Program and Knowledge Program have proven to be very successful in connecting actors from various governmental bodies, knowledge institutes, NGO' and private organizations. At the same time, the challenge remains to enhance the connection on the content. The Knowledge Program can play an important role in connecting flood risk safety, fresh water and spatial adaptation. Those three themes are explicitly addressed in the three sub-programs. As the Knowledge Program affects all three themes, it provides a major opportunity to enhance the integral character of the Delta Program.

Moreover, on a more local level this means that it must be clear how aspects related to flood risk safety, fresh water and spatial adaptation are connected. Links to water quality, nature and shipping are important as well. Those themes are more implicitly addressed in the Delta Program, but are often more profound on a local lev than a national level. An ex-ante evaluation is helpful about how different parallel strategies can both mutually strengthen - or weaken each other.

14.2.4 Provide guidance and formulate accountable goals

As observed, the responsibilities are fluid. This is also the case regarding the goals for the water system. While the norms for flood risk management are set in stone in the law, the goals regarding ecology and adaptation remain fuzzy. Hence, there seems to be a tendency towards flood risk management. This tendency alone is not necessarily problematic. However, when the Knowledge Program wants to adopt adaptive learning, accountable goals can help. Accountable goals interfere with the rhythm of diverging and converging, as presented in the conceptual model. Once parties are challenged to meet particular goals, it is needed to reach consensus or negotiate on the best strategy.

14.2.5 Explore shifts in the preferential strategy

Transformational change is often associated with fundamental and quick changes. However, the Delta Program is an example of incremental change. As noted in the previous chapter, there are different phases where different narratives are dominant. This does not mean that incremental change can not lead to transformations. However, to make transformations possible, it is important to know what the effects are when the decision is made to change the preferential strategy drastically. Only in this way, a potentially problematic lock-in is prevented. Moreover, the exploration of shift could also support the current preferential strategy.

14.2.6 "Water level follows function" and "function follows water level"

One of the observations was about the dominant train of thought that water level follows function, which limits the window of opportunity in decision-making and the learning potential. The challenge is to both use "water level follows function" and "function follows water level". The combination of both approaches results in different positions for flood risk management and spatial adaptation aspects. Moreover, as responsibilities related to spatial planning belong to regional parties, those parties have more room and responsibility in establishing the contextual setting. This also results in more equivalent use of quantitative and qualitative approaches.

14.2.7 Shift to mix of converging and diverging

More diverging activities are required to enhance learning potential (Figure 14.12). In diverging, new ideas are coined and new connections are made between existing knowledge. Also, it is argued that converging stages are aimed at reaching consensus. Although this can be beneficial in reaching a solution, it constrains the learning potential. More diverging stages allow expanding the current knowledge base and enable more opportunities for creating mutual understanding, sense making and ideation to design solutions.

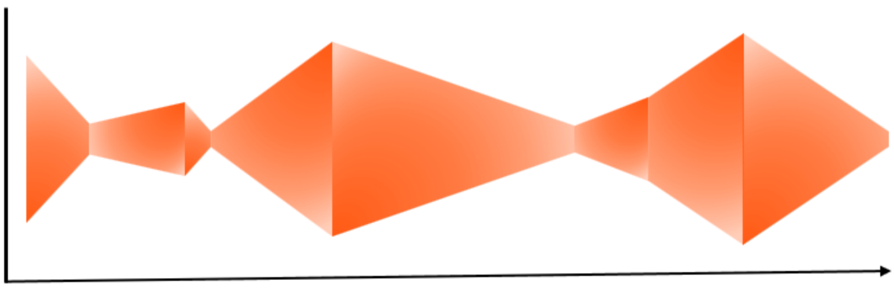


Figure 14.12: Illustration of the ideal situation. Adaptive social learning is about finding a good mix between diverging and converging learning practices.

CONCLUDING REMARKS

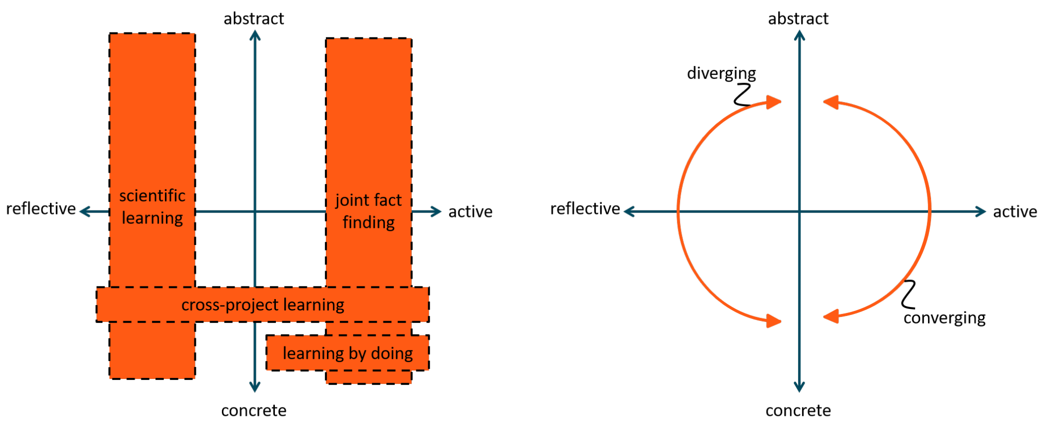
Challenges related to adaptive social learning have been derived for the Knowledge Program Sea Level Rise. The challenges are aimed at improving adaptive social learning and are located on the intersection between decision-making and learning. Due to large uncertainties about the circumstances, the frames of actors are polarised which poses challenges for decision-making. Moreover, the Knowledge Program is national sub-programme of the Delta Program, which makes it more difficult to involve local actors in learning activities. Knowledge is developed parallel to other strategies (e.g. regarding fresh water). To make the information more valuable it is necessary to align the knowledge to other sub-programmes. As actors have different frames about the problems and solutions, it is important to formulate accountable goals. Moreover, the exploration of shifts in preferential strategies helps to develop a more fundamental understanding of the water system and deliver information which can make alternatives more promising. The final challenge is to make use of "water level follows function", and "function follows water level". Both lines of reasoning can complement each other and enhance adaptive social learning.

The challenges raised above support divergent learning. Alternating between divergent and convergent learning processes maximises learning potential and helps to develop knowledge that is valuable for decision-making in management of the Rhine-Meuse estuary.

14.3 Roadmap for adaptive social learning

In the previous chapter, different learning types have been identified (Section 13.2). It has been found that - through the lens of the conceptual model - these learning types have a more diverging or converging character. Adaptive social learning is about tailoring learning activities on the circumstances, involved actors and other processes in the decision-making arena. This means that there are no recipes or blueprints for adaptive social learning, as circumstances, challenges and parties involved are simply too different. Nevertheless, based on my understanding and the conceptual model, a roadmap is created. The roadmap provides an example of different activities that are related to particular learning types.

A roadmap helps to structure the program and also enhances the visibility of different learning processes. Generally speaking, the tendency exists to only present outcomes with outsiders. Especially in diverging learning processes, it is important to enhance the visibility of preliminary results. This is important for making a shift from hard results, such as concrete plans, to aspects as mutual understanding, cooperation and a sense of community. As a result, people have the feeling that progress is made which induces a feeling of satisfaction.



(a) Different types of learning projected on design thinking (b) Converging and divergence in design thinking.

Figure 14.13: Relation between different types of learning, and converging and diverging which is originating from the conceptual model. Learning types can contribute to both convergent and divergent learning, depending on how they are applied in learning activities. This figure shows the relation between the learning types defined in the previous chapter, and convergence and divergence which is central in the conceptual model.

14.3.1 Structure of the program

As explained in Chapter 10, the Knowledge Program Sea Level rise is structured in five different tracks. In the context of the conceptual model, track I, II and III are affiliated with the problem stream. These tracks have the objective to gain more insights about the rate of sea level rise (track I), designing a proper monitoring strategy to follow sea level rise (track III) and to determine the consequences of sea level rise for the current strategy (track II). Track IV is affiliated with the solution stream, since this track is about exploring different alternative strategies to satisfy the flood risk norms in the Rhine-Meuse estuary. Track V is indirectly involved in the political stream, as this track is about communication and thus important for improving legitimacy.

The current planning is developed from the perspective of the different tracks (Figure E.1). Although this is logical from an internal perspective, it advised to take a different perspective in designing the planning of the learning activities. This is reflected in the roadmap on the next page. It is advised to take into account the diverging and converging rhythm, and the different learning types (Figure 14.15). In this way, adaptive social learning predominates in the planning and stresses an integral approach. In the subsequent sections, more elaborations are made on the structure of the roadmap and rationale behind the development.

14.3.2 Balancing the act of convergence and divergence

An adaptive social learning strategy is proposed based on the insights of the conceptual model, different learning types of the Delta Program and the structure of the Knowledge Program. Learning is something that we all do every day as we process new information and is a process with which we are highly familiar. To engage actors in this learning process, it is valuable to acknowledge that individuals have distinct preferences for learning types or activities that are part of the collaboration. So, adaptive social learning also means that individuals - with different learning style preferences - need to be matched.

By constantly shifting between convergence and divergence, the learning process moves actors between abstract and concrete worlds, and it uses alternately analysis and synthesis to come up with new ideas, other designs and different approaches to challenges in delta management (Figure 14.13b). This can be put in practice by alternating activities that are related to converging and diverging. For instance, a brainstorm is typically a divergent process. New ideas are coined and connections are made within existing knowledge. In designing learning activities, it is valuable to determine beforehand if divergence or convergence design thinking is preferred in the activity.

14.3.3 Frequency and sequence

Besides the content, the timing and order of learning activities is important as well. Whereas sufficient time investment is needed to include and process the diverse contribution from participants (Gramberger et al., 2015), it can be challenging to plan ahead to ensure that stakeholders will make this time investment through sustained engagement. Actors can find it difficult to attend multiple events or respond to evaluations, whether because participants are constrained bu their own responsibilities or because of stakeholder fatigue (Carlsson-Kanyama et al., 2008; Elsawah et al., 2020). Hence it is recommended to use a layered approach in the roadmap. Depending on the power, interest and discipline, actors can be more or less frequently involved. This further stresses the fact that soft results should be communicated as well as it reduces the threshold in becoming involved.

This connects to the sequence of activities. In adaptive social learning, it is important that activities are varied and complement each other (Figure 14.14). Hence, it is advised to connect each learning activity to other learning activities. In this way, information from previous activities is included in follow-up activities. This can be done by creating a library of the outcomes of previous activities which is accessible for actors. This library can be categorised based on the learning types, or the different tracks that are present in the Knowledge Program.

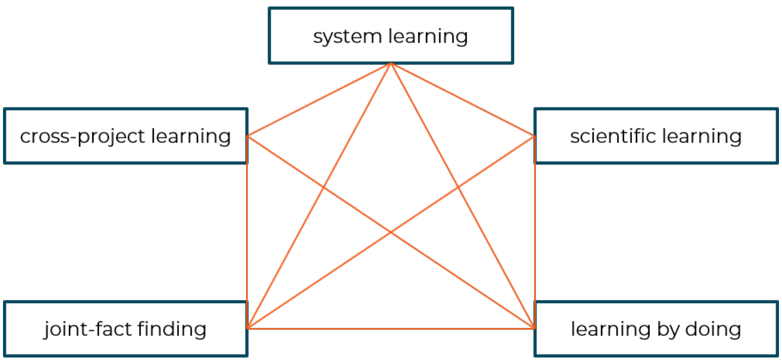


Figure 14.14: Interaction between different forms of learning. In designing learning activities, it is valuable to determine how different forms of learning pick up on one another.

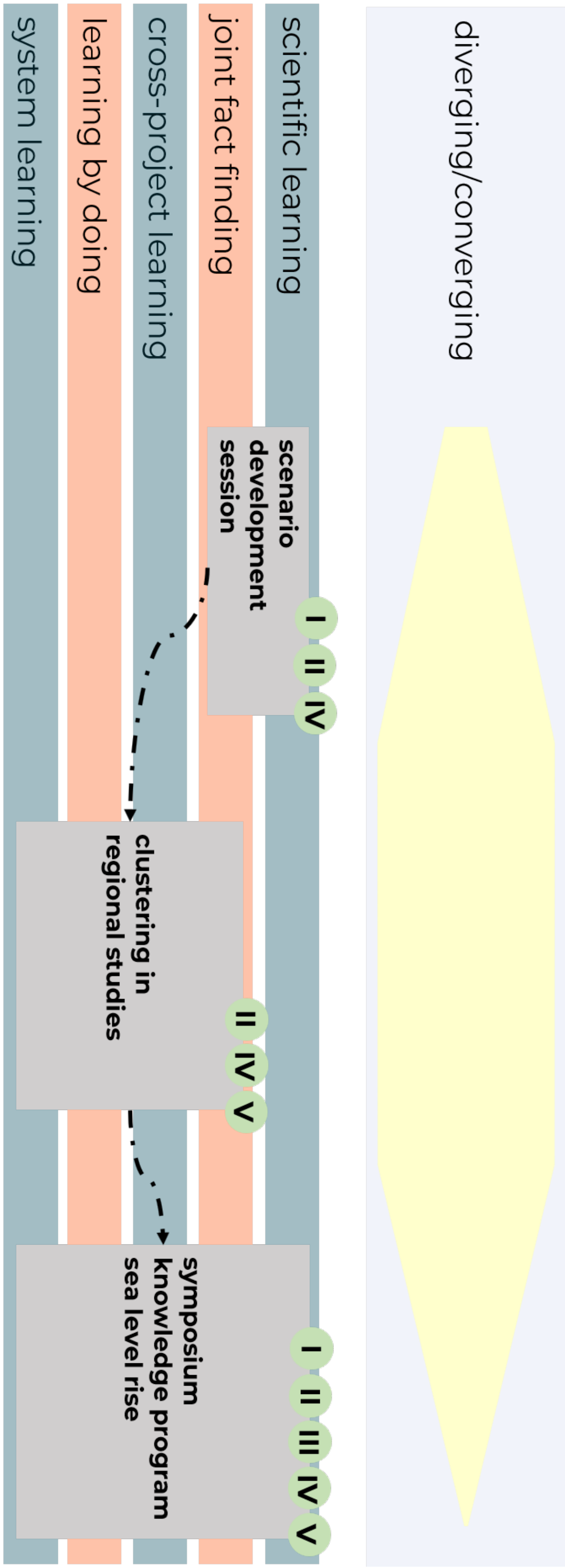


Figure 14.15: Roadmap of different activities. In gray boxes, three different activities are depicted and related to the different types of learning. The green circles indicate which tracks of the Knowledge Program are involved. In the top beam, the converging and diverging direction of the activities is illustrated.

14.3.4 Activities

In the Figure E.1, the current planning of the Knowledge Program Sea Level Rise is depicted. The conceptual model can assist in determining which activities are needed at what time, by comparing the desired decision-making to the current decision-making rhythm. In the end, the information of the Knowledge Program Sea Level Rise is delivered to the Delta Program. Based on the input, the Delta Program takes decisions about the preferential strategy for particular areas in the Netherlands. In this section, three activities that are denoted in the roadmap are discussed in more detail. This shows the relation to the insight of previous chapters and is aligned to the principles of adaptive social learning.

Scenario development session

Adaptive delta management is about preparing for different scenarios. The scenarios can be related to various themes such as the rate of sea level rise or spatial planning developments. It is important to choose a clear focus in participator scenario planning and think about the following aspects:

1. What are the core activities or tasks when facilitating a workshop for scenario development?
2. How may these core activities differ depending on the stage of the scenario development process?
3. How do different facilitation techniques and practices influence the process dynamics and outcomes?
4. What is the role that technology can play in the facilitation process?

Coming up with different scenarios can be designed in both a divergent and convergent manner. If the aim is to explore the range of different scenarios and interactions between other themes it has a divergent character. On the other hand, when it is designed to establish a number of scenarios from a wide range of aspects, it has a more converging character. More explanation about the character of scenarios is provided in the integrated perspective (Section 16.1.1).

Clustering in regional studios

Clustering activities are different from converging or diverging activities. Although clustering is mostly seen as part of converging stages and categorized as a selection technique, this does not justify this activity. It is about connecting ideas and perspectives, building a shared understanding and sense making on how more abstract ideas to reality. Currently, the structure of the Knowledge Program allows regional actors to deliver input for discussions and the knowledge agenda. Clustering of research questions and plans takes place at the national level. It is recommended to also organise clustering activities on a regional level to address at least three different challenges, 1) keep the local parties involved, 2) unravel relations between parallel strategies and 3) use both ”water level follows function” and ”function follows water level”.

Yearly Knowledge Program Day

Each year, a symposium is held in which the progress of the Knowledge Program is shared. This day should be the cornerstone of the Knowledge Program. It provides an excellent opportunity to both evaluate past activities and share the structure and approach of upcoming activities. When more different roadmaps of subsequent activities are developed, the outcomes of the different roadmaps can be discussed during the Yearly Knowledge Program Day. In this way, outcomes can be discussed together to foster integration between the different subjects and tracks of the Knowledge Program. Moreover, it provides an opportunity for actors to collaborate with each other. In this way, new actor coalitions can be formed which can work together in upcoming learning activities.

CONCLUDING REMARKS

In this section, a roadmap is developed including three learning activities. This roadmap addresses the challenges raised in the previous section. The Knowledge Program consists of five tracks with their own objectives. In the current planning, learning activities are defined for each track. It is advised to not take the tracks as point of departure, but the learning type that is preferred. In this way, the learning activities can be aligned to the learning types and can have a convergent or divergent character. This supports the idea that alternating between divergent and convergent design thinking is needed to maximize adaptive social learning.

Three activities are included in the roadmap; scenario development session, clustering in regional studios and the yearly knowledge program day. Those activities pick up on each other. The scenario development session can be designed in both a divergent and convergent manner. This scenario development study is followed by clustering in regional studios. In this activity, local actors are involved to build a shared understanding. Scenarios of the scenario development studies can be connected to perceptions and experience of local actors. The results of both sessions are subsequently presented on the Yearly Knowledge Program Day. It is advised to share the integrated outcomes of both sessions on a symposium. In this way, past activities can be evaluated and input can be developed for the structure of upcoming activities.

14.4 Handbook: DEALTa learning

Until now, this chapter has shown how the model can be used in designing activities that are tailored to adaptive social learning. However, it would interesting when the model can be used in a group setting with people that are involved in the program. In this way, the knowledge and experience of the actors can be enabled to take the application to another level. When this model is used regularly over the course of a program, it allows mapping how different streams evolve over time. Doing so, the model can be used to track progress on the various objectives of programs and sub-programs. Activities can be tailored to the (communication) challenges that become apparent over the course of a project and could enhance both the knowledge exchange within the programme as well as communication to other parties. The main objective of the models is to increase the quality of the conversations and generate more valuable input for decision-making. All the aforementioned factors contribute in the end to the adaptive learning capacity of the programme.

The suggestions made in the following sections are especially important for the facilitators of learning activities. The core team of the Knowledge Program has the experience and domain knowledge that is valuable for establishing contextual boundaries, and converging and integrating the numerous ideas coined by other actors. The suggestions are meant to support the facilitators in keeping the approach tailored to the experience and learning capacity of the actors engaged. One of the main goal is to prevent lack of ownership and cognitive dissonance from participants.

In this section, the DEALTa learning handbook is presented. In this handbook, all major insights of this research are combined to improve adaptive social learning in delta management. The name DEALTa learning refers to the intersection between deals in decision-making and learning. The model consists of four subsequent steps; 1) collecting, 2) guiding, 3) designing and 4) integrating (Figure 14.16). These steps are similar to

14.4.1 Collecting: what to look for?

The input for this model is based on the various (knowledge) frames of actors. How do they perceive the problems, solution and politics that are present within delta management? Both the actors and perspectives can be bound to a specific project at a certain scale. There are multiple ways to collect the different perspectives of actors. For learning, it is interesting how actors view uncertainty, awareness and ambiguity. One of the ways is to query actors about their perspectives regarding those three factors. Examples of questions about awareness of uncertainty are:

1. Can you describe which underlying assumptions are used?
2. Have you chosen a train-of-thought (or mental model) that fit the available facts or your preferences?

3. Would you be able to describe your mental model of the problem and solution to others?

These questions help in creating mutual understanding and aspects on sense-making. When it comes to the level of uncertainty, one could ask the following questions:

1. Where does your knowledge come from?
2. Do you trust these sources?
3. Are you able to conceive alternative scenarios, different circumstances or other facts that are counter-intuitive?
4. How likely is that your problem or solution is the right one?

To assess ambiguity in the network, the following questions might be relevant:

1. Do you know what assumptions are underneath each actor's reasoning?
2. What are the mental models of other actors?
3. How similar are those mental model to mine?
   (a) Are they so similar as to prevent us from coming up with alternative problem definitions or solutions?
   (b) Are they so different as to prevent us from reaching common ground?

In the collection stage, ambiguity should not be viewed as counter effective. Rather, it enables us to make sense of concept and relate concepts to one another. The learning potential in ambiguous settings is very large. It stimulates actors to give insight into the reasoning behind their standpoint and how they relate objective to objectives held by other actors. The following question addresses the relation between adaptive social learning and decision-making:

1. What information, novel insight or re-framing would lead you to reconsider your conclusion?

This question also relates to the main deliverables of the Knowledge Program. In the end, the knowledge program must provide input for the perennial revision (in Dutch: "Herijking") of the Delta Program. The advice about whether the preferential strategy should be revised could be assessed by the above question. For example, what would be the rate of sea level rise for which the preferential strategy does not hold any more? This requires to look back at the underlying assumptions and how uncertainty propagates through the used approach.

14.4.2 Guiding: when to shift phases?

Several factors are important in recognizing when shifting between Note that the same set of questions apply for shifting from diverging to converging, and from converging to diverging. This is because shifting is about increasing learning potential. Negative answers to the following factors indicate a low learning potential, which makes shifting beneficial:

1. There are no interesting stories being told about the current situation.
2. There are no signs that actors are seeing the situation in new ways.
3. There is no reframing going on.
4. Actors do not engage because a model or framework is too difficult to internalize.
5. Ideas are not grounded. Abstract, floaty and lofty ideas can be valuable to inspire other actors. However, too many examples that are not connected to current practices do not lead to real opportunities. This makes those ideas vulnerable to pseudo-diverging, in which new ideas are not alternatives but rather support the status-quo.

14.4.3 Designing: which learning activities?

In this step, learning activities can be designed. Following the previous step, a choice has been made for activities that are more divergent or convergent. In designing learning activities, it is important to develop clear objectives and determine which actors need to be involved. In the collection phase, information about the frames of actors is collected. These knowledge frames provide the starting point in designing learning activities. The quality of learning activities can be improved by taking into account three criteria: salience, credibility and legitimacy (Section 11.2). Salience refers to the fact that the subject and information must be relevant to actors. Only in this way, the discussed becomes meaningful. Only meaningful information will have an influence on the knowledge frames of actors. Credibility refers to the scientific and technical believability. Actors are more likely to accept technically sound information. Credibility also relates to the process used in the learning activity. When actors trust the used process they find the developed knowledge more convincing. Legitimacy is more related to the political stream. If the values and concern of actors are taken into account, they are more engaged and tend to contribute more to a learning activity

14.4.4 Integrating: how to include in current practices?

Learning activities do no stand alone. Besides the design of learning activities, it is valuable to integrate those activities in the current planning. The rationale behind this stage is that the model is most effective when it is merged in other activities of the program. Learning activities do not compete but rather strength one another. In this way, it does not become a stand-alone side project, but are actors challenged to integrate the findings in current practices.

This is also shown in the roadmap. It is not so much about developing new activities or completely change the structure of the program, but rather about aligning current practices. The structure and activities of the Knowledge Program already have large learning potential. At the same time, in adaptive social learning the challenge is to continuously adjust the learning activities by switching between learning types, and converging and diverging stages. For integration, the current activities could be categorised in diverging and converging activities. In this way, it can be evaluated if the current planning is aligned with what is needed for the decision-making rhythm. Adjustments can be made in involved actors, sequence and frequency of meeting and learning activities.

14.4.5 Other opportunities

This chapter showed one of the ways to use the model. There also numerous other possibilities to use the model. A few of these alternatives are listed below:

1. Involve a larger group of people. One of the advantages of the model is that it can be used on different scales. For instance, it could also be used to provide an idea about the perception of the rate of sea level rise. It would be interesting to map the different perceptions of actors about sea level rise. In this way, the model can disclose the relation between different perspectives. Are the actors aligned? Are there large differences in the perception of actors?

2. Share results with actors. From the perspective of social learning, it would be interesting to discuss the results of the perspectives with actors. The results of the model can be an interesting point of departure for discussion. When there is a large divergence in one of the three streams, it can generate more tension between actors which is beneficial for learning. This provides opportunities to check if actors find problem or solutions directions legitimate and challenge the accountability of themselves, and other actors.

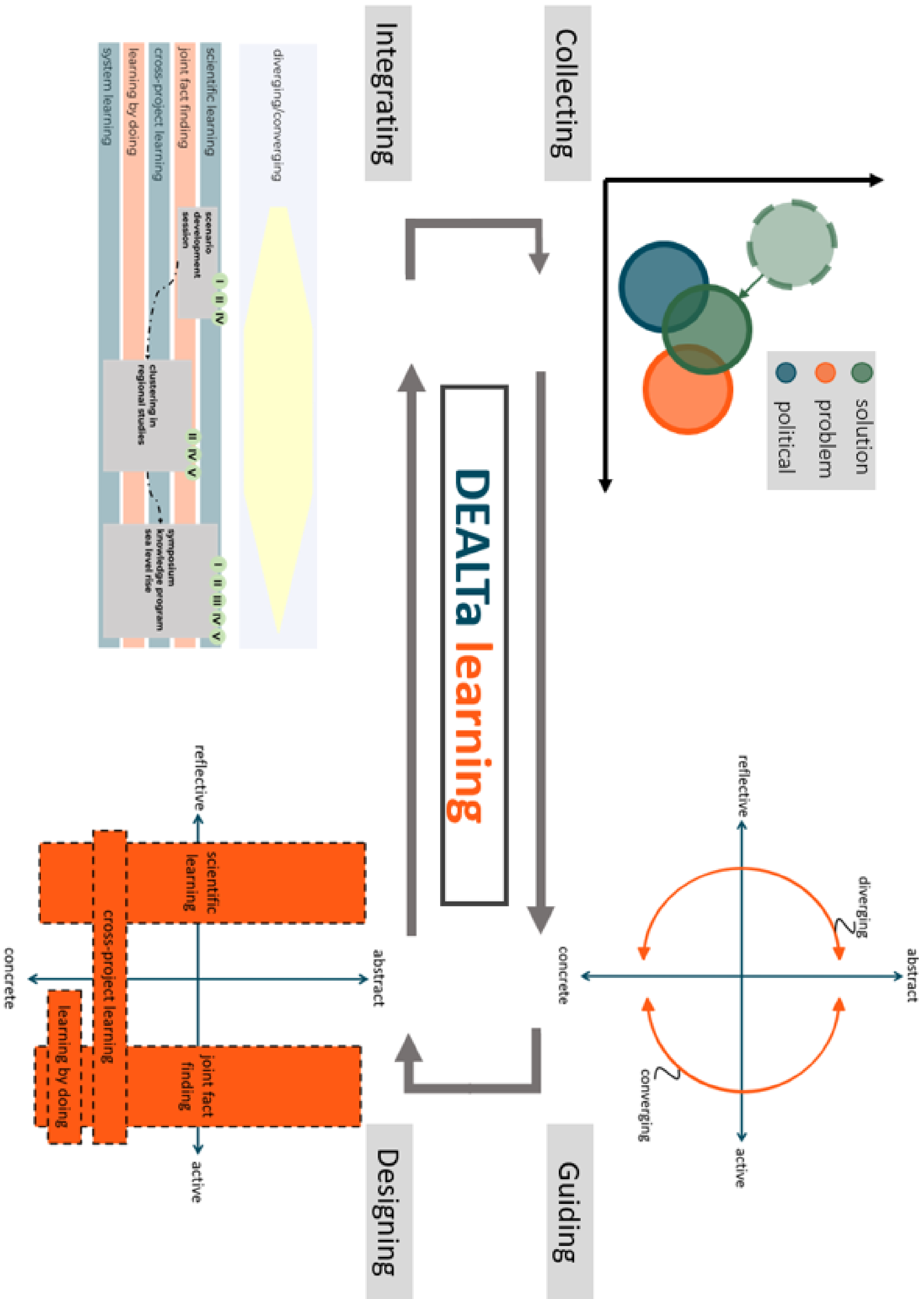


Figure 14.16: DEALTa learning handbook. The four steps of collecting, guiding, designing and integrating are depicted in the handbook. The collecting step is about analysing the different frames of the solution, problem and political stream. Subsequently, the choice can be made for diverging or converging. In the designing steps, learning types can be selected that form the basis for learning activities. In the last step, the learning activities can be integrated and aligned to other activities.

CONCLUDING REMARKS

In this section, the DEALTa learning handbook is presented. DEALta learning provides guidance on how adaptive social learning can be applied in practice to improve decision-making. With the handbook, involved actors are able to exclude their own information, experience and best practices in the learning activities. The handbook is based on notions of the conceptual model, insights from the Delta Program analysis, and observations about the Knowledge Program. The handbook uses four steps; 1) collecting, 2) guiding, 3) designing and 4) integrating. In the collection phase, frames of actors are collected to provide a point of departure for learning. Based on the frames of actors, a choice can be made whether divergent or convergent activities are preferred. Subsequently, learning activities can be designed. To improve the quality of the learning activities, the criteria salience, credibility and legitimacy are important. In the last steps, learning activities are integrated in the current planning to ensure that they are embedded in the Knowledge Program.

The DEALTa learning model has an iterative character. Adaptive social learning is about adjusting learning activities on the circumstances. Hence, it is valuable to use the DEALTa model at different moments and with various groups of actors.

Chapter 15

Closure of socio-political perspective

15.1 Limitations

The limitations of the socio-political perspective are discussed in relation to the reliability and validity. Whereas reliability is mainly related to the methods used in this research, the limitations concerning the results mostly have to do with validity.

15.1.1 Reliability

Reliability refers to the consistency of a measure of a concept and assesses whether the results of the study are repeatable (Bryman, 2016; Babbie, 2013). As this study is mostly qualitative, this is difficult to achieve (Bryman, 2016).

The biggest challenge of this research has been to formulate a conceptual model and an implementation the complexity of adaptive delta management, and regarding the wide range of perspectives about the case studies of the Delta Program and Knowledge Program. An attempt has been made to collect the most important perspectives in the interviews, but it cannot be known if this happened successfully. Although an interview guide has been used during the interviews, it would be difficult to reconstruct the interviews because of the semi-structured character. As the questions were largely about current affairs, it is also difficult to trace-back whether the interviewer has a different interpretation or the interviewee changed his/her perspective along the way. This affects the test-retest reliability.

Issues of inter-observer consistency were not available as the research is conducted by one person. One person is never diverse, which challenges the capacity to understand and grasp complexity in all its dimensions. At the same time, because a diverse range of actors is interviewed and a extended document analysis is conducted, the subject is approached from multiple different ways offering many new perspectives in relation to adaptive delta management. The next limitation comes with the use of open coding and axial coding. These methods are known to be susceptible to the interpretation of the researcher. This interpretation bias is counteracted by the theoretical foundation of the codes and the operationalisation tables. Hence, the author believes that most concepts would be picked up by other researches as well.

15.1.2 Validity

Validity refers to the extent to which an empirical measure adequately reflects the real meaning of the concept under consideration (Babbie, 2013). Triangulation - the use of multiple sources of information - enhances the internal validation of the problem exploration, observations and recommendations. A second round of interviews has not been conducted. This second round could have further enhanced the validity of this research. Moreover, it remains to be seen if the findings are operable for an actor in practise. The interviews are transcribed, which reduced the potential of bias entering the observations and improves internal validity. Also, face validity is argued to be satisfied, as interviewees are interviewed and directly asked about their perceptions of the Delta Program and Knowledge Program.

Regarding the generalizability, the signs are mixed. On the hand, a broad perspective is used to align social learning and decision-making in adaptive delta management. Many issues regarding decision-making in delta management are known to also exist in other climate adaptation settings. At the same time, the findings are tailored to the Delta Program and more specifically to the Knowledge Program. It means unknown whether the findings of this study can be generalised to other domains in and outside delta management.

15.2 Conclusions

This research aimed to gain insight into the relation between decision-making and learning in delta management in the Rhine Meuse estuary by creating a conceptual model. After performing a review of literature, developing the conceptual model and applying it to two case studies, this section draws conclusions by answering the sub-questions. The main research question for the socio-political perspective is answered in Chapter 17, along with the conclusion of the physical and integrated perspective.

SQ-II.a How can decision-making be characterized in delta management in the Rhine-Meuse estuary?
Decision-making in the Rhine-Meuse estuary is increasingly characterized by a network structure. This means that knowledge and decisions do not belong to one single actor or group of actors, but those decisions come about during interactions between various groups of actors. Actors have a wide range of interests, perspectives and power. Moreover, disparate knowledge systems are present which means that the knowledge about delta management is not centred around one actor, but that different actors possess knowledge that is valuable to decision-making. The variety of actors and dimensions make a collaborative approach necessary in reaching decisions. This collaborative approach is also deemed necessary because of the focus on adaptive water management, which is build upon the idea of stakeholder involvement. The legitimacy for water management interventions is not solely dependent on scientific evidence but needs to be earned in a deliberative process with all relevant actors.

The Delta Program plays an essential role in connecting various actors and providing funds to finance interventions. The Delta Program performs various projects: implementation programs for strengthening dikes and protecting the coast, making room for rivers and sub-programs investigating what needs to be done on the long-term From a network perspective, the Delta Program fulfils the role of a bridging organisation.

Specifically for the Rhine-Meuse estuary, three sub-programmes of the Delta Program are important. The first two are regional sub-programmes: Rijnmond-Drechtsteden and Zuidwestelijke Delta. These sub-programmes play an important role in mobilizing actors in the Rhine-Meuse estuary and realizing consensus about the preferential strategy. The third sub-programme, the Knowledge Program Sea Level Rise, is a national joint research program and aims to deliver insight on the rate of sea level rise, the consequences for water related challenges and spatial adaptation. This program is also one of the case studies and consists of five different tracks that have their own objective.

SQ-II.b What theories and frameworks are important in adaptive social learning for delta management?
Three strands of literature have been investigated in the context of adaptive delta management; decision-making, social learning and framing. Adaptive social learning is aimed at integrating these three strands of literature.

For the decision-making, a combination of agenda-setting theory and decision-making under uncertainty is used, which has both descriptive and prescriptive power. The following descriptive elements can be identified:

- It is valuable to assess the chaotic behaviour of decision-makers with the Multiple Streams Framework, consisting of: 1) a problem stream, 2) a solution stream, 3) a political stream and 4) a choice opportunity stream. Hence, this multiple streams framework will form the blueprint of the conceptual model.

The prescriptive elements, according to literature, are mentioned below:

- Adaptive delta management demands: 1) connection between short-, medium and long term objectives 2) embrace uncertainty by taking into account an ensemble of scenarios, 3) explicit addressing of time periods for implementation and construction and 4) integrate the diverse knowledge of the actors involved.

- Adaptive delta management should enhance five governance capabilities that are required to deal with wicked problems: 1) reflexivity, 2) responsiveness, 3) resilience, 4) revitalization and 5) rescaling.

Social learning emerges from knowledge exchange and recognises that knowledge is contested, socially constructed, and used in specific contexts. It describes how information, which is the basis for decision-making, is developed networks of actors. The following insights are important to improve learning processes:

- Modes of belonging: 1) engagement, 2) imagination and alignment;
- Competences in communities of practice: 1) joint enterprise, 2) mutuality and shared repertoire;
- Bridging boundaries between communities of practice can be done via one of the following ways: 1) boundary brokers, 2) boundary objects, 3) boundary interactions and 4) cross-disciplinary projects. Boundary organisation can facilitate bridging and thus play a critical role in learning processes;
- In effective knowledge exchange, information is 1) credible, 2) legitimate and 3) salient.

Social learning governs the knowledge and information that is used to make decisions. Hence, social learning has a large influence on both the content of decisions and how decisions come about. For the conceptual model, the aspects of social learning are included to improve learning processes.

Frames provide insights in how actors perceive aspects in decision-making and how actors filter incoming information. Hence, framing literature is an important addition to decision-making and learning literature. In this research, an relational focus on framing is taken. Three kinds of knowledge relationships - related to uncertainty and ambiguity - are distinguished: 1) unpredictability due to non-linear and chaotic behaviour of socio-technical systems, 2) incomplete knowledge comes from incomplete information which can be reduced with enough time and means and 3) multiple knowledge frames is characterised by different - and sometimes conflicting - views about how to understand and manage the socio-technical system. Those different relationships require a different approach to designing learning activities.

Framing literature provides the third building block for the conceptual model as it offers more depth on how decision-making and learning take place in practice. To just provide information to the decision-making arena is not enough to influence decisions. Information needs to be connected to existing knowledge frames in order to become meaningful to actors. Framing literature recognizes that actors have different perceptions about which information is meaningful.

SQ-II.c How can the insights from these theories and frameworks be combined in a conceptual model?

Aspects that are valuable for both decision-making and social learning are integrated in a conceptual model. The conceptual model is based on the Multiple Streams Framework. The aim of the conceptual model is to make interactions between decision-making and learning more explicit. It is expected that more explicit notions enable actors to understand the processes at hand and provide guidance in designing learning activities. In order to so, the multiple streams framework is extended to make it more sensitive to communication and learning processes. It is argued that the streams, in reality, have a certain bandwidth, indicating that multiple frames exist within one stream. This is due to different actor coalitions with their own knowledge frames, interest and perspective on problems, solutions and politics.

The dynamic and erratic behaviour of decision-making and learning is reflected in the conceptual model by convergent and divergent thinking. Convergent thinking is related to consensus-oriented activities and approaches where the focus is on realizing agreed-upon decisions. Although this might benefit decision-making in first sight, it can also induce path-dependency, fact fighting and controversies. Divergent thinking is related to issue-linking and varying solution directions. This fosters an integral approach, but also is susceptible to indecisiveness and negotiated non-sense. The conceptual model provides a lens to which processes in delta management can be viewed, and is particularly tailored to recognize converging and diverging tendencies. It also follows from the model that decisions improve when convergent and divergent thinking are used in an alternate way. In this way, conflicting frames are used to maximize learning and complementary frames are used to reach common ground for decisions.

SQ-II.d How is the concept of learning defined and used by the Delta Program?
The frame and used narratives of the Delta Program changed over time. This affected the interplay between learning and decision-making. The first phase - from 2007-2011 - concerned the initiation of the Delta Program. It had a strong political character as the Delta Committee was mainly aimed at reaching political support to launch the Delta Program. By using a crisis and climate adaptation narrative the Committee succeeded in achieving three things: 1) creating awareness and setting adaptation on the political agenda, 2) getting their political frame accepted by other actors and 3) already gained some progress in converging the frame of the problem and solution direction. The second phase - from 2011 to 2015 - worked towards the Delta Decisions. Large actor coalitions were formed and explicit interaction was sought with other disciplines. This reflected the integrality narrative, which was key in this phase. At the same time, multiple frames about integrality exist among stakeholders: 1) integrality as win-win and 2) integrality as a viscous and inefficient process. In the last phase - from 2015-2021 - the shift was made towards implementation. At the same time, pressure increases to initiate to expand the knowledge base with new research. The preferential strategy includes incremental and adaptation actions are primarily aimed at maintaining the status quo.

A document analysis of all the Delta Programs shows that the concept of learning is used extensively. Different learning types can be distinguished. A scientific learning frame which is mainly focussed on sound science, building an evidence base and performing technical studies. The joint fact finding frame concerning the development of knowledge with a diverse group of actors to create mutual understanding and broad support base for new knowledge. The cross-project learning frame is about sharing best practises between different projects. Learning by doing stresses that learning is achieved to practise, self-perfections and a series of minor innovations. The last frame - system learning - refers to reflection and focus directly on the learning potential of various activities. System learning is vital for adaptive social learning, as it allows us to evaluate and adjust learning practises depending on the circumstances.

SQ-II.e How can the conceptual model be used to enhance adaptive social learning in the Knowledge Program Sea Level Rise?
This question is answered in four steps. First, observations related to conducted interviews and background documents are discussed. Subsequently, challenges for the Knowledge Program are defined related to adaptive social learning. Next, a potential roadmap of activities is presented to illustrate how insights of the conceptual model can be used. To conclude, the DEALta learning handbook is presented.

In this research, eight valuable observations have been made based on the conducted interviews and background documents. The observations show that actors have large confidence in the Knowledge Program, which reflects large engagement and is important for social learning. The Knowledge Program provides input for the preferential strategy. This information is mainly developed on the system level which puts pressure on the implementation of the preferential strategy. As the knowledge program is primarily about developing knowledge, interactions with decision-making are more implicit. Hence, decision-making and learning are not optimally aligned. As decision-making is complex due to many actors and interests, there exist ambiguity about the responsibilities of actors. Moreover, water level follows function appeared to be the dominant train-of-thought. Overall, activities show converging behaviour. This means that the activities are aimed at convergence of the solution and problem stream. It is argued that although diverging activities take place, this divergence is not reflected in the development of actors' frames. This is denoted as pseudo-divergence, as it seems that actors are coming up with alternatives for the status-quo, while in fact, they are reducing the number of alternatives related to knowledge and perception of the early exploration of the situation.

Challenges related to adaptive social learning have been derived for the Knowledge Program Sea Level Rise. The challenges are aimed at improving adaptive social learning and are located on the intersection between decision-making and learning. Due to large uncertainties about the circumstances, the frames of actors are polarised which poses challenges for decision-making. Moreover, the Knowledge

Program is national sub-programme of the Delta Program, which makes it more difficult to involve local actors in learning activities. Knowledge is developed parallel to other strategies (e.g. regarding fresh water). To make the information more valuable it is necessary to align the knowledge to other sub-programmes. As actors have different frames about the problems and solutions, it is important to formulate accountable goals. Moreover, the exploration of shifts in preferential strategies help to develop a more fundamental understanding of the water system and deliver information which can make alternatives more promising. The final challenge is to make use of ”water level follows function”, and ”function follows water level”. Both lines of reasoning can complement each other and enhance adaptive social learning. The challenges raised above support divergent learning. Alternating between divergent and convergent learning processes maximises learning potential and helps to develop knowledge that is valuable for decision-making in management of the Rhine-Meuse estuary.

A roadmap is developed including three learning activities. This roadmap addresses the challenges raised in the previous section. The Knowledge Program consists of five tracks with their own objectives. In the current planning, learning activities are defined for each track. It is advised to not take the tracks as point of departure, but the learning type that is preferred. In this way, the learning activities can be aligned to the learning types and can have a convergent or divergent character. This supports the idea that alternating between divergent and convergent design thinking is needed to maximize adaptive social learning. Three activities are included in the roadmap; scenario development session, clustering in regional studios and the yearly knowledge program day. Those activities pick up on each other. The scenario development session can be designed in both a divergent and convergent manner. This scenario development study is followed by clustering in regional studios. In this activity, local actors are involved to build a shared understanding. Scenarios of the scenario development studies can be connected to perceptions and experience of local actors. The results of both sessions are subsequently presented on the Yearly Knowledge Program Day. It is advised to share the integrated outcomes of both sessions on a symposium. In this way, past activities can be evaluated and input can be developed for the structure of upcoming activities.

The DEALta learning handbook provides guidance on how adaptive social learning can be applied in practice to improve decision-making. With the handbook, involved actors are able to exclude their own information, experience and best practices in the learning activities. The handbook is based on notions of the conceptual model, insights from the Delta Program analysis, and observations about the Knowledge Program. The handbook uses four steps; 1) collecting, 2) guiding, 3) designing and 4) integrating. In the collection phase, frames of actors are collected to provide a point of departure for learning. Based on the frames of actors, a choice can be made whether divergent or convergent activities are preferred. Subsequently, learning activities can be designed. To improve the quality of the learning activities, the criteria salience, credibility and legitimacy are important. In the last steps, learning activities are integrated into the current planning to ensure that they are embedded in the Knowledge Program. The DEALTa learning model has an iterative character. Adaptive social learning is about adjusting learning activities on the circumstances. Hence, it is valuable to use the DEALTa model at different moments and with various groups of actors.

15.3 Recommendations

15.3.1 Further close the gap between decision-making and learning

Adaptive delta management is rapidly evolving and much research is performed in this field. The role of learning in adaptive delta management remains an understudied topic. It is recommended to recognize the importance of learning processes in adaptive delta management, and the interaction with decision-making. It is argued that effective learning is the only way to make management practices truly adaptive. Hence, it is advised to further close the gap between decision-making and learning, preferably with empirical studies.

15.3.2 External validation of the conceptual model and DEALTa learning handbook

In this research, there is lack of a external validation of the conceptual model and DEALTa learning handbook. Although concrete recommendations have been made, it is not checked whether these recommendations hold in practice and enable actors to increase the learning potential. As a first step, it is recommended to perform an external validation. This validation could consist of multiple steps, the first step could be to investigate whether actors recognize the problem originating from the discrepancy of the problem, solution and political stream. This would provide the necessary common ground to grasp the essence of the conceptual model. A subsequent step would be to use the DEALTa learning handbook to come up with learning activities. This step could show to what degree the model helps to design a planning for learning activities. Furthermore, the handbook can be improved based on the experiences of actors.

Moreover, even though the model is developed specifically in the context of delta management, the approach might also make sense for people from other fields. Hence, it is recommended to test the conceptual model and DEALTa learning handbook in other settings, to see which premises of the model hold and which aspects can be improved or revised.

15.3.3 Adjust handbook for reflection

Adaptive social learning is about contentiously changing learning activities based on the circumstances. This research provides insight in the relation between decision-making and learning in delta management on a theoretical, conceptual and practical level. At the same time, the train of thought is not optimal for reflective activities. It would be interesting to investigate to what degree the tool can be used to assess and evaluate current learning activities of the Knowledge Program or other programs. A reflexive attitude is likely to enhance collaborative learning processes. Furthermore, it would be interesting to map or compare different activities regarding their learning potential and extract best practices.

III

Integrated perspective

Chapter 16

Synthesis

This part aims to integrate the physical perspective (Part I) and socio-political perspective (Part II). The physical perspective investigated the influence of extra storage and pump capacity on the water levels in the Rhine-Meuse estuary. This could be considered as one of the many interventions that can be taken to satisfy the flood risk norms and other functions for the coming decades or centuries. This fits within the rationale that flood risk management must be adaptive to prepare for uncertain climate change. The socio-political perspective adopted a broader view, considering that the decision-making is bot objective but can be characterized as an erratic and chaotic process. The insights that are obtained with the conceptual model among others can be used to enhance adaptive social learning in technical studies. It has been argued that adaptive social learning is indispensable for adaptive delta management.

This chapter further explores the connection between the physical and socio-political perspective, and tries to further bridge the gap between theory and practice:

> **RQ-III: How can the socio-political and physical perspective be integrated to enhance adaptive social learning in technical studies?**

By showing the relation between theoretical, conceptual and practical notions, this chapter aims to make a contribution on how adaptive social learning can be applied in technical studies. This chapter is structured in three parts. First, the different elements in technical studies are "dissected". It is argued that socio-political and physical perspectives are already intertwined and that it is value to back-trace to underlying perspectives. Subsequently, different approaches are proposed to rebuild those dissected elements in a way that adheres to principles of adaptive social learning. To conclude, the possible impact of alternative approaches is shown and discussed on the basis of the conceptual model used in the socio-political perspective.

16.1 Dissecting elements technical studies influencing adaptivity

It is broadly recognized that adaptivity is needed in delta management, particularly in the view of rate of sea level rise and connections to other socio-political aspects. Yet, there is little known how this can be pursued on the level of technical studies. In other words, which methods or tools are available in practice which directly complement current approaches. In this section, the different dimensions or point of views regarding adaptivity are discussed and related to issues that occur in technical studies. Different aspects use different definitions or approaches for adaptivity. Here, three aspects are discussed: 1) scenarios, 2) scales and 3) interventions. This list of aspects is not exhaustive, Hamilton et al. (2015) for instance marks 10 aspects that have to be integrated. Special attention is paid how scenarios relate to the hybrid approach of quantitative and qualitative methods, or elements corresponding to a physical or socio-political perspective.

16.1.1 Scenarios

Scenarios are fundamental for technical studies. Although the future is inherently uncertain, it is not entirely unknowable. Scenarios are not so much about predicting the future, but rather exploring and comparing a range of diverse and plausible futures. The different amounts of sea level rise used in the physical perspective are an example of the use of scenarios. It has long be recognized that scenarios play a crucial role in improving decisions and policies in delta management. Nonetheless, the link between scenario (analysis) and decision-making are still weak.

Scenarios provide an answer to different questions and require different methods. The multiple streams framework - which consisted of a solution and problem stream (Section 12). Predictive scenarios - What will happen? - and exploratory scenarios - What could happen? are problem focused as these scenarios end up with projections or explorations. Normative scenarios - How can as specific future be realized? - make use of backcasting and are more solution-focused. This means that the type of scenario has a considerable impact for the kind of research and the connected learning features.

So, different scenario indicators may be selected for different purposes. Lyytimäki et al. (2013) identified three types of scenario usage related to decision making: 1) instrumental usage which is directly related to decisions, 2) usage for strategic planning and 3) conceptual usage for learning. An example of the latter would be the concept of an ecological footprint, coined as a general concept related to sustainability. Again, it is shown that scenarios are intertwined with objectives and interests of actors.

For scenario development in technical studies, it is important that the objective of the scenario is clear to everyone. Hence, the choice has been made in the physical part to evaluate different sea level rises instead of KNMI scenarios with a specific time frame. A KNMI scenario is typically a predictive scenario, as this assigns different sea level rises for different temporal scales. Furthermore, part of the controversies and dilemmas are coming from choices in scenarios. As explained in the Chapter about the Delta Program (Chapter 13), in the beginning a quite extreme scenario was selected to support the narrative. As it was not explicitly mentioned whether this was a predictive or exploratory scenario, actors interpreted the scenarios in different ways leading to controversies that could have been prevented.

16.1.2 Scales and system boundaries

Actors at different geographical and sectoral scales have different perceptions. As the policy sector winners and loses differ at scale, the system boundary of a technical study also interferes with how the outcomes are perceived. Currently, the method of downscaling qualitative scenarios to starting point for local scenario development is the most common way to deal with multiple scales. This is also observed in the Delta Program; scenarios and strategies on a system scale are downscaled to strategies that have to be implemented locally, for instance in the Rijnmond-Drechtsteden area.

Hence, it is proposed to use multi-scale scenarios whenever possible. Multi-scale scenarios can take the afore-mentioned issues into account and thus add more value to the content of technical studies and the relation to decision-making. An example are the KNMI '14 scenarios (Figure 16.1) in which a so-called "two-axes" approach is taken. In this approach, two drivers are selected and plotted on each axis. This leads to four scenario quadrants with their own line of reasoning.

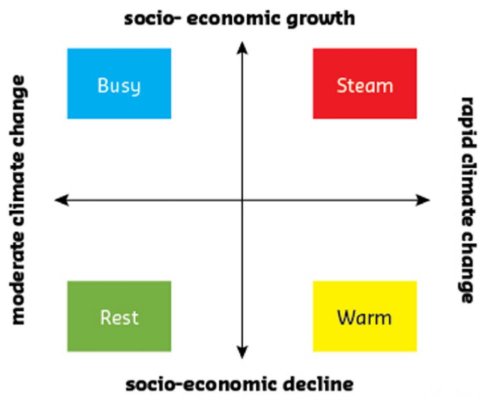


Figure 16.1: KNMI '14 scenarios. The scenarios are based on two main variables, temperature and economic development. The combination of a high and low value of both variables leads to different quadrants (Attema et al., 2014).

Another interesting example in flood risk management is the concept of multi-layered safety (In Dutch: Meerlaagse veiligheid). This concept is coined in the National Waterplan Ministerie van Infrastructuur en Waterstaat (2008) and knows three layers: preventive measures such as dike reinforcement (layer 1), measures in spatial planning that limit damage (layer 2) and interventions related to evacuation or crisis management (layer 3).

16.1.3 Interventions

The range of interventions is broad, ranging from new storm surge barriers to establishing new norms in the Water Act. This also means that adaptivity can be found in different shapes. For example, adaptivity can be demanded from hydraulic engineering structures themselves. Currently, most hydraulic engineering structures are passive and static. For instance, the Haringvliet sluices are designed for particular conditions and remain functional in case of particular maximum of sea level rise. Often, it is technically and financially hard to modify and adjust a particular intervention or water system. Hence, there is an increasing tendency to demand flexibility, or adaptivity from hydraulic engineering structures. The processes that are supporting the adaptivity and flexibility of structures show many similarities with the design of multifunctional structures. The design of multifunctional flood defences is tailored to combining different functions, and also takes into account the different time scales of the combined functions. If these time scales differ from the design life time of the structure, there is a need for flexibility and adaptability of multifunctional flood defences (Voorendt, 2017). Moreover, integrating various functions involves an ongoing debate between actors about what is going on and what the best strategy is to cope with the circumstances. In multifunctional projects, actors are constantly confronted with competing values and knowledge claims about different functions and the order of preference (Matos Castano, 2016).

Not only the hydraulic structures themselves can be made adaptable or flexible, but also the governance system can stimulate adaptive policy-making. This is a different form of adaptivity and is more about shifting between multiple strategies. Moreover, it is more related to a sequence of interventions and preventing lock-in situations. It is argued that all these frames on adaptivity are used interchangeably. Hence, it is hard to pin-point which interventions should enhance adaptivity. What is the role of flexibility of interventions? Or is it more about developing an adaptive governance system? This ambiguity makes it difficult to concretize and realize adaptivity in interventions. Furthermore, it makes it difficult to designate who is responsible for (the lack of) adaptivity

16.1.4 In the light of the conceptual model

Scenarios, scales and system boundaries and interventions all influence the solution space. These might seem to be purely technical aspects, but determine to a large extent the room for adaptive social learning. So, the conclusion is drawn that socio-political and physical aspects are already integrated to a large degree. As the lines indicate in the figure below, adaptivity is mainly a matter of translation between hybrid forms of knowledge. Hybrid indicates the mix of quantitative knowledge, such as numerical models, and qualitative knowledge based on for example local forms of evidence or storylines.

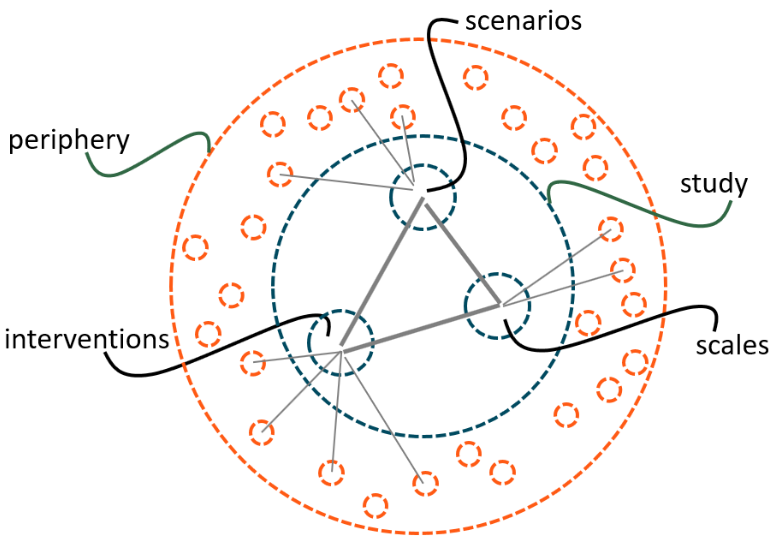


Figure 16.2: Relation between aspects of technical studies and the "periphery". This figure shows the mutual relationship between the aspect within and outside the system analysis of a technical study.

CONCLUDING REMARKS

Dissecting is about identifying the components of technical studies that influence adaptivity; scenarios, scales and interventions. Scenarios, scales and interventions all influence the solution space. These might seem to be purely technical aspects, but determine to a large extent the room for adaptive social learning. Predictive scenarios - What will happen? - and exploratory scenarios - What could happen? are problem focused as these scenarios end up with projections or explorations. Normative scenarios - How can as specific future be realized? - make use of backcasting and are more solution-focused. This means that the type of scenario has a considerable impact for the kind of research and the connected learning features. Actors at different geographical and sectoral scales have different perceptions. As the policy sector winners and loses differ at scale, the system boundary of a technical study also interferes with how the outcomes are perceived. Hence, it is recommended to use a multi-scale approach whenever possible. There exists ambiguity about adaptivity of interventions.

16.2 Rebuilding the hybrid approach in technical studies

It is argued that current approaches in delta management often are a hybrid approach of qualitative and quantitative elements. In the previous section, an attempt is made to dissect those elements and indicate what makes this approaches hybrid. This section proposes ways to rebuild the dissected elements while adhering to the principles of adaptive social learning.

16.2.1 Communicating with the periphery

In general, outcomes of technical studies emphasizes the results of the process, rather than the process itself. Technical studies are typically developed by a group of stakeholders, experts, and/or modellers, which puts pressure on the legitimacy. It is crucial for the Knowledge Program to also include those who stand at a distance. As mentioned, one of the challenges is to communicate information in a polarized world (Section 14.1). In other words, communication to the people who stand at a distance and do not actively participate in the Knowledge Program. Frequent communication about what is being discussed - including trade-offs - and in which direction the processes is headed is vital. Doing so, the Knowledge Program ensures that there are as few as possible barriers to stop outsiders from getting actively involved. The following pointers can help in communicating with the periphery (Adapted freely from Wals et al. (2009)):

- Take advantage of "hot themes";
- Link up with people's own concerns, perceptions and understandings of the issue at stake;
- Offer a realistic action perspective;
- The underlying goals must be clear, although it may change over time;
- Support information for implementing the actions must be comprehensible and accessible for all those involved, and those who want to become involved.

16.2.2 Flip the sequence

Too often, communication is subordinate to knowledge development. The physical perspective is argued to be the point of departure, and subsequently, knowledge developed within this perspective needs to be shared with the audience. Although this might work for linear decision-making problems, it is argued that this is a clumsy approach for complex decision-making problems such as climate adaptation in the Rhine-Meuse estuary. Throughout this research, there are many opportunities to adopt a more equal and two way approach and make socio-political factors governing in the physical perspective.

16.2.3 Images and imagining

For example, Jasanoff (2015) use the concept of sociotechnical imaginaries. They define this as collectively held, institutionally stabilized and publicly formed visions of desirable futures (Jasanoff, 2015). According to Hajer and Pelzer (2018), imaginaries are not solely a normative construction, but a contested and politicized configuration at the same time. In other words, imaginary shape expectations which activate the socio-political network. These imaginaries occupy the undeveloped space between idealistic water management visions and the networks with which actors often describe reality. In the context of Figure 16.2, imaginaries can connect the inner blue circle - representing a study or exploration - to the orange circle which is assembled of socio-political components. Imaginaries also serve a double function, they are both an achievable aim and a way to achieve this aim (Hajer and Pelzer, 2018). Moreover, some actors are only able to reflect on a scenario or possible future if they can visualize options. This is especially the case when it involves trade-offs among several objectives. It also helps to focus on the key information instead of being overwhelmed with (technical) details (Seijger et al., 2019). Similar to the different learning types in the socio-political perspective, the effectiveness of imagining depends on the audience, intent of the message as well as the medium (e.g. graphs based on data or storytelling). The strength of strategies is connected to the attractiveness of the future outlay of choices. Does it fit the imagination of present and future actors? As the image of a strategy becomes more persuasive, it becomes also more likely that the strategy will propagate through different decision-arena and planning cycles (see also Olesen (2017); Rijcken (2017)).

16.2.4 Analogies

Besides images and imagining, analogies can also inspire or reflect on strategies. In this section, two analogies are used to illustrate this effect. Here, these analogies are used to reflect both on the process, which is more related to the socio-political perspective, and the content, which is more related to the physical perspective.

Analogy: communicating vessels

The system of communicating vessels can be used to further explore the interaction between the problem, solution stream. The rationale behind the theory of communicating vessels is that the different water containers are connected. When the pressure is raised in one of the containers, the water level in the other containers will react. This analogy can be used to express that diverging and converging in the separate streams is connected to the other streams. For example, once the pressure on the political stream is raised by a discussion about what values are important in delta management, the solution window might change as well. In this way, the knowledge development does not take place in isolation is stressed again. Moreover, this analogy illustrates that consensus can not be reached in the separate streams without addressing the complete system. For example, it is impossible to reach consensus on a solution without a legitimate basis in the political stream.

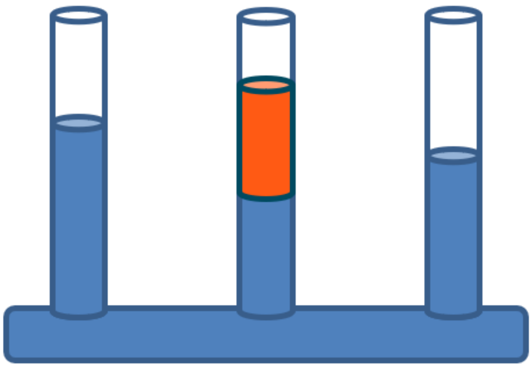


Figure 16.3: Illustration of communicating vessels.

Analogy: the urge to sit dry

Use imagination to reflect on the design process. The urge to sit dry questions whether the system of dike reinforcements is a problematic lock-in. The urge to sit dry grasps the system of continuous dike reinforcements and stimulates a debate about the current strategy. It also shows the fragility of the system. Moreover, if the image is followed, one could ask the question how much space there is up to the ceiling. The answer to this question could provide interesting insights which strategy is preferred, and what the sustainability is of that strategy.

Figure 16.4: Urge to sit dry by Boris Maas. This design project symbolizes the system of dike reinforcements (Maas, 2018).

CONCLUDING REMARKS

Rebuilding refers to the connection of scenarios, scales and interventions to socio-political aspects within collaborations and communications. Methods are proposed on how to communicate the results of studies with a hybrid approach of both qualitative and quantitative elements. Among others, it is advised to make use of imaginaries. Imaginaries are not solely a normative construction, but a contested and politicized configuration at the same time. In other words, imaginary shape expectations which activate the socio-political network.

16.3 Assembling technical studies

The entire knowledge base of all involved actors consists of the evidence gained in technical studies among others. All these knowledge frames make up the solution space that is available for adaptive delta management (Figure 16.5). This follows the train-of-thought of the conceptual model. The overlap between solution stream, problem stream and political stream leads to a space in which solutions are feasible and legitimate. For example, flood risk norms change over time due to societal developments. As particular areas represent more value because of higher investments or more inhabitants, the urge to protect that area increase as well. This leads to stricter flood risk norms, which affect in turn the solution space. Adaptive social learning accelerates and diversifies the directions in which this solution space is headed. How adaptive social learning can be implemented in technical studies is discussed in the previous section. In this section, some final remarks are made on the impact of this approach on the solution space.

The solution space also stresses that non-decisions are also decisions, as waiting or delaying decisions affects the solution space. For example, the long lead time of adaptation option in delta management makes that some options are excluded without an explicit choice having been made (Section 2.1.3).

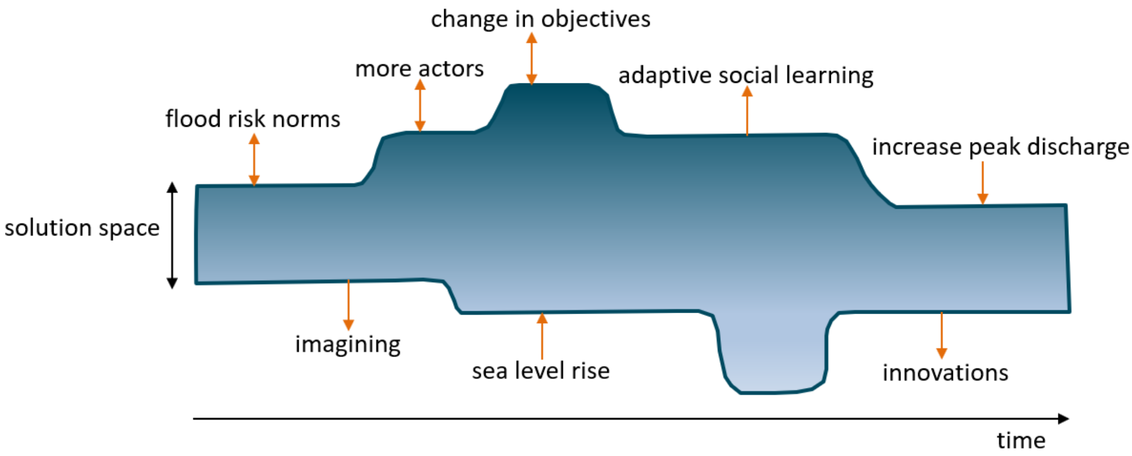


Figure 16.5: Illustration of solution space over time. The arrows indicate if a converging or diverging force is excited on the solution space. In the light of the conceptual model, the solution space corresponds to frames in the solution stream. This diverging and converging force are related to aspects of the problem and political stream (adjusted from Haasnoot et al. (2020))

CONCLUDING REMARKS

Assembling relates to gathering all the information of technical studies and connecting it to the socio-political surrounding. Frames about problems, solutions and politics compose together a solution space which contains solutions that are feasible and legitimate. It is shown how new knowledge affects the solution space within projects. The solution space stresses that non-decisions are also decisions, as waiting or delaying decisions affects the solution space.

Chapter 17

Conclusions

This research aimed to contribute to knowledge about climate adaptation in the Rhine-Meuse estuary. This chapter draws conclusions after having investigated climate adaptation from a physical, socio-political and integrated perspective. In the chapters 7 and 15 the answers to the sub-questions have already been formulated, so this chapter focuses on the answer to the main research questions RQ-I and RQ-II, as well as the overarching research question RQ-III.

17.1 Physical perspective

In the physical perspective, one of the possible adaptation options in the Rhine-Meuse estuary is investigated which led to the following research question:

> **RQ-I: What is the potential of Delta21 in reducing both the hydraulic loads and failure probabilities of flood defences in the Rhine-Meuse estuary under sea level rise?**

Delta21 succeeds in reducing the hydraulic loads throughout the entire Rhine-Meuse estuary. At the same time, these reductions differ depending on the dominant area. The reduction of governing water levels is based on water level frequency lines for various steps of sea level rise. For the storm surge dominant area, the reduction in governing water level is 10-20 cm, for the flood storage area 1-1.5 m, for the discharge dominant area 10-40 cm and for the transition area 30-60 cm.

The difference in failure probabilities follows a similar pattern as the reduction in hydraulic loads. For a sea level rise of 0 meters, 45 percent of the section fails on either piping or height in the current system. For Delta21, this percentage is equal to 30 percent. In case of 1 meter sea level rise, 77 percent and 42 percent do not meet the norm for the current system and Delta21 respectively. For 2 meters, 82 percent of the flood defences in the current system and 65 percent in a configuration with Delta21 do not have sufficient resistance. An improved Europoort barrier increases the number of sufficient section by 3 percent, but only in case of limited sea level rise (0 - 0.25 m).

Delta21 succeeds in lowering the hydraulic loads and corresponding failure probabilities. At the same time, reductions are disproportionately over the Rhine-Meuse estuary leading to low reductions in some sub-areas. This can be attributed to the open connection between the Rhine-Meuse estuary and the sea among others.

17.2 Socio-political perspective

Many actors are involved in flood risk management in the Rhine-Meuse estuary. The call for adaptivity and flexibility, which is increasing due to changing circumstances, inspired the following research question:

> **SQ-II: How can factors in decision-making and social learning be integrated into a conceptual model and support adaptive social learning in the Rhine-Meuse estuary?**

The concept of adaptive social learning has been coined to explicitly address the link between social learning and decision-making in adaptive delta management. An extensive literature review resulted in a theoretical framework that showed the interplay between social learning, decision-making and framing. An agenda setting theory, the multiple streams framework, formed the basis for the conceptual model.

The multiple streams framework is made more sensitive to communication processes by integrating elements related to learning. The resulting conceptual model allowed to study the Delta Program and Knowledge Program Sea Level Rise.

It is concluded that the Delta Program makes use of different types of learning leading to various forms of impact on decision-making. Using distinct narratives, the problem, solution and political stream are framed in particular ways. It is shown that the narratives, types of learning and decisions are strongly intertwined. For the Knowledge Program Sea Level Rise, it has been argued that the learning potential can be maximized by more alternating between converging and diverging design thinking. This leads to more negotiating about complementing or conflicting frames and stimulates actors to constantly reframe the situation leading to a more adaptive way of dealing with the changing circumstance. Moreover, it is expected to further contribute to the integrality already established in the Delta Program. Moreover, the conceptual model is supplemented with the DEALTa learning handbook, allowing actors to design learning activities that enhance adaptive social learning in delta management of the Rhine-Meuse estuary.

17.3 Integrated perspective

The integrated perspective is aimed to integrate the physical and socio-political perspective within technical studies. It provides an answer to the last research question:

> **RQ-III: How can the socio-political and physical perspective be integrated to enhance adaptive social learning in technical studies?**

The first conclusion is that the socio-political and physical perspective are already integrated to a large degree. Actors often deal with the combining of qualitative and quantitative knowledge sources in delta management. It has been concluded that adaptive social learning in delta management can be enhanced when this hybridity is dealt with in a more explicitly and reflexive ways. Three steps have been taken to provide more explicit relations.

Dissecting is about identifying the components of technical studies that influence adaptivity; scenarios, scales and interventions. Scenarios, scales and interventions all influence the solution space. These might seem to be purely technical aspects, but determine to a large extent the room for adaptive social learning. Predictive scenarios - What will happen? - and exploratory scenarios - What could happen? are problem focused as these scenarios end up with projections or explorations. Normative scenarios - How can a specific future be realized? - make use of backcasting and are more solution-focused. This means that the type of scenario has a considerable impact for the kind of research and the connected learning features. Actors at different geographical and sectoral scales have different perceptions. As the policy sector winners and loses differ at scale, the system boundary of a technical study also interferes with how the outcomes are perceived. Hence, it is recommended to use a multi-scale approach whenever possible. There exists ambiguity about adaptivity of interventions.

Rebuilding refers to the connection of scenarios, scales and interventions to socio-political aspects within collaborations and communications. Methods are proposed on how to communicate the results of studies with a hybrid approach of both qualitative and quantitative elements. Among others, it is advised to make use of imaginaries. Imaginaries are not solely a normative construction, but a contested and politicized configuration at the same time. In other words, imaginary shape expectations which activate the socio-political network.

Assembling relates to gathering all the information of technical studies and connecting it to the socio-political surrounding. Frames about problems, solutions and politics compose together a solution space which contains solutions that are feasible and legitimate. It is shown how new knowledge affects the solution space within projects. The solution space stresses that non-decisions are also decisions, as waiting or delaying decisions affects the solution space.

Chapter 18

Discussion

This research has investigated ways to improve flood risk management strategies in the Rhine-Meuse estuary from a physical and socio-political perspective. In the previous chapter, answers are presented to questions which guided this research. The questions - and results - were focused on the case studies. In this chapter, the findings of the studies will be embedded in a broader context. This is discussed in the next section (Section 18.3). Subsequently, the contributions of this research are summarized (Section ??). General limitations are discussed in the third section of this chapter (Section ??). These limitations are not so much related to considerations about the methodology, as these have already been discussed in Sections 15.1 and 7.1. Lastly, opportunities in research are treated for both further research and implementation in practice.

18.1 Implications

In the introduction to this research, the subject is places in a broader context of adaptive delta management. Due to large uncertainties in both physical and socio-poltical settings, adaptive delta management has been proposed an approach to develop suitable delta management strategies. As the pressure on deltas will rise in the future, it is envisioned that many regions around the world are forced to adopt an adaptive mindset.

In the physical perspective, insights are gained about the effect system intervention - Delta21. Due to more advanced computational models and increasing computational power, aspects that were previously investigated in the detailed design stage can now be investigated in a conceptual design stage. An example of a model that allows to do many computations is the MHWp5 processor, which is used for the first time in this research. Faster and completer models provide many opportunities to investigate other system interventions and determine their effect on different dimensions of the water system. At the same time, this does not mean that the analyses of conceptual designs can replace detailed design stages. There remains a need to specifically research system interventions on a detailed scale to validate both the results of the conceptual design stage and deliver new insights valuable for establishing a preferred strategy.

From the socio-political perspective, it was found that multiple knowledge frames among actors are recognized by the Delta Program and Knowledge Program. At the same time, the steering uses a convergent approach aimed at reaching consensus. This research explicitly connected learning and adaptive decision-making aspects. It is argued that this perspective is a complementing approach to bridge the gap between that exists between theory and practice in adaptive delta management. An ongoing open discussion about how learning activities can be designed for adaptive delta management increases the understanding of how socio-political factors can be truly integrated in the efforts of the Delta Program. It supports the notion that delta management should not only be about correct sum of benefits of costs or about the right application of the rules. In complex problems within adaptive delta management, it is often impossible to compute a complete overview of benefits and costs and is not crystal clear which rules are applicable. In these situations, the supporting narrative becomes important, and if this provides a meaningful perspective to water managers and water users.

Integrating analytical and policy processes remains a challenge in adaptive delta management. A process that is truly iterative and open for learning would recognize the close relationship between product and process, and plans and planning. It would also create are more widely shared understanding that any intervention, whether it is physical or in policy, could be viewed as an experiment in the sense that observations provide an opportunity for learning. Instead of plans that tend to foster exclusion, integrality would be implemented in such a way that still permits the process to move forward towards effectuation. Uncertainties, rather than being taken into account implicitly, would instead be explicitly addressed by actors and be part of a deliberative decision-making process.

18.2 Contributions

The first contribution is found in the integration between the physical and socio-political perspective. These perspectives are rarely included in one research. Addressing both perspectives in one research led to valuable notions about the interaction between both fields. As discussed in the previous section, the implications of this research fit in a broader context wherein the main limitations in decision-making can not be ascribed to either physical or socio-political constraint, but in the interaction between both fields. Suggestions are made to bridge the gap between these fields and how concrete learning activities can be designed.

The physical perspective provided a preliminary insight into the effect of pump capacity on the water system, hydraulic loads and probabilities of failure mechanisms. The effects of the conceptual design are translated into a first estimate of expected savings on dike reinforcements. The used approach can provide a basis to compare other system interventions to the current system.

In the socio-political perspectives, first the theoretical gap between adaptive delta management and social learning is bridged. Although there is still room for further research into the overlap between social learning and adaptive delta management, this research contributed in showing how aspects from both literature strands overlap. Moreover, it is shown how these theoretical notions are translated into a conceptual model which again can be used to design concrete learning activities. It is hoped that both the Delta Program and Knowledge Program can benefit from the reasoning elaborated in this thesis. This research, and the DEALTa learning handbook in particular, might help in increasing the learning potential within delta management by embracing uncertainty and ambiguity in both the preferential strategy as the learning process working towards that strategy.

18.3 Limitations

The research focussed on multiple case studies. The scope of the physical perspective was framed around the implications of Delta21 on flood risk safety in the Rhine-Meuse estuary. In the socio-political perspective, the scope was limited to the collaboration within the Delta Program and Knowledge Program. These case studies narrowed down the contextual boundaries while at the same time introducing limitations. Shortcomings regarding the methods used have already been discussed in the closing of the physical and socio-political perspective, so these are not treated in this section.

As denoted throughout the research, it is hard to adopt a truly integrated approach to problems in adaptive delta management. This also holds for this research. This research is conducted by one researcher, making it vulnerable to notions that can be traced to the bias of the researchers. This particularly plays a role in the socio-political perspective, as perception plays a large role in observation, the definition of challenges and suggestions to improve adaptive social learning. Although the steps in retrieving results are documented by the author, other researchers would have used different approached the problem differently and leading to different end results.

The physical perspective made use of a limited number of representative locations to draw conclusions about the entire domain of the Rhine-Meuse estuary. Although this might be in line with the conceptual character of the case study, more diversification and detailed investigation is needed to substantiate the findings of this research. Moreover, the socio-political perspective showed that there are many angles which need to be taken into account in delta management. To make it possible to come up with concrete results, the perspective is narrowed down to flood risk safety aspects. As other aspects are neglected, the results only provide limited insights into the feasibility of Delta21.

18.4 Opportunities

The limitations and scope of the research provide many opportunities. Opportunities that can be researched by academia are discussed followed by possibilities to apply insights in practice.

18.4.1 In research

For adaptive delta management, it recommended to investigate dependency amongst measures. Estuaries often require a combination of flood reduction measures, which complicates the search for the best strategy. Often, the effect of isolated interventions is analysed with computational models. At the same time, it would be interesting to gain more knowledge about the interaction of multiple parallel strategies. This would provide insight on whether interventions tend to complement or compete with each other. This is especially relevant for the Rhine-Meuse estuary. As the water system consists of multiple lines of defence; storm surge barriers and dikes. Storm surge barriers are meant to lower the hydraulic loads. As the failure probability of the first line of defence - storm surge barriers - increases, the second line of defence - dikes - need to be reinforced. Hence, investments in water systems with multiple lines of defence is always a balancing act and decision-makers would greatly benefit when the effects of a portfolio of interventions are known.
The opportunities regarding the socio-political perspective are partly about further closing the gap between decision-making and learning in adaptive delta management. Learning and decision-making often occur at the same time. However, the nature of learning and the nature of decision-making can be different. Learning is more about diverging and asking questions, while decision-making is more converging and providing answers. Hence, more research is needed how an environment can be created in which actors are both are free to learn without compromising the legitimacy of decisions. Specifically, research to more psychological and cognitive aspects is interesting. Research about collaboration processes on an individual of team level in relation to decision-making can provide more background and explanation about why certain policies came into place.

For the integrated perspective, the development of tools provides a host for opportunities. The main challenge is to research how one integrated decision-making support tool can be developed, or how different tools can be made compatible. Especially, it will be a challenge to unite the increasing complexity of numerical models to the more inclusive and participatory style of decision-making. In other words, there are numerous research opportunities about analytical models and decision-making support tools can be made more transparent to foster decision-making. For example, in the physical perspective the propagation of uncertainties is not clearly documented which makes it difficult for decision-makers to value the outcomes. Further research could be aimed at not so much including more features in numerical models, but rather on how current numerical tool and implicit choices can be made more transparent. On the socio-political side of the coin, it could be researched to what degree underlying cognitive factors play a role in decision-making and how we can give those factors the attention that they deserve.

18.4.2 In practice

Besides the theoretical opportunities, insights in this report also give rise to practical opportunities. Here, some more elaboration is provided on directions that provide opportunities in the implementation of adaptive delta management.

This thesis endorses the idea that technology is never neutral. This means that engineers always should be aware of the importance of socio-political aspects. A narrative supporting the numbers is indispensable. So, for engineers - and other actors - it is always helpful to think about what information decision-makers need to make legitimate decisions and also what novel insights could convince decision-makers to reconsider their conclusion. Such questions about the interrelation between the two perspectives might have more impact than further developing numerical hydrodynamic models. More opportunities could be provided by education, but also governmental and private parties allow themselves to spend more time about interdisciplinary aspects within projects.
The author is pleased to see that different types of learning are mentioned in the latest Delta Program (Delta Commissioner (2020), p.30). This further confirms that learning takes a central place in the

Delta Program and that the Delta Programs recognizes the challenge to make different learning activities complementary to one another.

The main challenge is to internalize the integrated way of thinking. Van Hemert (1999) has a rather cynical explanation about the background behind room for the river; it is meant to continue engineering of rivers rather than changing the mindset related to river management. In other words, the shift is only discursive and not factual. She describes that the shift to room for the river is made to provide room to the engineer. I believe that adaptation to sea level rise in the Rhine-Meuse estuary is only successful when not only the discourse elements are changed but also the deep core beliefs.

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Chapter A

Sea level rise

Sea level rise is connected to global emission scenarios. As emissions are the most important driver of climate change, these scenarios govern also the rate of sea level rise (Table A.1) . In sea level rise research, large uncertainties exist since the rate of sea level rise is determined by complex feedback loops. As is indicated in the figure below, many phenomena have a influence on the rate of sea level rise. Currently, especially ice sheet losses are hard to predict (Figure A.1.

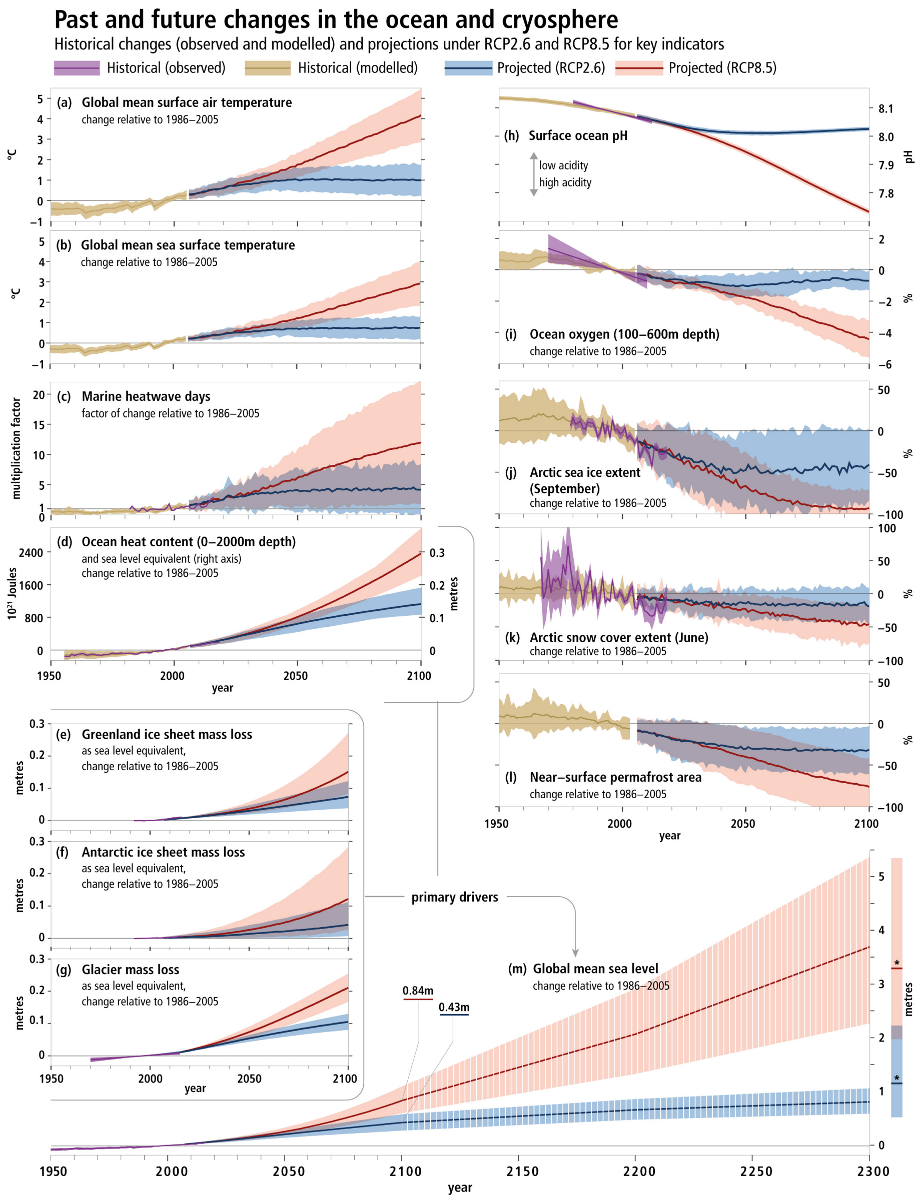


Figure A.1: Observed and modelled historical changes in the ocean and cryosphere since 1950, and projected future changes under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios (Portner et al., 2019).

Table A.1: List of included sea level rise literature published between 1983 and 2019. This list of studies is used in the literature review of sea level rise and gives the different values for sea level rise in 2100.

Year of publication	Reference
1983	Hoffman et al. (1983)
1986	Hoffman et al. (1986)
1987	Thomas (1987)
1988	Jaeger, Jill and Clark (1988)
1988	Van der Veen (1987)
1989	Oerlemans (1989)
1990	Warrick et al. (1990)
1992	Wigley and Raper (1992)
1993	Warrick et al. (1993)
1996	Warrick et al. (1996)
1996	Raper et al. (1996)
1997	De Wolde et al. (1997)
2001	Church et al. (2001)
2007	Meehl et al. (2007)
2007	Rahmstorf (2007)
2008	Pfeffer et al. (2008)
2008	Cayan et al. (2007)
2008	Horton et al. (2008)
2009	Vermeer and Rahmstorf (2009)
2010	Moore et al. (2010)
2010	Grinsted et al. (2010)
2010	Hunter (2010)
2010	Jevrejeva et al. (2010)
2012	Jevrejeva et al. (2012)
2012	Sriver et al. (2012)
2012	Zecca and Chiari (2012)
2013	Miller et al. (2013)
2013	Perrette et al. (2013)
2013	Church et al. (2013)
2014	Horton et al. (2014)
2014	Kopp et al. (2014)
2014	Slangen et al. (2014)
2016	Mengel et al. (2016)
2016	Kopp et al. (2016)
2016	Jackson and Jevrejeva (2016)
2017	Kopp et al. (2017)
2017	Le Bars et al. (2017)
2017	Goodwin et al. (2017)
2017	De Winter et al. (2017)
2017	Nauels et al. (2017)
2017	Bakker et al. (2017)
2017	Wong et al. (2017)
2019	Portner et al. (2019)

Chapter B

Hydrodynamic model

Throughout the research, various (Python) applications and programs have been used to model the Rhine-Meuse estuary. In this appendix, more background to this models is provided. First, the governing equations will be discussed followed by the adjustments that have been applied to the SOBEK 3 model. In the remainder of this chapter, an comparison is made between the used model and the WBI model. To conclude, the simulation approach that has been used to compare Delta21 and the current system is discussed.

B.1 Governing equations

SOBEK 3 is part of the D-flow 1D model (Deltares, 2020). For this research, SOBEK suite 3.7 is used. The software is best used in situation where simulation effort and robustness are considered more important than a high level of accuracy. In this 1D-model the flow computations follow the De Saint Venant (1871) equations for unsteady flow which are simplified versions of the Navier-Stokes equations. This set of equations consists of the 1D continuity equation (equation B.1):

$$\frac{\delta A_T}{\delta t} + \frac{\delta Q}{\delta x} = q_{lat} \tag{B.1}$$

Where:
A_T Total area (sum of flow and storage area)[m^2]
Q Discharge [m^3/s]
q_{lat} Lateral discharge per unit length [m^2/s]. Positive values refer to inflow, negative values to outflow.

And the 1D momentum equation (equation B.2):

$$\frac{\delta Q}{\delta t} + \frac{\delta}{\delta x}\frac{Q^2}{A_F} + gA_F\frac{\delta \zeta}{\delta x} + \frac{gQ|Q|}{C^2RA_F} - w_f\frac{\tau_{wind}}{\rho_w} + gA_F\frac{\xi Q|Q|}{L_x} = 0 \tag{B.2}$$

Where:
A_F Flow area [m^2]
C Chézy value [m$^{1/2}$/s^2]
g Acceleration due to gravity [m/s^2]
ζ Water level [m]
L_x Length of branch segment, accommodating an Extra Resistance Node [m]
Q Discharge [m^3/s]
R Hydraulic Radius [m]
t Time [s]
w_f Water surface width [m]
x Distance along the channel axis [m]
ρ_w Density of fresh water [kg/m^3]
τ_{wind} Wind shear stress [N/m^2]
ξ Extra Resistance coefficient [s^2/m^5]

The Saint Venant Momentum equation often consists of the first four terms. These terms represent the intertia, convection, water level gradient and bed friction respectively. Two terms have been added in teh D-Flow 1D software to account for wind force and resistance. The combination of these 6 terms is depicted in the latter equation and holds under de following assumptions (Deltares, 2020):

- The flow is one-dimensional which means that the velocity can be represented by a uniform flow over the cross section and the water level can be assumed to be horizontal across the section;

- The streamline curvature is small and the vertical accelerations are negligible leading to an hydrostatic pressure;
- The effects of boundary frictions and turbulence can be accounted for through resistance laws analogous to those used for steady flow;
- Higher order (2D or 3D) effects in bends are not taken into account.

As the model is primarily used to compute water levels throughout the Rhine-Meuse estuary, the results of the model are deemed to be accurate enough. The domain that is investigated is relatively large, which means that studying 2D and 3D effects would have an dramatic effect on the computation time of the model.

B.2 Structure of Rhine-Meuse Model

As denoted, the current model was not working optimal for the application of this research. Multiple adjustments have been made to tailor the model to the research objectives. The main adjustment is that the main properties of Delta21 have been added to create an alternative model. But first, as the model was not stable for all combination of boundary conditions, the real-time control of the Haringlviet sluices is adjusted.

B.2.1 Real-time control of Haringvliet sluices

Real time control (RTC) is used to simulate various real-time control and decision support techniques in application to water resource system (Deltares, 2019). In the Rhine-Meuse Mouth model (RMM-model) several control groups are implemented to regulate the storm surge barriers and pumps that are included in the system.

The RTC-group of the Haringvliet sluices resulted in instabilities when it was used in combination with MHWp5. In the previous RTC-group, the 17 doors of the Haringvliet had the same control scheme and were controlled via a so-called standard trigger(Deltares, 2019). A standard trigger compare two input variables and return True (1) or False (0):

$$y^k = \begin{cases} 1 & if \zeta_{up} - \zeta_{down} > \Delta h_{trigger} \\ 0 & otherwise \end{cases} \tag{B.3}$$

Where:
ζ_{up} water level upstream (Haringlviet side) [m]
ζ_{up} water level downstream (Sea side) [m]
$\Delta h_{trigger}$ head difference [m]

For seventeen doors, the trigger was set to a head difference of 0.12 m. After the fead difference exceeded the threshold of 0.12 m, the sluices were opened - resulting in a lowerering of the water level upstream and higher water level downstream. When the head difference went below the threshold, the doors were closed again. This leaded to opening and closing of doors in multiple subsequent time steps and produced unrealistic results (Figure B.1).

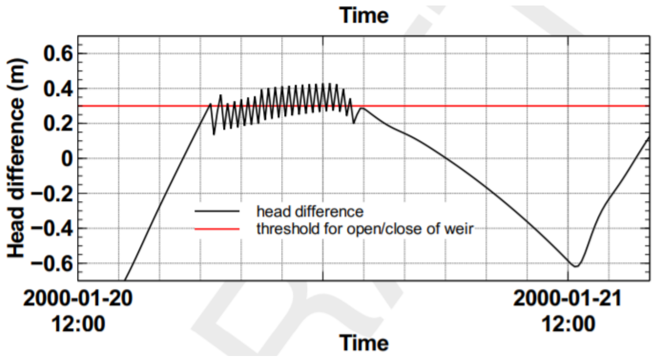


Figure B.1: Illustration of on-off control of the Haringvliet sluices triggered by the head difference (Deltares, 2019).

Therefore, two adjustments have been made: 1) a dead band is implemented which checks the input data for an upper or lower crossing. The trigger returns True (1) in case of an up-crossing of the upper threshold and returns False (0) in case of a down-crossing of the lower threshold. In the range in-between, the trigger keeps its state:

$$y^k = \begin{cases} 1 & if \zeta_{up} - \zeta_{down} > \Delta h_{trigger,up} \\ 0 & if \zeta_{up} - \zeta_{down} < \Delta h_{trigger,down} \\ y^{k-1} & otherwise \end{cases} \tag{B.4}$$

Where:
ζ_{up} water level upstream (Haringlviet side) [m]
ζ_{up} water level downstream (Sea side) [m]
$\Delta h_{trigger,upper}$ upper bound of head difference trigger [m]
$\Delta h_{trigger,down}$ lower bound of head difference trigger [m]

This results in more reliable behaviour of the doors, which is depicted in Figure B.2. Moreover, the values for the triggers are tailored to the different doors to enhance the reliability and validity of the RMM-model (Table B.1).

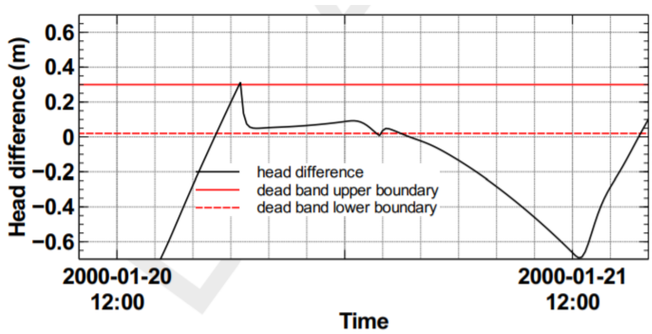


Figure B.2: Illustration of dead-band control of the Haringvliet sluices triggered by the head difference (Deltares, 2019).

Table B.1: Specification of upper and lower bound for the head difference trigger for the RTC-group of the Haringvliet sluices. Different closure and opening levels have been applied to come to reach a stable SOBEK model and represent reality.

Number of sluice	Upper bound [m]	Lower bound [m]
1	0.22	0.12
2	0.27	0.14
3	0.32	0.16
4	0.37	0.18
5	0.42	0.20
6	0.47	0.22
7	0.52	0.24
8	0.57	0.26
9	0.62	0.28
10	0.67	0.30
11	0.72	0.32
12	0.77	0.34
13	0.82	0.36
14	0.87	0.38
15	0.92	0.40
16	0.97	0.42
17	1.02	0.44

The release that has been used in this thesis is sobek-rmm-vozo-j15 _ 5-v2 (Deltares, 2016).

B.2.2 Delta21

The characteristics of Delta21 in that are included in the model of the water system are the pump capacity and increased storage area.

B.3 Singlerunner

The SingleRunner is an Python application that is closely related to both the MHWp5 and SOBEK 3 (Deltares, 2018). The main feature of the SingleRunner is that the simulation of the barriers can be controlled similarly to reality. This means that the barriers not only react on water level at the current time step, but also can act upon predictions of water levels.
The SingleRunner allows to switch between states of the barrier. The states of the barrier determine the cross-section that is applied in the SOBEK-3 model (FigureB.3). For example, when the Maeslant barrier is closed, the timesteps are computed with a closed Nieuwe Waterweg. This prevents water from flowing out from the Nieuwe Waterweg into the sea. The SingleRunner operates the barriers according to the decision-support system (In Dutch: Beslissings- en ondersteuningssysteem (BOS)). The criteria that are governing in operations are depicted below (Figure B.4).

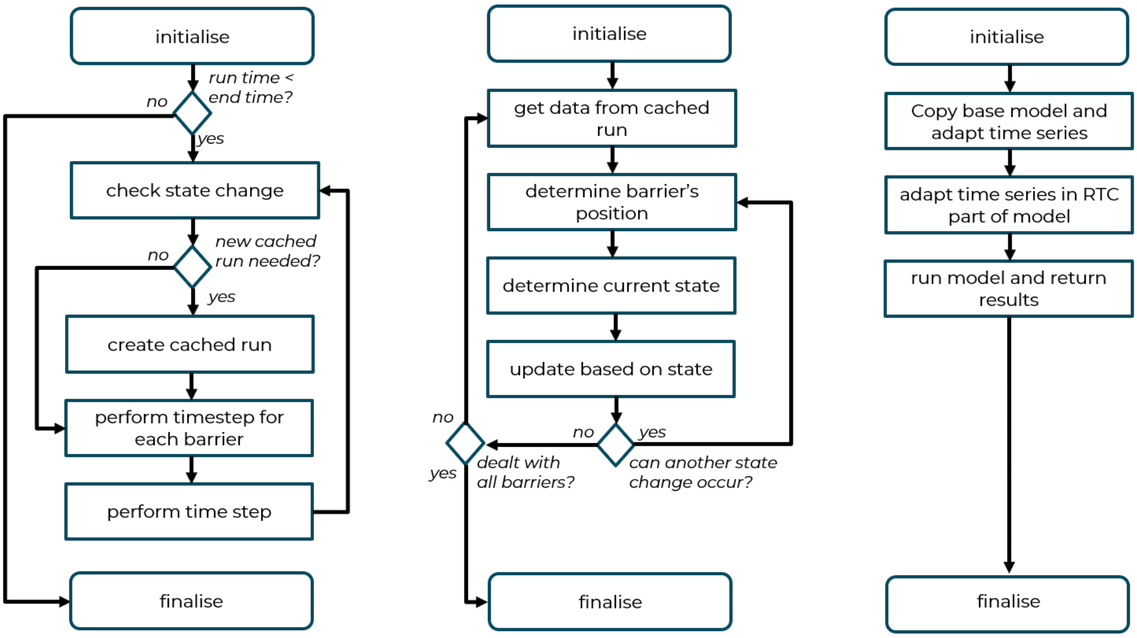


Figure B.3: Various loops of Singlerunner. The left loop investigates whether a new cached run is needs, the loop in the middle updates the state and corresponding position of the barrier and the right loop writes the results of the RTC to SOBEK (Adjusted from Deltares (2018)).

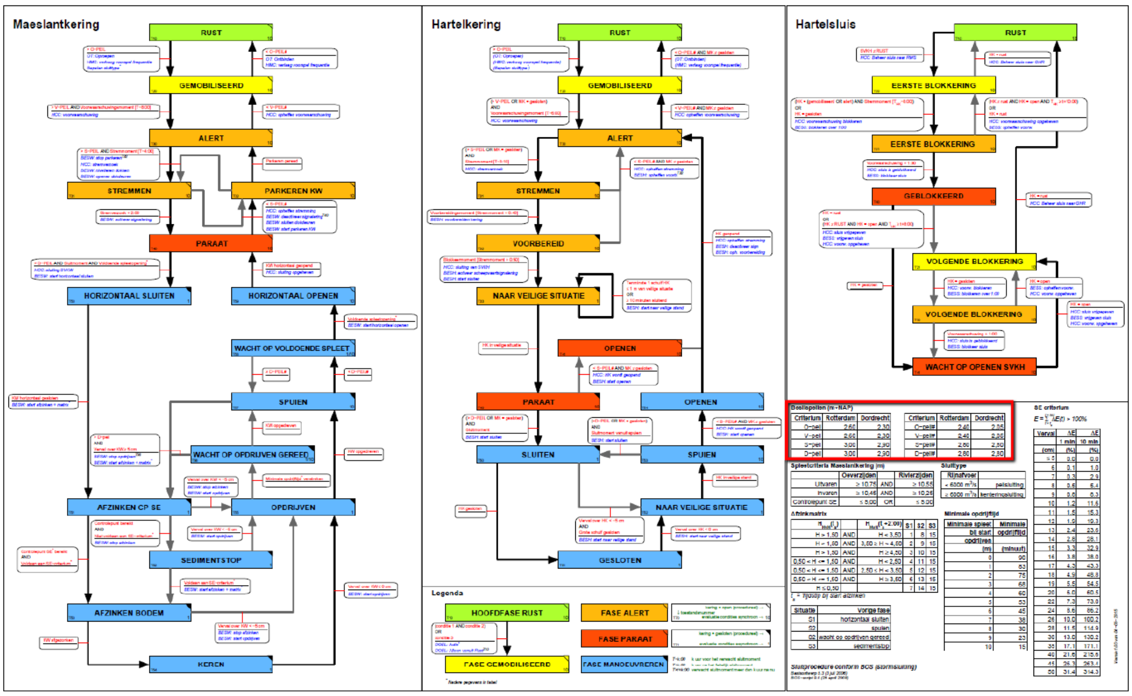


Figure B.4: Decision-support system of Maeslant barrier, Hartel barrier and Hartel sluice. In the flow diagram, the different states of the barrier are depicted along with the governing criteria based on both the current water level as well as the predicted water level. For each timestep, it is checked whether the barriers have to switch between states Deltares (2018)

B.4 Comparison to WBI-model

Databases with hydraulic loads are filled with the MHWp5 processor. The results of the database are compared to the WBI-database, which is currently governing in establishing hydraulic loads for different dike stretches.

Table B.2: Difference in water levels between MHWp5 and WBI database. The difference - in absolute values - is computed for water levels (MHW) and hydraulic load levels (HBN) at the norm of the dike stretch.

Location	Stretch	Difference WBI and MHWp5 MHW [m]	HBN [m]
Rotterdam	14-2	0.09	0.21
Maassluis	14-3	0.13	0.32
Lek 1	15-1	0.28	0.17
Lek 2	15-2	0.17	0.45
Boven-hardinxveld	16-1	0.14	0.73
Ablasserdam	16-2	0.08	0.14
Schoonhoven	16-3	0.25	0.09
Nederhoven	17-1	0.06	0.08
Waalhaven	17-2	0.00	0.00
Slikkerveer	17-3	0.14	0.20
Pernis	18-1	0.04	0.07
Rozenburg	19-1b	0.07	0.27
Spijkenisse	20-3	0.28	0.21
Haringvliet 1	20-4	0.05	0.08
Oude maas	21-1	0.07	0.08
Numansdorp	21-2	0.03	0.10
Nieuwe maas	22-1	0.09	1.22
Dordrecht	22-2	0.01	0.28
Steurgat	23-1	0.12	0.12
Biesbosch	24-2	0.17	0.18
Sleeuwijk	24-3	0.21	0.33
Middelharnis	25-2	0.04	0.05
Drimmelen	34-1	0.16	0.10
Noordschans	34-2	0.09	1.05

B.5 Simulation approach

With the model set-up as described so far, simulation results are obtained for the current situation and the situation including Delta21. By applying extra water storage and pump capacity for the Delta21 configuration, effects on the hydrodynamic system and flood risk of the Rhine-Meuse estuary can be investigated. Stochastic variables of boundary conditions are combined into different realizations to obtain water level frequency lines. For the Rhine-Meuse estuary, combination of 9 Rhine discharges (Table B.3) and 6 storm surges are necessary to compute reliable water level frequency lines (Geerse, 2013a; Nicolai et al., 2014; Chbab and Groeneweg, 2017). These 54 realizations form the core of the simulation approach. This core is extended with three different failure modes of the Europoort Barrier (Section 3.1.4).

The realizations are collected in a database, for steps of 0.5 m sea level rise (Table B.4). For the sea level rise of 1.5 m and 2 m, an higher closure level is applied to the simulation (Section 3.1.4). For the current system, overflow of the Haringvliet is allowed. This results in ten databases, five belonging tot the current configuration and five corresponding to the Delta21 configuration (Table B.4).

Table B.3: Discharge distribution confirm WBI-2017 (Agtersloot and Paarlberg, 2016). These nine discharges are used in the hydrodynamic model.

Q_{Lobith} [m^3]	$Q_{Hagesteijn}$ [m^3]	Q_{Tiel} [m^3]	Q_{Lith} [m^3]
600	25	550	55
2000	308	1401	217
4000	750	2697	687
6000	1158	3997	1156
8000	1572	5296	1626
10000	2062	6516	2095
13000	2701	8314	2800
16000	3382	10012	3504
18000	3868	11028	3974

Table B.4: Different databases to compare system effects. The databases differ in the system that is used, the amount of sea level rise (SLR), the closure level (CL) for both Rotterdam and Dordrecht, and whether overlow is allowed. Each database is filled with 162 different combinations (9 discharges, 6 storm surges and 3 failure modes).

System	Abbreviation	SLR [m]	CL RDAM [m+NAP]	CL DORDT [m+NAP]	Overflow HV
Current	CS_SLR0.0	0.0	3.0	2.9	Yes
	CS_SLR0.5	0.5	3.0	2.9	Yes
	CS_SLR1.0	1.0	3.0	2.9	Yes
	CS_SLR1.5	1.5	3.5	3.4	Yes
	CS_SLR2.0	2.0	4.0	3.9	Yes
Delta21	D21_SLR0.0	0.0	3.0	2.9	No
	D21_SLR0.5	0.5	3.0	2.9	No
	D21_SLR1.0	1.0	3.0	2.9	No
	D21_SLR1.5	1.5	3.5	3.4	No
	D21_SLR2.0	2.0	4.0	3.9	No

Table B.5: Discharge distribution confirm WBI-2017 (Agtersloot and Paarlberg, 2016). These nine discharges are used in the hydrodynamic model.

Q_{Lobith} [m^3]	$Q_{Hagesteijn}$ [m^3]	Q_{Tiel} [m^3]	Q_{Lith} [m^3]
600	25	550	55
2000	308	1401	217
4000	750	2697	687
6000	1158	3997	1156
8000	1572	5296	1626
10000	2062	6516	2095
13000	2701	8314	2800
16000	3382	10012	3504
18000	3868	11028	3974

Chapter C

Literature review into adaptive social learning

This appendix maps the process used to gather, select and integrate results from literature. First, the search and selection strategy is explained.

C.1 Search and selection strategy

The aim is to map the factors around adaptive social learning in a structured way. As explained troughout the socio-political part. An explicit overlap between decision-making and (social) learning in delta management is sought after. Scopus is the primary search engine which has been used. The searches are limited to English-language and peer-reviewed articles or books, to ensure a certain level of quality of the included items.

C.2 Systematic review

For the primary search, the following query is applied to the title, keywords and abstract (see next page). Overlap is sought between adaptivity - or related concepts - and decision-making and learning. Furthermore, literature related to water management is preferred for the primary search. Hence, literature related to other sub-areas or with key-words related to computer science are excluded. This query leaded to 554 results. Based on the exclusion criteria mentioned below, many results were excluded. In the end, 35 studies were deemed eligible to be included in the first search (Figure C.1).

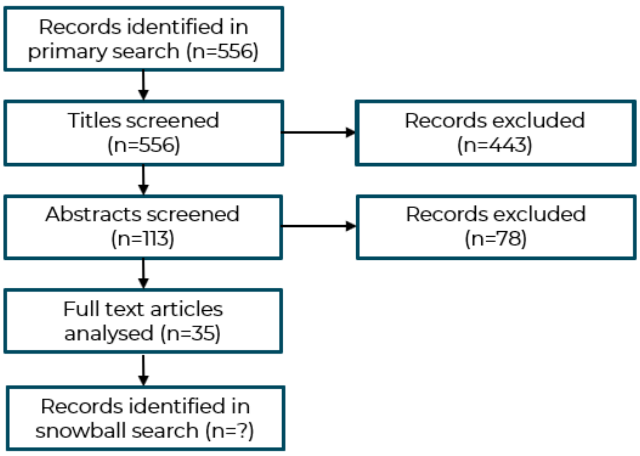


Figure C.1: General layout of literature review. Based on the primary search, articles are screened on the title and abstract. Records are excluded based on the exclusion criteria. In the last step, the 35 records of the systematic literature review are used as base for snowball sampling.

```
SEARCH QUERY
TITLE-ABS-KEY (
( adaptive OR adaptable OR flexibility OR robustness OR resilience )
AND
( delta OR flood OR coastal OR river* )
AND
( decision-making OR learning )
AND NOT (
biodiversity OR ecosystem OR disaster OR forest OR health )

AND (
LIMIT-TO ( SUBJAREA , ”EART” )
OR LIMIT-TO ( SUBJAREA , ”SOCI” )
OR LIMIT-TO ( SUBJAREA , ”AGRI” )
OR LIMIT-TO ( SUBJAREA , ”ENGI” )
OR EXCLUDE ( SUBJAREA , ”COMP” )
OR EXCLUDE ( SUBJAREA , ”ENER” )
OR EXCLUDE ( SUBJAREA , ”ECON” )
OR EXCLUDE ( SUBJAREA , ”MATH” )
OR EXCLUDE ( SUBJAREA , ”AGRI” )
OR EXCLUDE ( SUBJAREA , ”CHEM” )
OR EXCLUDE ( SUBJAREA , ”PHYS” ) )

AND (
EXCLUDE ( EXACTKEYWORD , ”Neural Networks” )
OR EXCLUDE ( EXACTKEYWORD , ”Optimization” )
OR EXCLUDE ( EXACTKEYWORD , ”Learning Algorithms” )
OR EXCLUDE ( EXACTKEYWORD , ”Artificial Intelligence” )
OR EXCLUDE ( EXACTKEYWORD , ”Artificial Neural Network” )
OR EXCLUDE ( EXACTKEYWORD , ”Numerical Model” )
OR EXCLUDE ( EXACTKEYWORD , ”Algorithm” )
OR EXCLUDE ( EXACTKEYWORD , ”GIS” )
OR EXCLUDE ( EXACTKEYWORD , ”Machine Learning” )
OR EXCLUDE ( EXACTKEYWORD , ”Computer Simulation” )
OR EXCLUDE ( EXACTKEYWORD , ”Genetic Algorithms” )
OR EXCLUDE ( EXACTKEYWORD , ”Fuzzy Mathematics” )
OR EXCLUDE ( EXACTKEYWORD , ”Fuzzy Inference” ) )
)
```

C.2.1 Exclusion

The majority of the results were excluded based on a review of te title, abstract and keywords. The following criteria were used for exclusion:

- Too narrow research scope. E.g. some studies relied on very specific case studies in which the conclusions are not deemed to be valuable for this research;
- Too different context. It does not matter if the context is different, as long as there are interesting connections to be drawn between the various subjects;
- Out-dated. Studies that are too old and contain literature that is not relevant any more;
- Geographic location. When the geographic location is too different from the setting in the Netherlands and this propagates through in the results. E.g. conclusions drawn strongly connected to local organizations and institutes;
- Not accessible. Some articles are excluded simply because these were inaccessible.
- No empirical findings. The main goal of the articles is to gain insight in the relation between theory and practice. Hence, articles without empirical findings are excluded.

C.3 Snowball search

From the selected 35 studies, references were investigated for relevant articles. Duplicates and inaccessible items were excluded. Besides the primary search and snowball search, additional references have been included as well. These are resulted from less systematic literature searches around specific themes or topics in relation to learning and decision-making.

C.4 Limitations

This review has some limitations. Given the large volume of decision-making and learning literature in the context of water resource management and delta management, the primary search and snowball search focus on a specific subset of the literature. Hence, the review is capturing only a portion of the discussion about all aspects involved in decision-making, social learning, collaboration in teams, framing in these various strands of literature. Hence, it could be that important concepts or frameworks are missing out in this review.

Chapter D

Process tracing

D.1 List of included Delta Programs

The Delta Programs were corner stone of the longitudinal analysis. Based on the information in the Delta Programs, different narratives and learning types have been identified.

Table D.1: List of included Delta Programs.

Year	Source	Title
2010	Delta Commissioner (2010)	Working on the delta: Investing in a safe and attractive Netherlands, now and in the future
2011	Delta Commissioner (2011)	Working on the delta: Acting today, preparing for tomorrow
2012	Delta Commissioner (2012)	Working on the delta: The road towards the Delta Decisions
2013	Delta Commissioner (2013)	Working on the delta: Promising solutions for tasking and ambitions
2014	Delta Commissioner (2014)	Working on the delta: The decisions to keep the Netherlands safe and liveable
2015	Delta Commissioner (2015)	Work on the delta: And now we're starting for real
2016	Delta Commissioner (2016)	Work on the delta: Linking taskings, on track together
2017	Delta Commissioner (2017)	Continuing the work on a sustainable and safe delta
2018	Delta Commissioner (2018)	Continuing the work on the delta: Adapting the Netherlands to climate change in time
2019	Delta Commissioner (2019)	Continuing the work on the delta: Down to earth, alert, and prepared
2020	Delta Commissioner (2020)	Staying on track in climate- proofing the Netherlands

D.2 List of included background documents

Several background documents provided additional insights on top of the Delta Programs. These documents range from evaluations, to reports and flyers. The information in these background documents have proven to be useful in the process-tracing approach of this research.

Table D.2: List of included background documents.

Year	Source	Title
2012	Botterhuis et al. (2012)	Onderzoek faalkans in kader van Kennis voor Klimaat
2014	Biesbroek et al. (2014)	Integraliteit in het Deltaprogramma: Verkenning van knelpunten en mogelijke oplossingsrichtingen
2015	Rijcken (2015)	Een adaptieve blik op de Rijnmond puzzel
2016	Hermans et al. (2016)	Monitoring en evaluatie ten behoeve van leren voor adaptief deltamanagement
2016	Loeber and Laws (2016)	Reflecterend in de delta: Naar een systematiek voor monitoring en evaluatie in het Deltaprogramma gericht op lerend samenwerken
2019	Ministerie van Infrastructuur en Waterstaat (2019)	Kennisprogramma Zeespiegelstijging
2020	Hallie et al. (2020)	Kennisprogramma zeespiegelstijging - verslag eerste landelijke dag

Chapter E

Activities and structures of the Delta programme

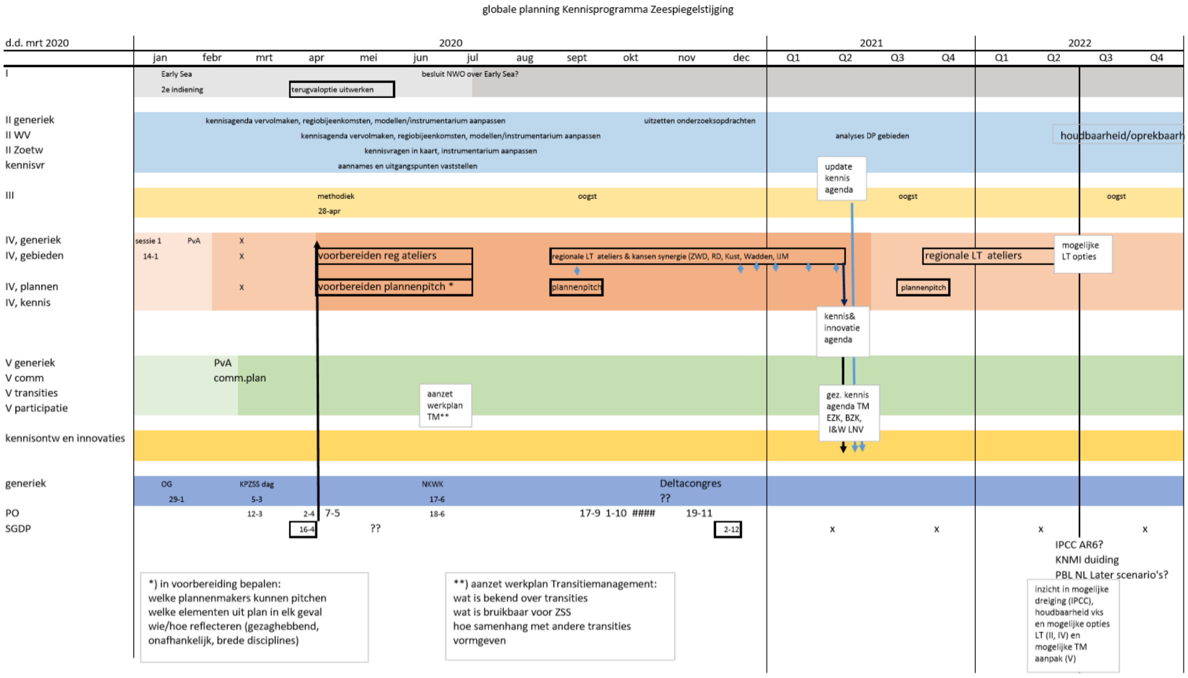
In this appendix, an overview of all activities of the Delta Program is given (Figure E.1) and the planning of the Knowledge Program Sea Level Rise is presented (Figure E.1).

Table E.1: Overview of activities about knowledge development, knowledge exchange, information work within the Delta Programme (part 1) (updated Loeber and Laws (2016)).

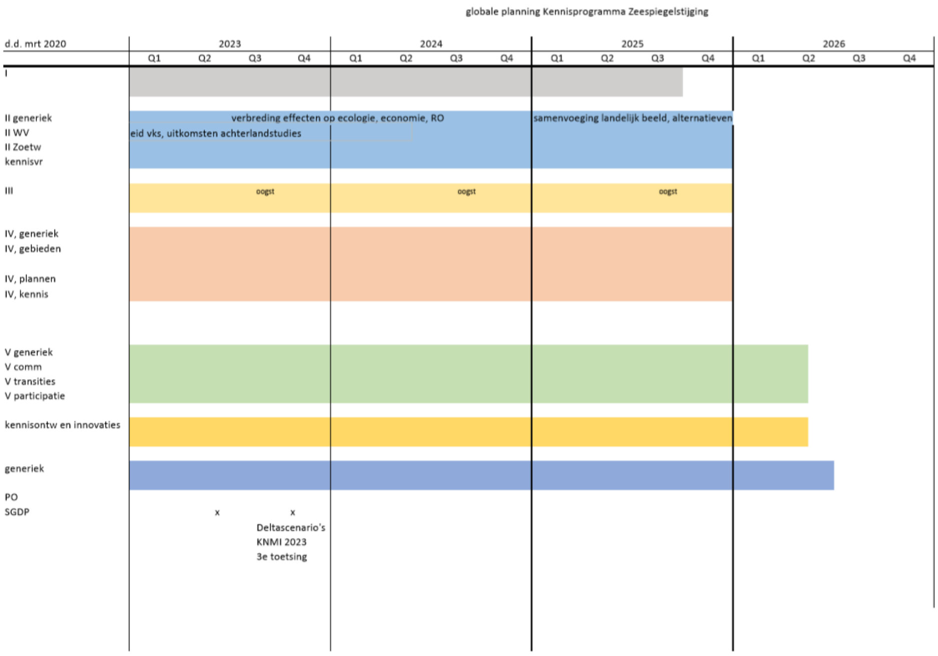
Sub(programme)	Name [frequency]	Involved actors
Delta Programme (general)	Knowledge development	
	Kennisnetwerk Deltaprogramme [once per 2 months] Nationaal Knowledge Programme "Water and Klimaat" (NKWK) Nationaal Water Model	sub programmes Delta Programme / knowledge institutes / IenW / EZ knowledge institutes / RWS / IenW / EZ / NWO / private parties RWS / knowledge institutes
	Knowledge exchange	
	Knowledge network Delta Porgramme (once per 2 months) Conference NKWK [yearly] Deltacongres [yearly]	sub programmes Delta programme / knowledge institutes / IenW / EZ Deltacommunity Detacommunity
	Information work	
	Delta Programme [yearly] Newsletter Delta Programme [quarterly] https://deltacommisaris.nl https://deltaprogramma.pleio.nl https://nkwk.nl	House of Representatives / regional and local officials / private parties / public Public Public sub programmes Delta Programme Deltacommunity
Flood risk management	Knowledge development	
	Research flood risk management (e.g. "Delta Plan Waterveiligheid") Pilots new flood risk norms Cross-project explorations HWBP: https://www.povmacrostabiliteit.nl https://www.pov-piping.nl https://pow-waddenzeedijken.nl Research Multi-Layer Safety Research GRADE Research programme "Riviergenese 1.0" Research programme Rivercare	Delta community / knowledge institutes Water boards / RWS / knowledge institutes Water boards / RWS / knowledge institutes Water boards / RWS / municipalities / knowledge institutes Water boards / RWS / knowledge institutes Water boards / RWS / knowledge institutes Water boards / RWS / knowledge institutes

Table E.2: Overview of activities about knowledge development, knowledge exchange, information work within the Delta Programme (part 2) (updated Loeber and Laws (2016)).

Sub(programme)	Name [frequency]	Involved actors
Flood risk management	Knowledge exchange	
	Knowledge programme Sea Level Rise	Water boards / RWS / knowledge institutes
	Project Water and Evacuation	V&J / Safety regions / RWS / water boards / knowledge institutes
	Education programme ”Implementatie Nieuwe Normering Waterveiligheid)	Water boards / RWS
	Information work	
	https://deltaprogramma.pleio.nl	sub programmes Delta programme / Knowledge institutes
	https://hoogwaterbeschermings programma.nl	RWS / Water boards / Knowledge institutes
	https://helpdeskwater.nl	Deltacommunity / Knowledge institutes
	https://infopuntveiligheid.nl	Public
	https://overstroomik.nl	Public
Fresh water	Knowledge development	
	Climate pilots (e.g. Delta Plan fresh water)	RWS / Water boards / knowledge institutes / private parties
	Explorations (Delta Plan fresh water)	RWS / Water boards / knowledge insititutes
	Research (e.g. slim watermanagement)	RWS / Water boards / knowledge insititutes
	Research Adaptive Deltamanagement	RWS / Water boards / knowledge insititutes
	Pilots Waterbeschikbaarheid	RWS / Water boards / knowledge insititutes / private parties
	Process evaluation Waterbschikbaarheid 2018	RWS / knowledge insitutes
	Knowledge exchange	
	Knowledge day fresh water [yearly]	Delta community
	Community of Practice fresh water	RWS / Water boards / provinces
	Information work	
	https://deltaprogramma.pleio.nl	sub programmes Delta Programme
Spatial adaptation	Knowledge development	
	Stimulation programme spatial adaptation	sub programme spatial adaptation / municipalities / knowledge institutes
	Area tailored implementation	Water boards / provinces / municipalities / private parties / knowledge institutes
	Process evaluation spatial adaptation	sub programme spatial adaptation / knowledge institutes
	Knowledge Exchange	
	Learning communities and events https://ruimtelijkeadaptatie.nl	sub programme spatial adaptation
	Information work	
	https://ruimtelijkeadaptatie.nl	Public



(a) Planning from 2020 to 2022.



(b) Planning from 2023 to 2026.

Figure E.1: Global planning of Knowledge Program Sea Level Rise (Hallie et al., 2020).

Chapter F

Interviews

F.1 Interviewees

Eight semi-structured interviews have been conducted in the context of this research (Table F.1). All interviews have been conducted online or by phone.

Table F.1: List of interviewees.

Nr.	Interviewee	Type	Interview date
1	Senior policy advisor Municipality of Rotterdam	Video call and transcript	June 19, 2020
2	Senior policy advisor Province of South-Holland	Telephone call and transcript	July 2, 2020
3	Program manager Knowledge Program Sea Level Rise and policy advisor at Ministry of I and W	Telephone call and transcript	May 13, 2020
4	Program manager Knowledge Program Sea Level Rise and senior policy advisor at Rijkswaterstaat	Telephone call and transcript	May 14, 2020
5	Program member Knowledge Program Sea Level Rise and senior policy advisor at Rijkswaterstaat	Telephone call and transcript	May 5, 2020
6	Program manager Knowledge Program Sea Level Rise and member of staff Delta Program	Video call and transcript	June 5, 2020
7	Senior advisor at the environmental management department of Rotterdam Port Authority	Telephone call and transcript	June 19, 2020
8	Senior advisor at Water Board Hollandse Delta	Telephone call and transcript	July 31, 2020

F.2 Interview guide

Some of the professionals that have been interviewed, are closely active and involved in the Knowledge Program Sea Level Rise. Others are connected to delta manaagement processes happening in the surrounding of the Knowledge Program. The interviews possessed multiple aims:

1. Understanding the general context in which the actors operate and how they perceived the developments within and without the Delta Program;
2. Understanding how the interviewees describe the decision-making structure and what the main barriers and improvements are;

3. Understanding how the interviewees describe learning in the Delta Program and provide examples of learning activities.

The following questions are part of the semi-structured interview.

F.2.1 Introductory questions

1. Wat is je huidige functie?
2. Op welke manier ben je betrokken bij het Kennisprogramma Zeespeigelstijging?
3. Waarom is het Kennisprogramma Zeespiegelstijging opgericht?

F.2.2 Questions about decision-making and framing

1. Hoe heb je het verhaal van het Deltaprogramma zien veranderen over de tijd?
2. Waardoor is het programma en verhaal veranderd?
3. Wat zijn de sterke - en zwakke - kanten van het verhaal van het Deltaprogramma en Kennisprogramma?
4. Op basis waarvan worden besluiten genomen? Op basis van consensus, de meerderheid beslist of een andere vorm?
5. Is er consensus over het probleem, de oplossingsrichting en de werkwijze van het Kennisprogramma?
6. Hoe vind je dat de besluitvorming in het Kennisprogramma verloopt?
7. Welke partijen hebben een belangrijke stem in de uiteindelijke besluiten die genomen worden?
8. Wat zijn de groootste uitdagingen rond de beslutivorming van het Deltaprogramma?
9. Op welke manier kan het kennisprogramma bijdragen aan betere besluitvorming in andere deelprogramma's van het Deltaprogramma?

F.2.3 Questions about learning and negotiating

1. Op welke manier wordt leren vormgegeven in het Kennisprogramma Zeespiegelstijging?
2. Op welke manier wordt leren vormgegeven in het Kennisprogramma Zeespiegelstijging?
3. Hoe wordt er voor gezorgd dat de ontwikkelde kennis ook wordt gebruikt in de uitvoering van andere projecten?
4. Is er discussie over de manier waarop systeemverkenningen worden uitgevoerd en op welke schaal?
5. Hoe kan je ervoor zorgen dat de discussies niet op de vlakte blijven, maar de diepte ingaan?
6. Zijn alle actoren het eens met de werkwijze van het Deltaprogramma en Kennisprogramma Zeespiegelstijging?
7. Hoe - en hoe vaak - worden actoren op de hoogte gebracht van kennis die ontwikkelt is?
8. Is er vertrouwen dat de kennis die ontwikkelt wordt voldoende handelsperspectief biedt voor bestuurders?
9. Welke kansen zie je om de samenwerking binnen en rond het kennisprogramma te verbeteren?

Voor een integrale aanpak heb je zowel kwantitatieve als kwalitatieve kennis nodig. Waterveiligheid is meer kwantitatief, waar ruimtelijke adaptatie meer kwalitatief is.

1. Hoe zorg je ervoor dat die kennisstromen goed op elkaar aansluiten?

2. Op welke manier zorg je ervoor dat de discussies zowel in breedte goed zijn als inhoudelijk?

3. Welke uitdagingen zitten hier in de communicatie?

Sommige actoren hebben een voorkeur voor een bepaalde strategie vanuit hun eigen ideeën omtrent waterveiligheid, ecologie en economische activiteiten. Het kennisprogramma levert handelsperspectieven voor bestuurders.

1. Is er ruimte om te onderhandelen tijdens de bijeenkomsten van het Kennisprogramma zeespiegelstijging?

2. Hoe wordt bepaald welke lange termijn opties uitgezocht worden en welke niet?

3. Wie draagt de verantwoordelijkheid voor de besluiten rond de voorkeursstrategie?

4. Is er ruimte voor discussies en/of het bespreken van conflicten over welke kennis verzamelt moet worden?

F.3 Operationalisation

Adaptive learning, and its related features, are further explored in the context of the Delta Program. The primary source of information are eight semi-structured interviews with involved actors from different parties. To be able to extract and compare results from interviews, the mechanisms that are important need to be made observable. This section provides insight in the indicators and contra-indicators that are used. This can be seen as the deductive basis, as concepts are directly related to the theories and frameworks presented in Chapter 11.

In coding, the different concepts are more specified. For example, it is hard to be engaged in the complete cycle of decision-making. An actor is rather engaged in specific activities that take place on a certain (geographical) scale. In processing the transcripts, those factors are included in an inductive way.

F.3.1 Learning

Table F.2: Operationalisation for learning.

Concept	Indicators	Contra indicators
Engagement	Actors identify gaps in their knowledge and work together to address them. Development of trust.	Troubling issues are not raised during discussions.
Imagination	Actors can anticipate misunderstandings. There is a guiding vision.	Actors don't see themselves as members of a community with common interests and needs.
Alignment	Goals are interpretable into action.	Commitments are not clear enough to reveal common ground and differences in perspectives.
Salience	Actors find information relevant.	Actors do not find knowledge meaningful.
Credibility	Actors find knowledge convincing.	Actors don't trust information.
Legitimacy	Actors perceive information as fair.	Not all actors are taken into account.

F.3.2 Decision-making

Table F.3: Operationalisation for decision-making.

Concept	Indicators	Contra indicators
Reflexivity	Dealing with different and conflicting frames.	Only make decisions when there is consensus. Tunnel vision.
Resilience	Adapting to unpredictable change.	Decisions are based on one scenario.
Responsiveness	Decisions are made in time.	Decisions are ineffective. Losing trust by overreacting.
Revitalisation	Overcome barriers in decision-making. Tolerance of disappointments.	No decisions due to information overload.
Rescaling	Openess to multiple scale logics. Linking different objectives.	Strict jurisdictions.

F.3.3 Framing

Table F.4: Operationalisation for framing.

Concept	Indicators	Contra indicators
Represents a desired future	Positive and clear framing which is meaningful. Feasible and connected to larger goal.	Doomsday scenarios, focus on what is not desired.
Provides direction without hindering innovation	Ambiguity, multiple knowledge frames, multiple feasible strategies.	Strict goals and sub-goals. Limited metrics to judge plans and strategies.
Challenges status-quo	Enhances reflection on current values, procedures and routines. Organises friction and discomfort.	Comfortable and safe. Disconnected from practice
Grounded	Connected to examples that show the best of the current practices.	Abstract, floaty and lofty.

Chapter G

Dike segments in the Rhine-Meuse estuary

Table G.1: Dike trajectories that are within the scope of this research. The corresponding specification and norms are mentioned, along with the corresponding sub-programme. DPR = Sub programme rivers, DPRD = Sub-programme Rijnmond-Drechtsteden and DPZWD = Sub-programme South-West Delta.

Dike-ring name	Stretch	Length [km]	Sub-programme	Sig. value 1/P	Low. limit 1/P
Zuid-Holland	14-2	16,5	DPRD	100.000	30.000
	14-3	4,4	DPRD	30.000	10.000
Lopiker- en Krimpenerwaard	15-1	23,1	DPRD	30.000	10.000
	15-2	24,4	DPRD	10.000	3.000
Ablasserwaard en Vijfheerenlanden	16-1	15,1	DPR&DPRD	100.000	30.000
	16-2	31,0	DPR&DPRD	30.000	10.000
	16-3	19,9	DPR&DPRD	30.000	10.000
	16-4	19,6	DPR&DPRD	30.000	10.000
IJsselmonde	17-1	26,9	DPRD	3.000	1.000
	17-2	26,6	DPRD	3.000	1.000
	17-3	9,4	DPRD	100.000	30.000
Pernis	18-1	5,2	DPRD	10.000	3.000
Rozenburg	19-1	8,1	DPRD	100.000	30.000
Voorne-Putten	20-2	13,0	DPRD	10.000	10.000
	20-3	21,9	DPRD	30.000	10.000
	20-4	19,8	DPRD	1.000	300
Hoeksche Waard	21-1	30,4	DPRD	3.000	1.000
	21-2	40,3	DPRD	300	100
Eiland van Dordrecht	22-1	17,5	DPRD	3.000	1.000
	22-2	21,5	DPRD	10.000	3.000
Biesbosch	23-1	2,6	DPR	3.000	1.000
Land van Altena	24-1	18,0	DPR	10.000	3.000
	24-2	13,0	DPR	1.000	300
	24-3	15.3	DPR	10.000	10.000
Goeree Overflakkee	25-2	26.9	DPZWD	1.000	300
West-Brabant	34-1	24,4	DPZWD	1.000	300
	34a-1	23,0	DPZWD	3.000	1.000
	34-2	9,9	DPZWD	1.000	300
Donge	35-1	13,8	DPR	10.000	3.000
	35-2	14,7	DPR	3.000	1.000