Adaptation Tipping Points and Pathways | Towards a long-term perspective on the solution space of coastal adaptation in the Southwestern Delta in the Netherlands

Master Thesis report

31-07-2023

Author:	Jeroen Lokker
Student number:	1493477
Contact:	1493477@students.uu.nl
Supervisors from Utrecht University:	Martin Wassen and Martijn Kuller
Supervisors from Deltares:	Marjolijn Haasnoot, Renske de Winter and Anoek de Jonge

Word count: 11129

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Summary

In the coming century and beyond it is certain that sea-level will continue to rise, having a big impact on millions of people and their environment. However, the extent and rate of future sea-level rise (SLR) remain uncertain. To address the consequences posed by future SLR, long-term adaptation planning is needed (IPCC, 2022). This thesis aims to explore the solution space for coastal adaptation to SLR in the Southwestern Delta of the Netherlands. Central question of the thesis is: "which adaptation tipping points (ATP's) and adaptation decisions are most decisive for the solution space for coastal adaptation to SLR, focussing on the Southwestern Delta and the management targets here for the sandy coastlines, flood risks and freshwater supply "? It presents an assessment that considers the risk caused by an ATP, as well as the need for incremental or transformational measures to reduce this risk, referred to as the "decisiveness" of an ATP. Insight into pivotal decisions could provide short-term action and potentially avoid mal adaptation. Dutch water management favours adaptive delta management via a DAPP approach (Haasnoot et al., 2019c). Within four solution directions ("Protect-closed", "Protect-open", "Seaward" and "Accommodate") the solution space of adaption to SLR can be described. This thesis is based on the same approach.

ATP's were collected for the Southwestern Delta based on available reports and data bases and analysed. For the (sub)-basins of the Southwestern Delta, a few ATP's were aggregated with exception of the Eastern Scheldt basin, where substantial ATP's were aggregated. Consequently, the focus of this thesis is predominantly on the Eastern Scheldt basin as the main aim is to develop and test a method to determine the decisiveness of ATP's. Further research is required to decide if all used ATP's represent the complete picture in the Southwestern Delta.

Findings of ATP assessment of the Eastern Scheldt basin are amongst others that, with higher sea-levels more decisive ATP's occur and incremental adaptations may result in transformational adaptations. For example, with a minimal SLR of 1 meter the decision to keep the Eastern Scheldt basin open or closed arises. In this thesis all (sub)-areas were assessed separately. It is recommended to conduct a follow-up study in which the sub-areas of the Southwestern Delta are combined based on the method assessed in this thesis.

Glossary

Table 1: List of abbreviations

Abbreviation	Definition
ATP	Adaptation Tipping Point
DMDU	Decision Making Under Deep Uncertainties
DAPP	Dynamic Adaptive Policy Pathways
GMSL	Global mean sea-level
IPCC	Intergovernmental Panel on Climate Change
KNMI	Royal Dutch Meteorological Institute
NAP	Amsterdam Ordnance Datum or 'Normaal Amsterdams Peil'
SLR	Sea-level rise

Table 2: Terminology

Term	Definition
Adaptation	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects (IPCC, 2022).
Adaptation tipping point	Conditions under which current management strategies perform insufficiently and additional adaptation measures are required to maintain the existing or desired functionality of an area (Kwadijk et al., 2010).
Adaptation pathway	A sequence of short-term and long-term adaptation measures along a time axis in which associated path-dependent conditions are met (Haasnoot et al., 2019a).
Delta Program	Dutch Governmental Program aiming at current and future flood protection; ensuring sufficient freshwater availability and contributing to a climate-proof and water-robust organisation of the Netherlands (Nationaal Deltaprogramma, sd).
Solution space	The available set of measures that are effective and feasible under specific physical and socio-economic conditions. In relation to climate change this encompasses measures that fall within boundaries of what adaptation is considered to be socially acceptable, economically affordable, politically feasible and technically possible (Haasnoot et al., 2020a).

1. Introduction

Sea-level rise (SLR) poses a pressing and severe adaptation challenge for low-lying coastal zones around the world as it implies dealing with an uncertain future, associated with the rate and magnitude of these changes (IPCC, 2022). Coastal environments, on the transition between land and sea, are naturally among the most dynamic and active environments on our planet (Ward et al., 2020). Humans have settled in deltas, as they provide fertile grounds for food cultivation and establish a vital connection between the sea and the hinterland. These low-lying areas host megacities, form major logistic hubs and have ecological value, demonstrating its vital source of livelihood for hundreds of millions of individuals (Hurlimann et al., 2014; de Andrés, Barragán & Scherer, 2018). In recent decades, there has been a significant increase in the development and utilisation of coastal areas. Projections for future population growth indicate a further increase in population in the coastal zones for various socio-economic scenarios in the next decades (Merkens et al., 2016; IPCC, 2022). Presently, about 11% of the global population lives in coastal zones at less than 10 meter above the global mean sea-level (GMSL) (Melet et al., 2020; Haasnoot et al., 2021; IPCC, 2022). With higher sea-levels, coastal zones are at increased risk of coastal flooding, shoreline relocation and reduced freshwater availability (Griggs & Reguero, 2021; IPCC, 2022). Moreover, failure to properly adapt to SLR can lead to serious consequences for coastal communities, economic activities and ecosystems (Magnan et al., 2022).

To effectively address the challenges posed by SLR long-term adaptation planning is needed (IPCC, 2022). Long-term planning involves anticipating changes of which some are characterised by a high degree of uncertainties, complicating decision making (Marchau et al., 2019). One such area of 'deeply uncertain' change is the rate and magnitude at which sea-levels will rise, particularly beyond 2050. Tide gauge measurements and, since the early 1990's, satellite-based measurements indicate a GMSL rise of approximately 0.21 meter since the year 1901 at an accelerating rate (KNMI, 2021; Steffelbauer et al., 2022; Deltares, 2023). Currently it is safe to conclude that GMSL will continue to rise in the upcoming decades and beyond the year 2100. The expected SLR, however, is strongly driven by global warming and largely depends on climate mitigation, and how the development of melting glaciers and ice sheets will progress and contribute to SLR. Current projections of the GMSL by 2100 show a possible further rise of 0.26 to 1.01 meter (IPCC, 2021). However, a GMSL of 2.00 meter in 2100 cannot be ruled out. Large uncertainties in the rate of future SLR arises from the onset of ice sheet instability and potential ice mass-loss, especially of the Antarctic ice sheet (IPCC, 2021). Even if the Paris Agreement's aim to limit temperature rise to less than 2°C above pre-industrial levels is met, the potential for high-end SLR remain (Hinkel et al., 2018). Therefore, every bit of warming adds to our commitment to SLR for centuries.

In addition to using probabilistic methods that strongly rely on SLR projections, various tools have been developed that aim to support decision-making under deep uncertainties (DMDU) and prepare for uncertain events and adapt (Marchau et al., 2019; Rohmer et al., 2019). Unlike probabilistic methods that uses a single format for uncertainty, these methods consider a wide range of plausible scenarios and potential futures that do not need to be likely happen (Le Cozannet et al., 2017; Stanton et al., 2021). Some examples of such include Robust Decision Making (RDM) (Lempert et al., 2019), Adaptive Policymaking (ATPM) (Walker et al., 2001) and Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot et al., 2019a). All of these adaptive planning approaches have in common that they are based on future uncertainties, making sure that vulnerabilities and alternative solutions are detected and evaluated and leading to solutions and actions for the short- and long-term. By timely identifying reliable early warning signals and monitoring changes to gather insights, the need for new decisions or reassessments can be signalled.

In the Netherlands, an adaptive approach has been installed for adaptation to SLR within the Delta Program. This nation-wide program, aims to anticipate socio-economic and climate change-related challenges that may arise as the future unfolds. Adaptive Delta Management entails a management approach that is deliberate and open in dealing with the possibility of unforeseen developments in the future (Haasnoot et al., 2020b). It exists of strategic options of short-term actions and long-term options based on pathways analysis, inspired by the development of the DAPP-approach by the knowledge institute Deltares. This approach addresses uncertainties by identifying various potential sequences of decisions or actions under multiple scenarios. To this end, the Delta Program aims to indicate the available set of measures that are effective and feasible under specific physical and socio-economic conditions, often referred to as "the solution space". The Delta Program has a specific focus on its three main pillars: (1) current and future flood protection; (2) ensuring sufficient freshwater availability, and (3) maintaining the sandy coastlines. This exploration builds upon recent studies on possible consequences of SLR (Haasnoot et al., 2018a); the effectiveness of current strategies (Haasnoot et al., 2019a); and possible strategies (Haasnoot et al., 2019b) for adaptation to SLR under different scenarios.

Regarding SLR in the future, it is highly uncertain how this will develop and consequently it creates an increasing risk that probably has to be addressed with additional measures. To make timely and informed decisions, a focused emphasis on understanding the pivotal impacts and effects of SLR is recognised as essential. However, a major knowledge gap remains in how to determine which impacts and effects are most "decisive" for the solution space. Decisive, in this thesis, refers to the extent to which sea-level conditions lead to major risks for sustaining the existing or desired functionality of an area, as well as the possibility and way of reducing this risk.

This thesis addresses this gap by focusing on the development of a systematic approach to determine the decisiveness of Adaptation Tipping Points (ATP's). ATP's, here, are defined as SLR conditions under which current management strategies perform insufficiently and additional adaptation measures are required to maintain the existing or desired functionality of an area (Kwadijk et al., 2010). This thesis presents an assessment that considers the risk of an ATP, as well as the need for incremental or transformational measures to reduce this risk (for further explanation see *3. Methodology*). This thesis has the Southwestern Delta as case study area and focusses on the management targets for the sandy coastline; flood risks and freshwater supply. ATP's and potential adaptation strategies to combat these ATP's were collected for four sub-basins within the Southwestern Delta. The approach is applied primarily on the Eastern Scheldt basin, to demonstrate and test its usefulness. For three other (sub) basins of the Southwestern Delta this is done less extensively (*see section 3.1*). Last, the thesis evaluates, and discusses which adaptation decisions are possible and most decisive in determining the solution space for coastal adaptation to SLR, considering uncertainty in the expected SLR. This thesis supports the ongoing developments for an approach towards an enhance understanding of critical adaptation tipping points and strategies. Outcomes of this thesis can support policy makers since improved insights will be given for long-term adaptation and the impact of strategic options on the solution space.

To conclude, the objectives of this thesis are: (1) to obtain an overview of ATP's and potential adaptation strategies to combat these ATP's for the Southwestern Delta; (2) to develop a method to determine which ATP's are most decisive for the SLR solution space to coastal adaptation; and apply the method on the (sub) basins within the Southwestern Delta; (3) To evaluate and discuss potential measures and solutions, and how and when "low-regret" measures should be taken.

The central research question in this thesis is therefore:

Which adaptation tipping points (ATP's) and adaptation decisions are most decisive for the solution space for coastal adaptation to SLR, focussing on the Southwestern Delta and the management targets here for the sandy coastlines, flood risks and freshwater supply?

To answer the central research question, three sub-questions (SQs) have been formulated.

SQ.1: *Which ATP's and potential adaptation strategies may the Southwestern Delta experience with increasing SLR, focussing on the management targets here for the sandy coastlines, flood risks and freshwater supply?*

SQ.2: *How can we determine decisive ATP's?; What are decisive ATP's for the Southwestern Delta?*

SQ.3: *Which decisive adaptation decisions may lead to the greatest reduction in the solution space?*

Chapter 2 of the report provides an explanation of the sea-level rise (SLR) challenge in the Netherlands, with a particular focus on the Southwestern Delta. It also highlights the concept of Adaptive Delta Management. In chapter 3, the methods of data collection used to address the research question(s) are elaborated upon. This chapter also offers a more detailed description of the specific methods employed in each research step.

The results are presented in chapters 4,5 and 6. chapter 4 offers a general overview of the collected ATP's for various basins within the Southwestern Delta, along with their potential implications for the effectiveness of current management strategies and possible adaptation measures and strategies. The level of "decisiveness" for each used ATP is systematically indicated and further discussed in chapter 5.

Chapter 6 evaluates and discusses potential strategies and solutions, and how and when "low-regret" measures should be taken. The discussion is presented in chapter 7, and chapter 8 concludes the main findings of this research.

2. Dutch water management approaches

2.1 Sea-level rise challenge in the Netherlands and Southwestern Delta

SLR may lead to existential threats for countries situated at low elevations, such as the Netherlands. Recent studies done by Deltares, commissioned by the Dutch Government, provided first insights into the possible consequences of high and accelerated SLR for the Netherlands (Haasnoot et al., 2018a) and the effectiveness of current water management strategies under different SLR scenarios (Haasnoot et al., 2019b). As time progresses and sea-level conditions change, current Dutch water management strategies may no longer meet their objectives and ATP's may be reached (Kwadijk et al., 2010: Haasnoot et al., 2019b). One such area in the Netherlands facing these challenges is the Southwestern Delta. The Southwestern Delta encompasses the Zeelandic and South Holland (peninsula) islands and the estuaries of three major rivers: the Rhine, the Meuse and the Scheldt. The area is a vital hub for commercial shipping, fisheries, and tourism, and serves as a gateway to several surrounding Flemish-Dutch cities and ports, including Rotterdam and Antwerp. Additionally, the region has substantial ecological value. In response to the catastrophic 1953 flood disaster known as the "Waternoodsramp", the Dutch Delta Works were constructed, providing hard coastal defence structures that substantially increased flood protection in the area. The Eastern Scheldt has a closable storm surge barrier, while the Haringvliet and the Grevelingen are separated from the North Sea by the Haringvlietdam and the Brouwersdam, respectively. Only the Western Scheldt remained to have a completely open connection with the North Sea. Due to (partially) closed estuaries a diverse range of ecosystems developed, including salt tidal flats (Eastern and Western Scheldt) and a non-tidal lake (Grevelingen), as well as freshwater habitats (Haringvliet, Hollandsch Diep and the Volkerak-Zoommeer).

Figure 2.1 Overview of the Southwestern Delta, with its various water systems (depicted in the different shades of blue) and the Delta Work structures (barriers, sluices, etc.) (Rijkswaterstaat, 2004). The completion years are indicated in parentheses. For instance, the Haringvliet is a freshwater system with current that is separated from the North Sea by the Haringvliet dam (4) that was completed in 1971.

2.2 Adaptive Delta Management

Effectively addressing uncertainty about SLR is part of anticipating the future. Therefore, the development of adaptive plans is emerging to deal with uncertain SLR. To further illustrate long-term strategies in the face of uncertain SLR, a Deltares report commissioned by the Dutch Government explored strategies for adaptation to high and accelerated SLR in the Netherlands (Haasnoot et al., 2019b). Partial results of this study illustrate four solution directions that broadly describe the solution space for the Dutch delta for long-term SLR (**Figure 2.1**). The study was based on an extensive inventory of over a hundred existing adaptation plans to adapt to SLR (Deltares, z.d.). Subsequently categories were defined that organised those to four main categories, classified as the four corners of the solution space. These solution directions aim to explore the solution space and can all be used for implementation of adaptation to SLR. In practice, a combination of these directions is expected to be necessary as the future unfolds. Haasnoot et al. (2019b) describe the four solution directions as follows:

Protect-closed (EN)/ 'Beschermen gesloten' (NL): "p*rotect the coast against flooding and erosion by means of hard or soft measures, such as flood defences, sand replenishment or wetlands. River arms are closed off (with dams or storm surge barriers)".*

Protect-open (EN)/ 'Beschermen open' (NL): *similar as above, however: "some rivers remain in open connection with the sea. Hence flood protection along those open river branches is needed".*

Seaward (EN)/ 'Zeewaarts' (NL): "*create new, higher and seaward-located land to protect the delta against flooding (this could be combined with a manageable waterbody in front of the present coastline)".*

Accommodate (EN)/ 'Meebewegen' (NL): *"reducing vulnerability to the consequences of a higher SLR: water or salt tolerant land use (e.g., building on piles or crop use), raising land, spatial planning and/or inland migration".*

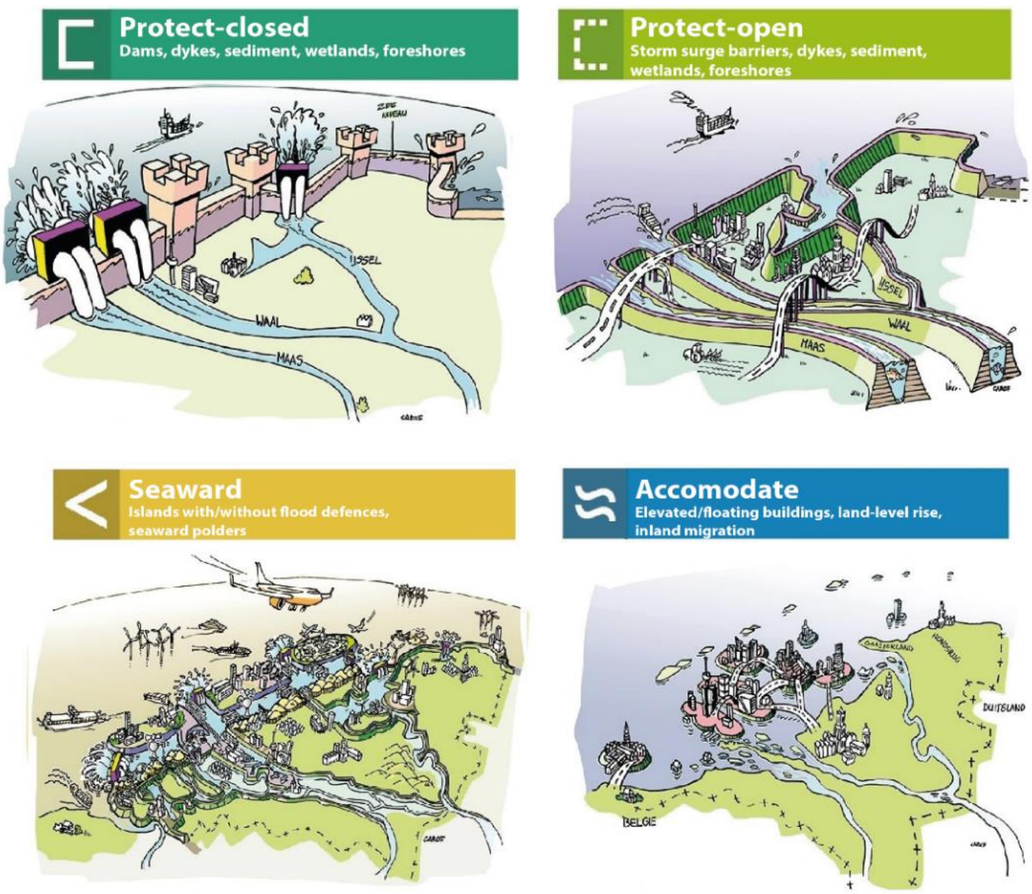


Figure 2.2 Solution space to adaptation and the adaptation strategies therein for the Dutch delta (Haasnoot et al., 2019b), with Protect-closed depicted in blue/green (upper left); Protect-open depicted in light green (upper right); Seaward depicted in yellow (bottom left) and Accommodate depicted in blue (bottom right). These directions are essentially different in how they deal with hard coastal protection or more flexible moving along with water solutions.

3. Methodology

3.1 Research scope

This thesis has the Southwestern Delta as case study area and focusses on the management targets for the sandy coastline; flood risks and freshwater supply. Although the focus of this thesis covers the entire Southwestern Delta, ATP's were found for four (sub) basins. Initially, analysis will be done on these (sub) basins, which include the Eastern Scheldt basin, the Volkerak-Zoommeer, the Haringvliet and the Bernisse-Brielse Meer system (**Figure 3.1**). Further analysis was then narrowed down to the Eastern Scheldt basin, where the most ATP's and pivotal impacts were found.

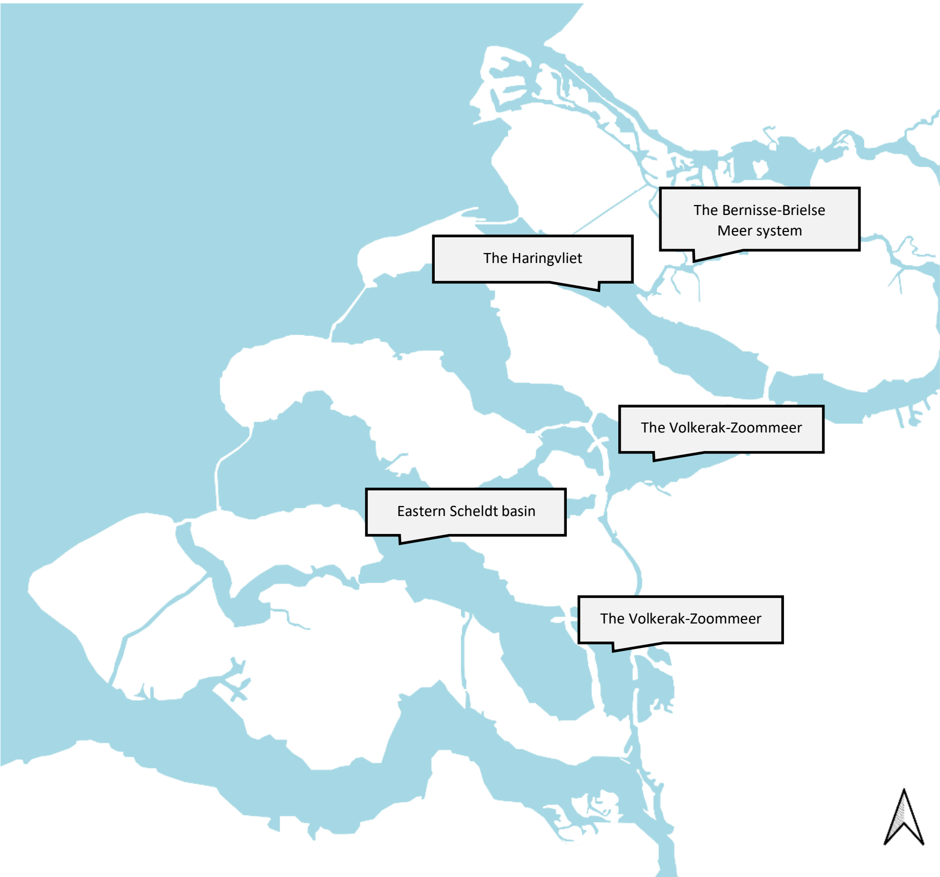


Figure 3.1 Overview of the Southwestern Delta and the considered (sub) basins.

3.2 General methods of data collection

Overall, this thesis combines data from a database developed within Deltares supplemented with an academic literature research and qualitative interviewing.

Deltares database

The Deltares database (Microsoft Excel file) was established to provide an overview of current insights into 'when, where, and how many ATP's may occur' in the context of climate change in the Netherlands, based on findings of recent studies. In this way, it facilitates their collective analysis. The use of this literature-based database (as described in *4.3 Methods per research step*) lays the foundation for aggregation of ATP's, within the scope of this research.

Literature review

The basis of this thesis relies on a theoretical framework that consists of multiple concepts stemming from different academic disciplines. These include long-term SLR, Dynamic Adaptive Policy Pathways and the solution space to coastal adaptation. Additionally, the analysis of studies done by e.g., engineering firms, facilitates the initial exploration of ATP's.

Qualitative interviews

The use of two qualitative open interviews allowed for the inclusion of input from experts across a range of specialities. This way, the two interviews were conducted based on the list of aggregated ATP's (*as presented in Tables 5.1 – 5.4*) and the methods (*as presented in section 3.3 step 2*), allowing for additional inquiries from the experts.

Ethical issues related to data collection, handling and storage

All data was collected and processed confidentially, in line with GDPR regulations (the General Data Protection Regulation and Personal Data Act). Prior to the interview sessions, informed consent forms were sent out to (and signed by) each interviewee. An overview of these forms can be found in *Appendix II*.

3.3 Research flow

In order to address the research questions, a set of steps were followed, as depicted in **Figure 3.2**.

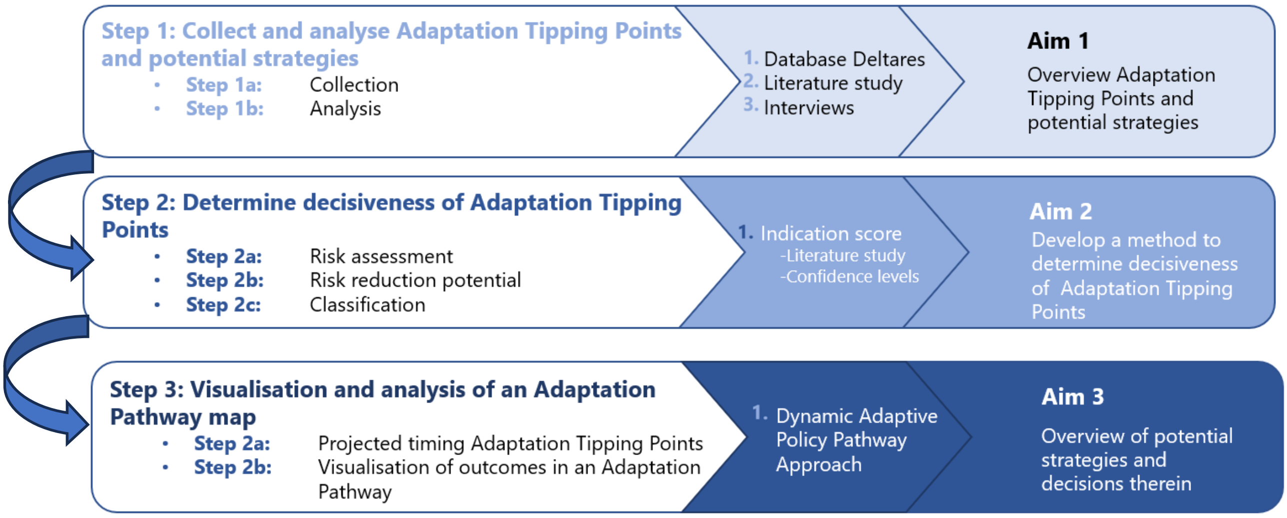


Figure 3.2 Research steps that were chronologically followed during this thesis, starting with step 1 at the top. Each step is divided into sub-steps. Various methods (depicted in an arrow) lead to the aim of each step.

Step 1 Collect and analyse Adaptation Tipping Points and potential measures

In this thesis an ATP is defined as: *sea-level rise conditions under which current management strategies perform insufficiently and additional adaptation measures are required to maintain the existing or desired functionality of an area, aiming at adaptation* and is based on the definition by Kwadijk et al. (2010) and Haasnoot et al. (2018a).

Step 1a: Collection

In order to collect current known ATP's and potential measures, this thesis made use of a database developed within Deltares. This database has been developed as part of the "ReThink the Delta" research program, and contains ATP's from scientific publications and research studies. In addition, a literature study and interview sessions were conducted.

To make the data usable for this research, the database was scoped specifically for the Southwestern Delta region and the management targets here for sandy coastlines, flood risks and freshwater supply in the light of future sea-level rise. Furthermore, after collecting the ATP's, the underlying literature/reports were examined to gain a better understanding of how the ATP's function.

To address any gaps in the database regarding current known potential ATP's, a literature review was conducted. Specifically, the literature study was carried out by analysing predominantly exploratory studies and academic peer-reviewed articles on ATP's for sea-level rise in the Southwestern Delta. In addition to the literature review, two qualitative interviews were conducted with two experts. Focus was laid on testing and demonstrating a first version of a method to determine the decisiveness of ATP's (*Step 2*), with the intention of gathering insights from experts to refine the method. Moreover, the experts were asked for the inclusion of new insights and potential addition of the aggregated ATP's, depending on their field of knowledge (coastline, flood risk or freshwater resources management).

Step 1b: Analysis

Further analysis was done by organising the collected ATP's in a map, indicating the location of occurrence along with a corresponding description. ATP's are represented by symbols indicating sea-level conditions under which they are likely to occur. A total of five snapshots were created, representing cumulative steps of SLR (*Step 1: 0.0 – 0.5 m SLR; Step 2: 0.0 – 1.0 m SLR; Step 3: 1.0 – 1.5 m SLR; Step 4: 1.5 – 2.0 m SLR, and Step 5: 2.0 – 3.0 m*). Overall, this approach allows for the determination of 'when, where, and how many ATP's may occur' in addition to the database.

Step 2 Determine decisiveness of Adaptation Tipping Points

To determine the decisiveness of ATP's a systematic approach was developed, consisting of three sub-steps: (2a) a risk assessment; (2b) a risk reduction potential assessment, and (2c) a classification matrix. To demonstrate and test its usefulness, this approach is applied primarily on the Eastern Scheldt basin. For three other sub-basins of the Southwestern Delta this was done less extensively (*see section 3.1*).

Sub-step 2a and 2b: Risk and risk reduction potential assessments

In both the assessments (*Sub-step 2a and 2b*), an indication score was assigned for each ATP from the list obtained in step 1. These indication scores are based on a literature study. The rationale behind the indication scores is presented in a table, providing explicit references for each statement. Uncertainty in these indication scores is represented through confidence levels that relied on the existing literature and the expert judgements. Other studies, including those conducted by the IPCC, use "Uncertainties Guidance's" to provide an indication of the reliability level of the presented results. These are based on scientific evidence and acceptance. In this research, a simplified classification is used (*low; medium, and high*).

Firstly, each collected ATP (resulting from *Step 1*) was assessed based on the magnitude of its impact on the aspects of sandy coastlines, flood risks and freshwater supply. Each ATP was assigned to an indication score of either 'high' or 'low'. ATP's that result in limited impacts on the mentioned aspects and that are considered acceptable, were given a 'low' indication score. ATP's that result in severe impacts on the aspects were given a 'high' indication score. In some cases, it was necessary to include other aspects along with the impact of an ATP on the mentioned aspects. For instance, under current management strategies, SLR may eventually lead to a permanent closure of the Eastern Scheldt barrier. When permanently closed, water levels in the Eastern Scheldt basin are quite static, only limited varying due to wind, and changes in inflow. From an ecological perspective and for certain economic sectors such as the mussel and oyster industry, this ATP is considered to have a severe impact.

Secondly, the possibility and way of adaptation that maintains the existing or desired functionality of an area was assessed. Such an indication was provided in this thesis by using two classifications as used in the IPCC AR6 report (2022): 'incremental adaptations' or 'transformational adaptations' (**Figure 3.3**).

Incremental adaptations are extensions of existing actions and behaviour that maintain the essence and integrity of a water system at a given scale, in anticipation of SLR and its impacts. Transformational adaptations change the fundamental attributes of a water system in anticipation of SLR and its impacts.

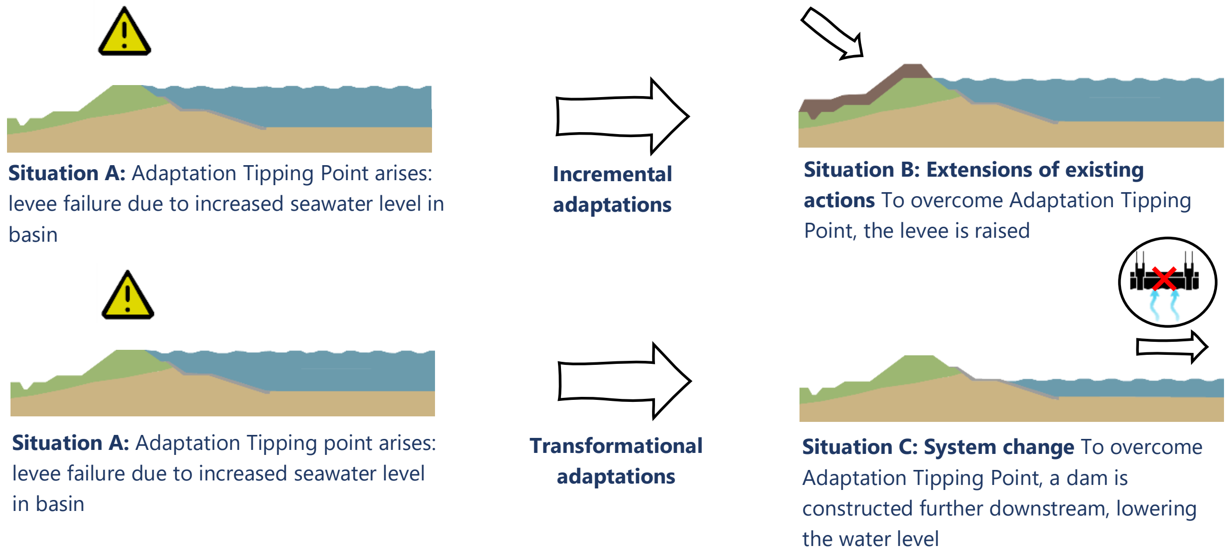


Figure 3.3 An example of incremental and transformational adaptations. In situation A, an Adaptation Tipping Point arises that can be addressed through incremental or transformational adaptations (arrows) leading to Situation B (after incremental adaptations) or Situation C (after transformational adaptations).

Sub-step 2c: Classification

To facilitate these individual assessments (*as resulted from Sub-steps 1 and 2*) into data that is useful for analysis, a classification matrix with a scoring system was developed (**Table 3.1**).

Table 3.1 Classification matrix with at the left side the risk reduction potential in either 'incremental' or 'transformational' adaptations and at the top the risk with either a 'low' or a 'high' score. A grey colour indicates a low risk and the need for incremental adaptations, thus a 'low level of decisiveness'. Yellow, red and purple indicate a 'moderate', 'high' and 'very high' level of decisiveness.

		Risk	
		Low	*High*
Risk reduction potential	*Incremental measures*	ATP results in limited impacts that are considered acceptable, and can potentially be reduced through incremental adaptations	ATP results in severe impacts that can potentially be reduced through incremental adaptations
	Transformational measures	ATP results in limited impacts that are considered acceptable, however necessitate transformational adaptations	ATP results in severe impacts that necessitate transformational adaptations

A low score (depicted in grey in Table 3.1) indicates a low risk and the need for incremental adaptations. Conversely, a very high score (purple in Table 3.1) indicates a high risk and the need for transformational adaptations. ATP's assigned a moderate score (yellow in Table 3.1) indicate a high impact that can be reduced with incremental adaptations, while a high score (red in Table 3.1) implies a low risk with the need for transformational adaptations.

The latter demonstrates that a "more decisive" score was assigned to ATP's resulting in low risk and requiring transformational adaptations, as compared to ATP's resulting in high risk and requiring incremental adaptations. This choice was made as it considers the extent to which an ATP is most crucial for the solution space in coastal adaptation to SLR. The solution space is substantially influence by fundamental changes to the water system in anticipation of SLR and its impacts.

Visualisation of outcomes

Outcomes of this scoring system are visualised in an overview of the occurrence of the collected ATP's due to changing sea-levels and their assigned 'level of decisiveness' with corresponding confidence levels. Moreover, the transition of decisive ATP's is visualised through a burning ember diagram, based on the (climate related) risk levels used by the Intergovernmental Panel on Climate Change (IPCC), Figure SPM.3 in the Summary for Policymakers (Pörtner et al., 2022). A burning ember diagram visualises the decisiveness of ATP's through colour transitions and therefore, in this thesis, aggregates the assessed decisiveness.

Step 3 Visualisation and analysis of an Adaptation Pathway map

To evaluate and discuss potential measures and solutions, this thesis adopts the Dynamic Adaptive Policy Pathways (DAPP) approach (Haasnoot et al., 2019a). This approach addresses uncertainties by identifying various pathways of potential sequences of decisions or actions under a wide range of plausible scenarios. These adaptation pathways are outlined in a conceptual manner, as it is uncertain how a future comprising socio-economic, climatic, and other physical developments, as well as their interactions, will unfold (Haasnoot et al., 2019a). Using this approach, it becomes possible to visualise which adaptation pathways lead to specific adaptation strategies and facilitates the discussion of potential measures and solutions.

Sub-step 3a: Projected timing Adaptation Tipping Points

The timescale of adaptation to SLR is often expressed in the degree of SLR at which the system change is expected [in meter]. To assess the time at which a collected ATP is reached, the expected SLR in meter will first be linked to its projected timeframe. To establish this, this thesis will consider the (most recent) SSP-scenarios obtained from the SLR projection tool that is developed by the IPCC and NASA (IPCC AR6 Sea Level Projection Tool, z.d.) (*Appendix II*). These SSP-scenarios provide potential developments in global greenhouse gas emissions, taking into account plausible socioeconomic, technological, and demographic developments in the future.

In this thesis, the second-lowest IPCC-scenario, SSP1-2.6, and a deep-uncertain scenario, SSP5-8.5 Low Confidence, are used. Assuming such rises, bearing in mind the uncertainties in the upper tail behaviour of SLR estimates, offers valuable insights into options on which measures may be considered at the earliest and latest occurrence of adaptation tipping points. Due to enormous differences between the two scenarios, particularly regarding SLR, an intermediate scenario (SSP2-4.5) is also considered. These three scenarios align with the scenarios used for the Dutch KNMI'21 climate signal scenarios.

Sub-step 3b: Visualisation of outcomes in an Adaptation Pathway

This sub-step describes the actions taken to develop a conceptual route-map, that illustrate actions to be taken with increasing SLR impact over time (an adaptation pathway). Previous work on adaptation pathways by Deltares has resulted in an adaptation pathway map of possible adaptation strategies for the Southwestern Delta (Haasnoot et al., 2019b). The focus of this section is to create and evaluate on an adaptation pathway map specifically for the Eastern Scheldt basin. This particular basin is chosen as, in this thesis, the most ATP's and pivotal impacts of SLR were found here. Elements considered to be relevant from the existing map for the Southwestern Delta have been used for the development of the adaptation pathway map for the Eastern Scheldt.

Adaptation measures (*resulted from Step 1*) and possible transitions between these measures were drawn based on ATP's (*resulted from Steps 1 and 2*) over time (*resulted from Sub-step 3b*). The set of possible adaptation measures is directed towards an adaptation strategy as defined in the Delta Program (Protect-open, Protect-closed, Accommodate or Seaward). Central to this map are ATP's. These are conditions under which a policy fails and therefore require additional measures. Additional measures can either be pursued following the same adaptation strategy, or through a transition towards an alternative adaptation strategy. Possible transitions between these strategies were drawn based on the ATP's. The level of decisiveness of these ATP's is indicated with colours (*resulted from Step 2*) and may lead to a system change and require possible transitions between the adaptation strategies.

4. Results: Adaptation Tipping Points and strategies for the Southwestern Delta

SLR may lead to different ATP's for the Southwestern Delta. ATP's are defined as: *SLR conditions under which current management strategies perform insufficiently and additional measures are required to maintain the existing or desired functionality of an area, aiming at adaptation*.

It should be noted that the present thesis does not encompass all ATP's that may arise, and it might therefore not show the full picture. However, the focus of this thesis is to develop a method to determine the decisiveness of ATP's and to demonstrate the usability of this approach, ATP's are therefore selected from a known source (*see Methodology section 3.2*). An overall overview of the used ATP's and the rate of SLR at which they are likely to occur can be found in **Figure 4.2**.

4.1 The Eastern Scheldt basin

The Eastern Scheldt basin is entirely enclosed by levees and the Eastern Scheldt barrier. Consisting of 65 pillars, the barrier uses movable barriers positioned between them to close off 3 tidal channels. The Eastern Scheldt barrier functions as a primary water defence and is intended to close only during storm surge conditions with elevated offshore sea-levels to prevent the hinterland from flooding. During calm non-storm condition, water levels within the basin can fluctuate with the offshore tidal water levels preserving natural dynamics and ecological values within the basin. This section highlights three main effects for the Eastern Scheldt basin:

1) The closure frequency of the Eastern Scheldt barrier and its impact on ecology;
2) The functional lifetime of the Eastern Scheldt barrier (based on height and closure frequency);
3) The functional lifetime of the Eastern Scheldt levees

Eastern Scheldt barrier closure regime and its impact on ecology

The Eastern Scheldt barrier closes when the sea water level is projected to be NAP +3 m (Dutch Ordnance Level) or higher. Currently, this occurs during storm conditions on average once a year. Due to SLR closing will occur more often, requiring more frequent and prolonged closures. A recent exploration on the consequences of accelerated SLR on the Dutch Delta Program (Haasnoot et al., 2018a) indicated that, under 0.50 m SLR, the barrier is expected to be closed 5 times per year. The annual number of barrier closures rapidly increases from a SLR of 0.75 and 1.00 m, reaching 22 and 45 closures, respectively, assuming that the present-day closing standards are not altered. The duration of these closures depends on the sea water level. It may be necessary for the barrier to remain continuously closed for multiple tidal cycles. With a SLR of 1.50 m, the Eastern Scheldt barrier may close around 100 times per year, possibly also during the summer months. To maintain the operational readiness of the barrier during the storm season, maintenance activities take place throughout the summer season. However, with closures during the summer months, it may become challenging to maintain the current maintenance routines. When permanently closed, the Eastern Scheldt becomes a lake (similar to the Grevelingen basin -*saltwater*- or the Haringvliet -*freshwater*). Water levels are quite static, only limited varying due to wind, and changes in inflow.

Prior to the construction of the barrier, the Eastern Scheldt was an estuary. Its open connection to the rivers and the sea, created a brackish-salt gradient in the Eastern Scheldt, supporting estuarine flora and fauna. Tidal currents and wave action caused erosion and sedimentation processes, resulting in a dynamic intertidal system. The construction of the barrier, and therefore the closure of multiple water basins that were previously connected to the Eastern Scheldt, resulted in a substantial reduction in tidal prism. This is the total amount of water that flows in and out during an ebb and flood cycle. Moreover, due to the barrier, the Eastern Scheldt is experiencing sediment imbalances with few to almost no sediment exchange with the North Sea (Slabbers et al., 2018; Deltares, 2023). Nonetheless, the Eastern Scheldt is still characterised as an intertidal area, with tidal influence.

However, more frequent closures of the Eastern Scheldt barrier limit the tidal influence and consequently affect the dynamic (eco)system and thereby biodiversity in the Eastern Scheldt (Zandvoort et al., 2019). These effects have implications for the extent and quality of the intertidal areas. This includes all areas exposed during low tide, including the unvegetated mudflats and sand banks, and the vegetated salt marshes. The results of a study on the effects of SLR and sediment deficits on the Eastern Scheldt (Zandvoort et al., 2019) showed that the combined effect of barrier closures and higher mean water levels, for a SLR ranging from 0.60 – 1.00 m, could potentially result in a decline in intertidal area by 57 – 68 % relative to the conditions in 2010. A reduction in intertidal area, along with the flattening of the highest sections of the sandbanks, diminishes the support base for both biodiversity and various forms of fisheries and shellfish farms. These sectors predominantly rely on the outer edges of the mudflats and sandbanks.

The functional lifetime of the Eastern Scheldt barrier

At the construction of the Eastern Scheldt barrier a SLR of 0.3 to 0.4 m, including an additional safety margin for settlement of the underlying ground, was included in the design (de Jong et al., 2022). It was assumed that this would be sufficient for a functional life span of 200 years, accounting for the SLR trend at that time, but not for climate change impacts on SLR. Recent research on climate change effects on SLR, however, indicates a faster rate of rise than initially anticipated, consequently reducing the projected functional lifespan of the barrier. The rise in sea-level introduces several potential failure mechanisms to occur earlier than anticipated during the design phase. These indicate the extent to which the operability of the Eastern Scheldt barrier can be ensured while meeting current societal needs and safety standard, without necessitating additional measures.

The research conducted by Witteveen+Bos, (2017) on Integrated Safety of the Eastern Scheldt revealed several of these failure mechanisms for the Eastern Scheldt barrier. The Roompotsluice, part of the barrier, facilitates maritime traffic between the Eastern Scheldt and the North Sea. The stone revetment of the lock platform is subjected to wave overtopping during storm conditions. With a SLR of less than 0.22 m, storm conditions may lead to an overtopping situation: during which the maximum overflow discharge may be exceeded and potentially damaging the revetment. A similar type of potential revetment damage is found at multiple locations along the Eastern Scheldt barrier from a SLR of 0.22 m. Similarly, grass cover erosion on the crown and inner slope may occur on several sections of the barrier. A low probability of other potential failure mechanisms was found for structural piping, inward macro stability and reliability of the structure closure, that could occur after a SLR of 0.72 m. With a SLR of 2.2 m, a storm event with a recurrence interval of 1:10 years results in a water level increase exceeding the design height (Haasnoot et al., 2018a).

The functional lifetime of the Eastern Scheldt levees

With the combined effect of SLR and in the absence of sediment supply, the Eastern Scheldt will likely experience elevated water depths (Witteveen+Bos 2017; Zandvoort et al., 2019). Larger water depths allows the development of large waves, leading to an increase of the forces exerted on the levees and therefore an increased risk for failure. Most of these potential failure mechanisms are expected to occur after a SLR of 0.72 m (Witteveen+Bos, 2017). However, research done by Witteveen + Bos (2017) found that, at some locations at the levees, failure mechanisms may arise from or with a SLR of less than 0.22 m. For instance, the overtopping of larger waves increases the likelihood of erosion of the levees inner slope and crown and damage on the stone revetment. For the levee locations Tholen and Oesterdam, these damages may arise from a SLR of less than 0.22 m. Moreover, a low probability was found for the failure mechanism inward macro stability, that could occur from a SLR of 0.22 m. In the event of occurrence of these failure mechanisms, and without implementing any subsequent measures, the risk of flooding increases.

Summarising adaptation tipping points

With a rising sea-level the current closure criterium of the Eastern Scheldt barrier (NAP +3m) will be reached more often, requiring more frequent and prolonged closures. Due to a combination of these closures and higher water levels, the estuarian dynamic (eco) system in the Eastern Scheldt will gradually disappear and eventually lose its vitality. Moreover, under higher sea-levels the functional lifespan of the Eastern Scheldt barrier will be shortened, potentially resulting in earlier replacement. Additionally, higher sea-levels will increase forces exerted on the levees and therefore, shorten their functional lifespan. A visual summary is presented in **Figure 4.1**.

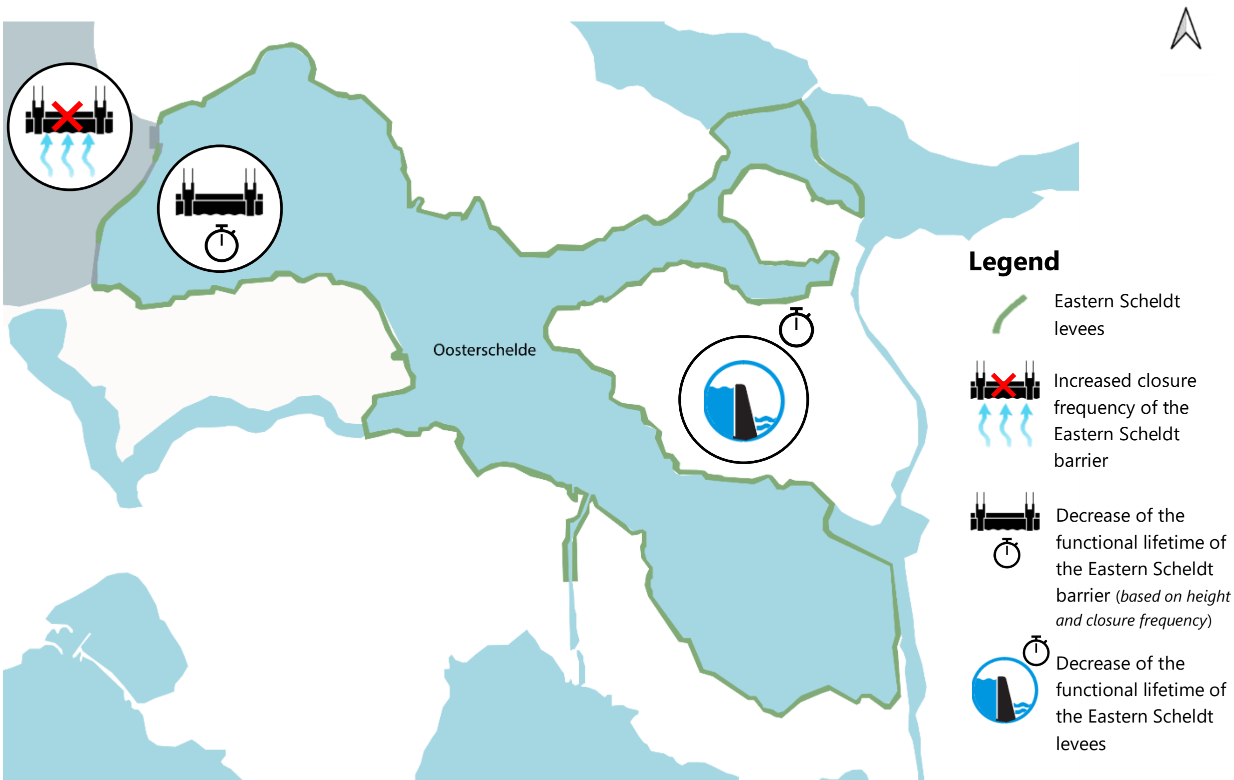


Figure 4.1 Overview of the main effects of Adaptation Tipping Points found for the Eastern Scheldt basin.

Adaptation strategies for the Eastern Scheldt

Given the ATP's, various implications may arise for the Eastern Scheldt. There are several alternative solution directions that can be followed to, in some extent, overcome or avoid these ATP's.

Haasnoot et al. (2018a) introduce an adaptation strategy which increases the current closing level of the barrier (NAP+3 m). By increasing the closing level, for instance with the same amount as the rate of SLR, the closure frequency of the Eastern Scheldt barrier remains constant. Hence, the barrier can remain open for nearly the entire year, similar to the current conditions ("Protected-open" strategy). However, a higher closing level would require the surroundings of the Eastern Scheldt to be raised to meet safety standards. An option for accomplishing this is by raising and reinforcing the old sea levees along the Eastern Scheldt.

An alternative way of meeting the safety standards is a transition towards the solution direction "Accommodate", by experimenting with land elevation. The aim of land elevation is to allow low-lying land to keep pace with SLR by facilitating sediment deposition. This can be achieved through either natural or artificial land elevation methods (Deltares, 2022). Due to minimal sediment exchange with the North Sea, natural land elevation is anticipated to be inefficient in the Eastern Scheldt (Haasnoot et al., 2019b). Artificial land surface elevation is possible on a small scale through mounts or on a large scale by raising entire polders (Deltares, 2022).

Another strategy to consider is a shift towards a "Protect-Closed" strategy. In the interview with A. Nolte (2023), it was suggested that an option worth considering is increasing the height or overflow resistance of the Eastern Scheldt barrier. Another option involves a permanently closure of the Eastern Scheldt. This transition would allow for the creation of a freshwater or saltwater reservoir within the Eastern Scheldt, similar to the Grevelingen or Haringvliet. However, such a transition necessitates adaptations in, for instance, ecology and mariculture practices (Haasnoot et al., 2018a).

Furthermore, the possibility of transitioning towards a "Seaward" strategy and establishing new land areas above sea-level in the North Sea off the Dutch or Belgian coast can be taken into consideration (Haasnoot et al., 2019b).

4.2 The Volkerak-Zoommeer

The Volkerak-Zoommeer consists of two lakes, the Krammer-Volkerak and the Zoommeer, that are connected through the Schelde-Rijnverbinding. Besides serving as a shipping route between the Rhine and Antwerp, the lake discharges water from the Hollandsch Diep, through the Volkeraksluices, and the Dintel and Steenbergse Vliet. Moreover the lake functions as an freshwater resource for its surrounding area and can be used for water storage. This section highlights two main effects for the Volkerak-Zoommeer:

1) The use of the Volkerak-Zoommeer as a water buffer;
2) The discharge capacity of the Bathse spuisluis (outflow of the lake) and its impact on water levels

The Volkerak-Zoommeer as a water buffer

To protect the hinterland during storm conditions from sea, the Maeslant barrier, Hartelkering and the Haringvlietsluices in the Rhine-Meuse Delta can be closed. When closed, river water cannot be discharged into the sea. Therefore, water levels in the Hollandsch Diep and the Haringvliet can rise to high levels. In these situations, the Volkerak-Zoommeer can function as a buffer, temporarily storing water. When fully used, this storage could decrease the water level in the Hollandsch Diep and the Haringvliet by up to half a meter (Rijkswaterstaat, 2012). Excess water is mainly discharged to the Western Scheldt via the Bathse spuisluis (sluice). During high-water events, the Krammersluizen can be used to discharge additional water.

With a higher SLR, the number of closures of the barriers in the Rhine-Meusedelta increases. Consequently, in case of high-water events, the need for water storage rises. A recent exploration of the climate resilience of the Volkerak-Zoommeer water management (Nolte et al., 2020) revealed that the probability for using the Volkerak-Zoommeer as a water buffer may increase from 1/1400 years to 1/25 years, with a SLR of 0.6 m and a peak discharge of 18.000 m3 /s from the Rhine.

The discharge capacity of the Bathse spuisluis

Using the Volkerak-Zoommeer as a water buffer involves an increased intake of water. To maintain a maximum water level, a high discharge capacity at the main outlet, the Bathse spuisluis, is needed. The water level at the Bathse spuisluis is managed between NAP -0.10 m and NAP +0.15 m. Water is discharged into the Western Scheldt, under free flow conditions. However, due to SLR, the water-level in the Western Scheldt may increase. When water level differences between the Volkerak-Zoommeer and the Westerschelde decrease, the discharge capacity of the Bathse spuisluis reduces (Van der Heijden et al., 2023). Nolte et al. (2020) found that with a SLR of 0.50, the discharge capacity of the Bathse spuisluis becomes limiting during substantial water inflow through the Volkeraksluizen, Dintel and Steenbergse Vliet and additional measures might be needed. For instance, the Krammersluizen may be used as an alternative, allowing for outflow towards the Eastern Scheldt (Geerse et al., 2017). With a SLR of 1 m and during high-water events, the discharge capacity of the Bathse spuisluis may reduce from 130 m^3/s to 70 m^3/s. Up to a SLR of 1.00 – 1.25 m, the discharge capacity of the Bathse spuisluis is anticipated to still be sufficient to maintain the desired water level, provided that saline seepage does not increase and sufficient water is available from the Hollandsch Diep (40 m^3/s year-round) (Nolte et al., 2020; Van der Heijden et al., 2023). With more than 1.00 – 1.25 m SLR, water storage in the Volkerak-Zoommeer is expected to become ineffective, assuming low to no adaptation (Kind et al., 2019).

4.3 The Haringvliet

The Haringvliet is separated from the North Sea by the Haringvlietdam, that protects the hinterland from high sea-water levels and discharges water from the Rhine and Meuse to sea through its sluices. The sluice complex consists of 17 openings, each 56.5 m wide, with a total of 34 closable sluice gates (Ministerie van Infrastructuur en Waterstaat, 2013). This section highlights a main effect for the Haringvliet:

- The design height of the Haringvlietdam

The design height of the Haringvlietdam

Under current conditions, in accordance with the Water Defense Act, a storm event with a recurrence interval of 1:4000 years results in a water level increase exceeding the design height of the Haringvlietdam (Leggerdocument Dijkringverbindende Waterkering Haringvlietdam, 2009). Haasnoot et al. (2018a) found that, considering the inner sluice gate design level of NAP+5 m, the design level of the Haringvlietdam is expected to be exceeded once every 100 years with a SLR of 1.00 m (1:100). With a SLR of 2 m, a storm recurrence interval of less than 1:10 years results in a water level increase exceeding the design height of the Haringvlietdam. “Exceeding the design level in the current condition of the barrier does not necessarily mean the barrier fails or collapses" (Kind et al., 2019). By reinforcing or raising the barrier, the barrier can withstand higher water levels, accordingly to the safety standards (Kind et al., 2019).

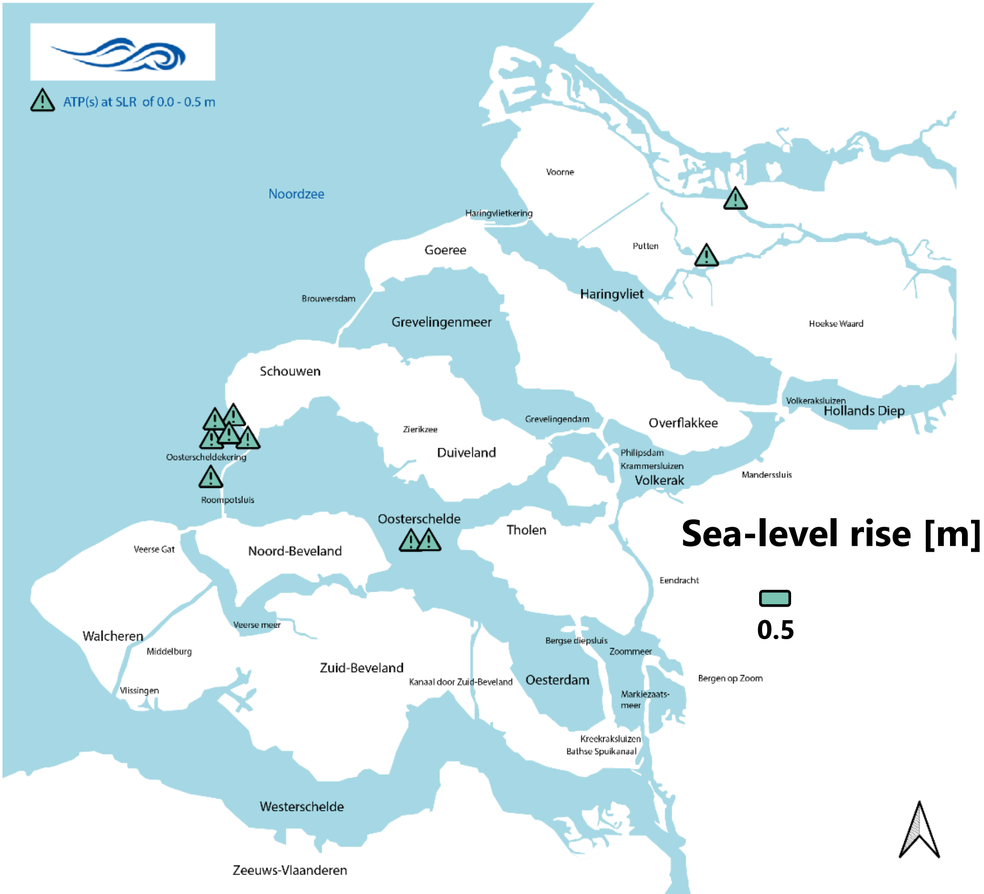
4.4 The Bernisse-Brielse Meer system

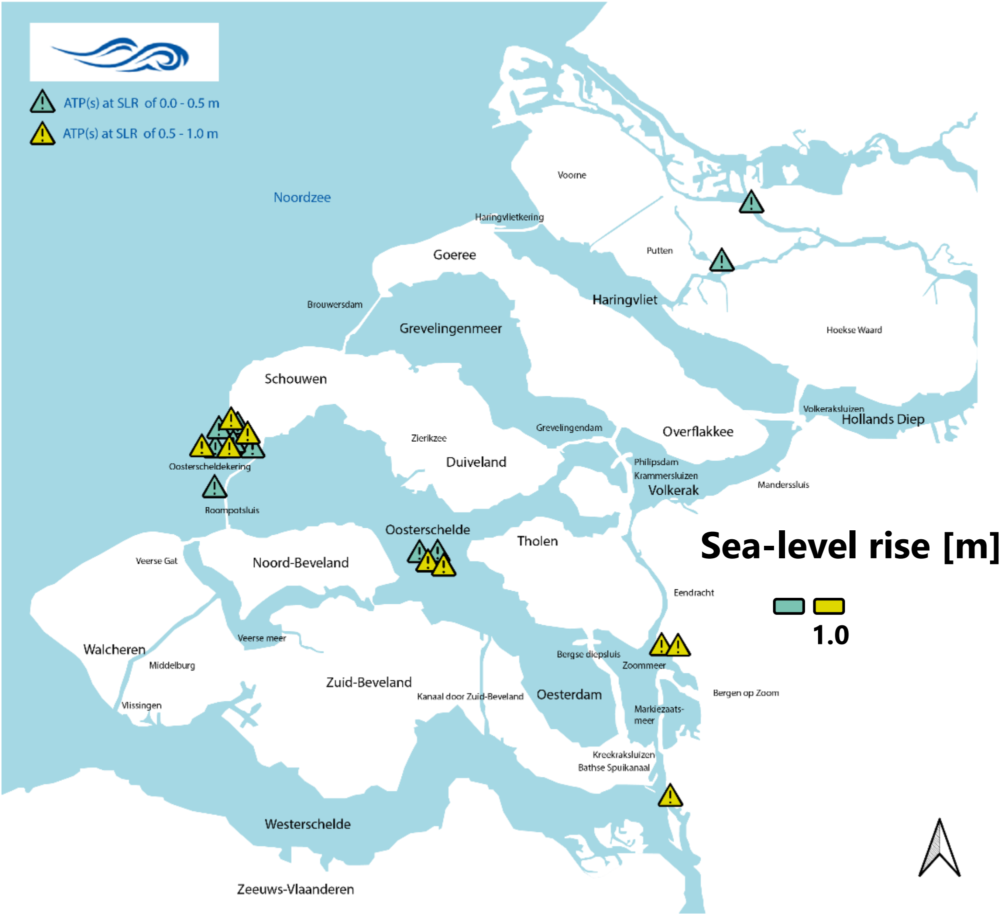
The Brielse Meer serves as an important freshwater supply for the southern and western parts of the Rijnmond region, including agriculture in Voorne-Putten and the industry in the Europoort/Botlek area (Baltissen et al., 2014). The lake receives it water from two inlet locks that connect the Spui (inlet point Bernisse) and the Oude Maas (inlet point Spijkenisse). This section highlights a main effect for the Bernisse-Brielse Meer system:

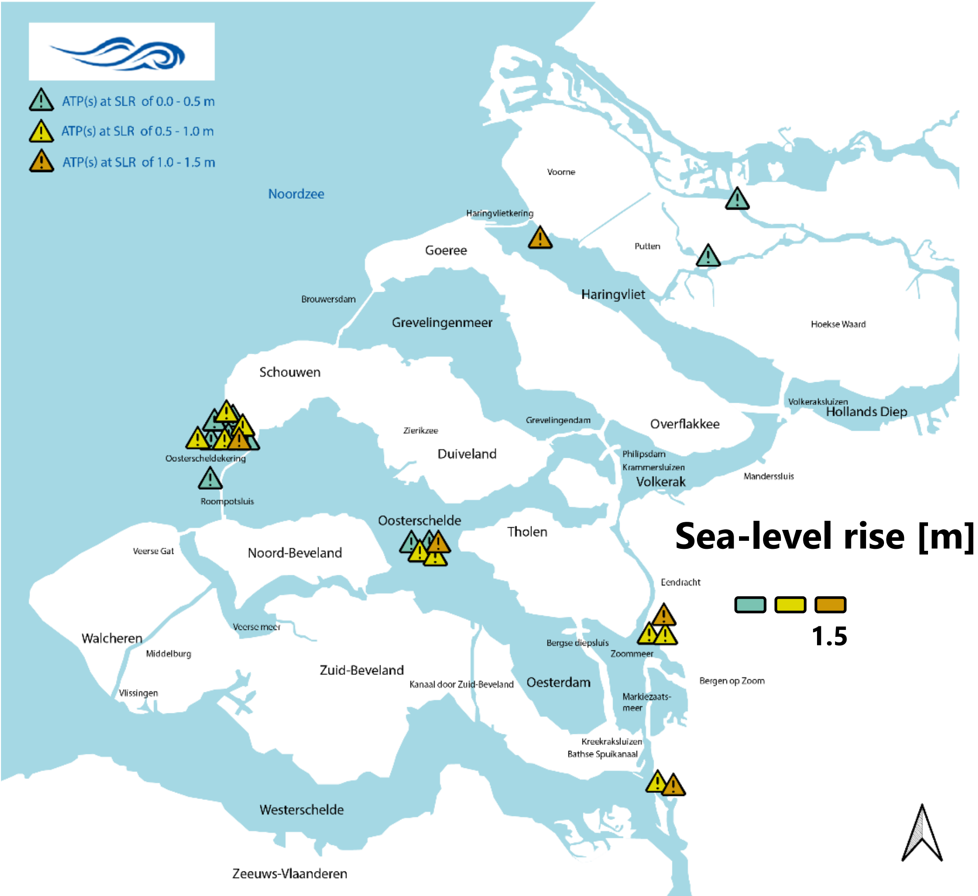
- Salinisation of the inlets Bernisse and Spijkenisse

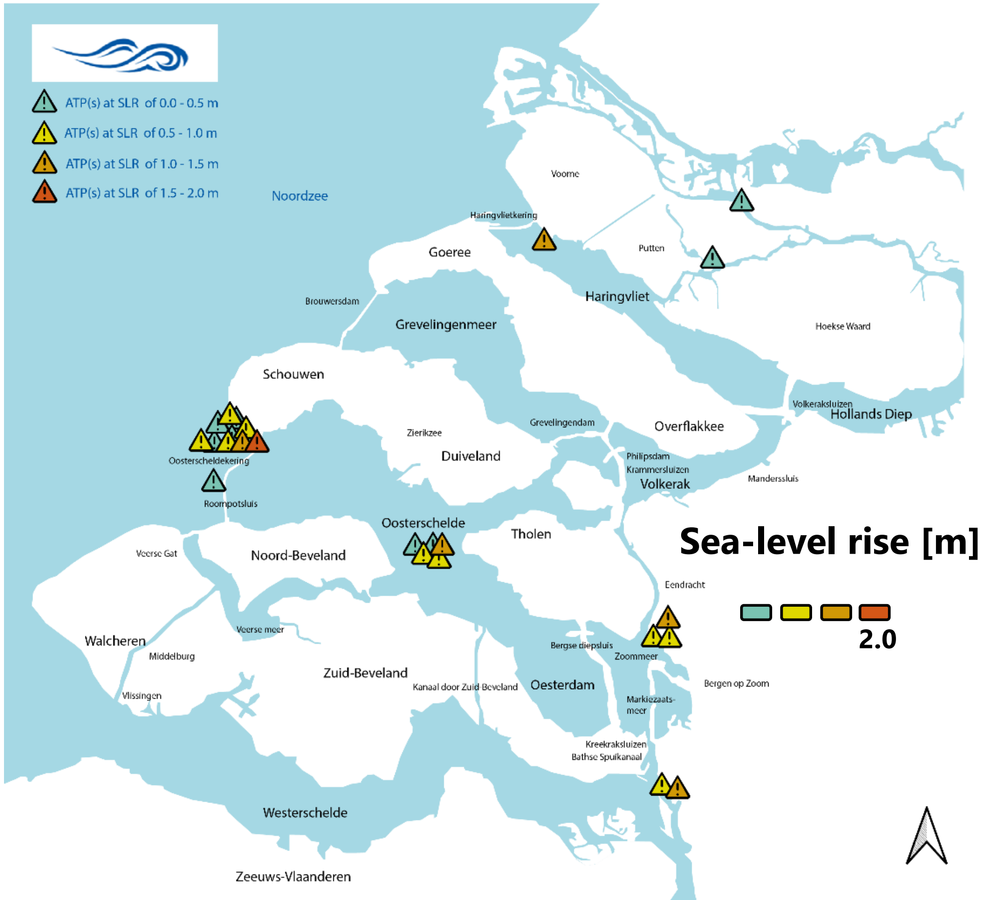
Salinisation of the inlets Bernisse and Spijkenisse

Under normal conditions, the water from the Bernisse inlet is freshwater. However, under specific wind conditions, saltwater may enter the Spui through the Nieuwe Waterweg and the Oude Maas, temporarily enabling the use of the Bernisse inlet (Huismans et al., 2018). The water at the Spijkenisse inlet, which is situated closer to the sea, fluctuates between freshwater and saltwater due to tidal flows. Haasnoot et al. (2018a) found that with a SLR of 0.4 m, salinisation of the Spui at the Bernisse inlet will occur more frequently and to a greater extent. It is unclear whether the Spijkenisse inlet is a sufficient alternative in case of prolonged salinisation of the Bernisse inlet (Haasnoot et al., 2018a). At a SLR of 2 m, an alternative water supply for the Bernisse inlet is needed, however the Spijkenisse inlet is anticipated to be no longer suitable for alternative water supply. Therefore, alternative water supply routes may be required (Deltabeslissing zoetwater, 2014).


ATP(s) at SLR of 0.0 - 0.5 m
Noordzee
Voorne
Haringvlietkering
Putten
Goeree
Haringvliet
Brouwersdam
Grevelingenmeer
Hoekse Waard
Schouwen
Zierikzee
Grevelingendam
Overflakkee
Volkeraksluizen
Hollands Diep
Oosterscheldekering
Duiveland
Philipsdam
Krammersluizen
Volkerak
Mandersluis
Roompotsluis
Oosterschelde
Tholen
Veerse Gat
Noord-Beveland
Sea-level rise [m]
Eendracht
0.5
Veerse meer
Walcheren
Middelburg
Bergse diepsluis
Zoommeer
Zuid-Beveland
Kanaal door Zuid-Beveland
Oesterdam
Bergen op Zoom
Vlissingen
Markiezaats-meer
Kreekraksluizen
Bathse Spuikanaal
Westerschelde
Zeeuws-Vlaanderen


ATP(s) at SLR of 0.0 - 0.5 m
ATP(s) at SLR of 0.5 - 1.0 m
Noordzee
Voorne
Haringvlietkering
Putten
Goeree
Haringvliet
Brouwersdam
Grevelingenmeer
Hoekse Waard
Schouwen
Zierikzee
Grevelingendam
Overflakkee
Volkeraksluizen
Hollands Diep
Oosterscheldekering
Duiveland
Philipsdam
Krammersluizen
Volkerak
Mandersluis
Roompotsluis
Oosterschelde
Tholen
Veerse Gat
Noord-Beveland
Sea-level rise [m]
Eendracht
1.0
Veerse meer
Walcheren
Middelburg
Bergse diepsluis
Zoommeer
Zuid-Beveland
Kanaal door Zuid-Beveland
Oesterdam
Bergen op Zoom
Vlissingen
Markiezaats-meer
Kreekraksluizen
Bathse Spuikanaal
Westerschelde
Zeeuws-Vlaanderen


ATP(s) at SLR of 0.0 - 0.5 m
ATP(s) at SLR of 0.5 - 1.0 m
ATP(s) at SLR of 1.0 - 1.5 m
Noordzee
Voorne
Haringvlietkering
Putten
Goeree
Haringvliet
Brouwersdam
Grevelingenmeer
Hoekse Waard
Schouwen
Volkeraksluizen
Hollands Diep
Zierikzee
Grevelingendam
Overflakkee
Duiveland
Oosterscheldekering
Philipsdam
Krammersluizen
Volkerak
Mandersluis
Roompotsluis
Oosterschelde
Tholen
Sea-level rise [m]
Veerse Gat
Noord-Beveland
Eendracht
1.5
Walcheren
Veerse meer
Middelburg
Bergse diepsluis
Zoommeer
Zuid-Beveland
Kanaal door Zuid-Beveland
Oosterdam
Bergen op Zoom
Vlissingen
Markiezaats-meer
Kreekraksluizen
Bathse Spuikanaal
Westerschelde
Zeeuws-Vlaanderen


ATP(s) at SLR of 0.0 - 0.5 m
ATP(s) at SLR of 0.5 - 1.0 m
ATP(s) at SLR of 1.0 - 1.5 m
ATP(s) at SLR of 1.5 - 2.0 m
Noordzee
Voorne
Haringvlietkering
Putten
Goeree
Haringvliet
Brouwersdam
Grevelingenmeer
Hoekse Waard
Schouwen
Volkeraksluizen
Hollands Diep
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Duiveland
Oosterscheldekering
Philipsdam
Krammersluizen
Volkerak
Mandersluis
Roompotsluis
Oosterschelde
Tholen
Sea-level rise [m]
Veerse Gat
Noord-Beveland
Eendracht
2.0
Walcheren
Veerse meer
Middelburg
Bergse diepsluis
Zoommeer
Zuid-Beveland
Kanaal door Zuid-Beveland
Oosterdam
Bergen op Zoom
Vlissingen
Markiezaats-meer
Kreekraksluizen
Bathse Spuikanaal
Westerschelde
Zeeuws-Vlaanderen

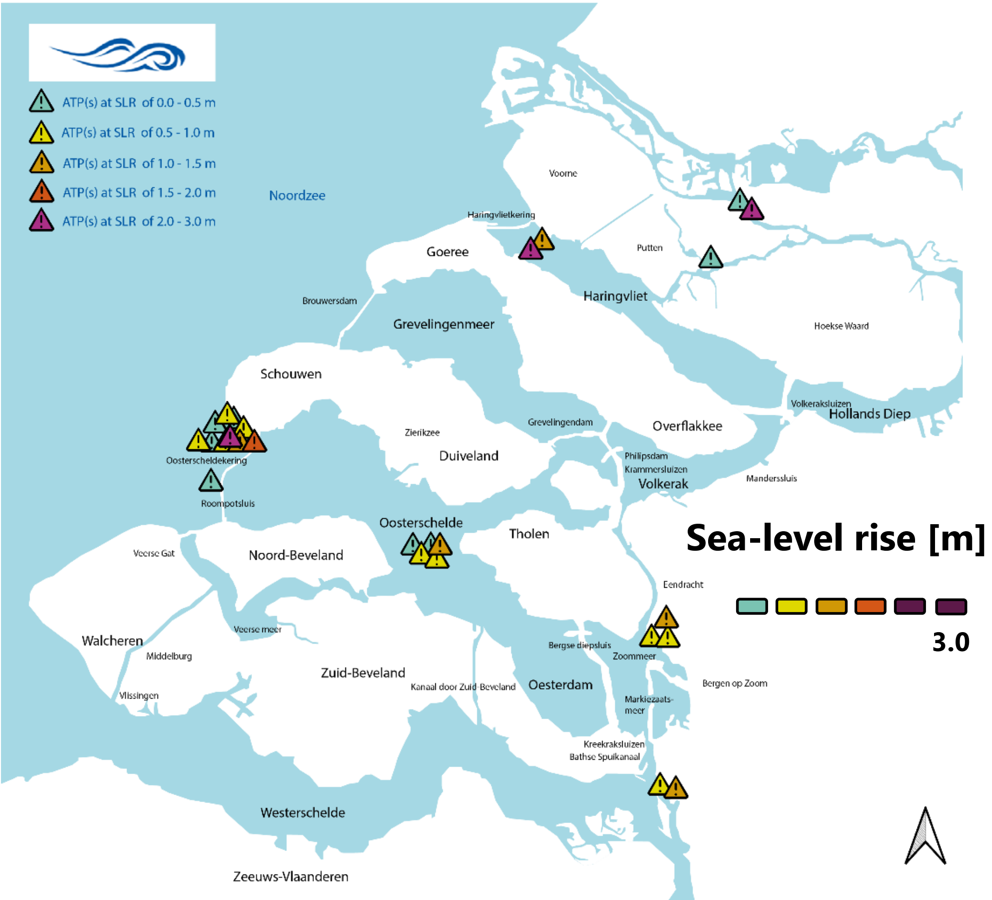

Figure 4.2 Map of used Adaptation Tipping Points (ATP's) for the Southwestern Delta, with the sea-level rise moment [m] of occurrence of ATP's, relative to 1995-2014, depicted in a green triangle [0.0 – 0.5 m], yellow triangle [0.5 – 1.0 m], orange triangle [1.0 – 1.5 m], red triangle [1.5 – 2.0 m], and purple triangle [2.0 – 3.0 m]. As sea-level rise increases, more ATP's arise.

5. Results: Decisiveness of Adaptation Tipping Points for the Southwestern Delta

For each ATP, the level of decisiveness, has been indicated using a systematic approach (as described in step 2 of the *Methodology section 3.2*). Decisive, in this thesis, refers to *the extent to which an ATP leads to impacts on the aspects of sandy coastline, flood risks and freshwater supply (risk), as well as the possibility and way of adaptation to reduce this risk for a system or process at a given scale (incremental or transformational).*

5.1 The Eastern Scheldt basin

The rise in sea-level introduces the occurrence of effects for the Eastern Scheldt, that may result in the need for transformational measures. An overview of these 'decisive ATP's' is presented in **Figure 5.1**. The rationale behind the indication scores is presented in **Table 5.1**, providing explicit references for each statement. In some cells of the table, additional information is provided (in italics). Indication scores are depicted in grey/coloured that correspond to their level of decisiveness. Uncertainty in these indication scores is represented through confidence levels.

This thesis highlights three main findings regarding decisive ATP's and their effects and adaptation options for the Eastern Scheldt basin:

1) For the collected ATP's: with higher sea-levels, more decisive ATP's occur;
2) The adaptation decision of whether to keep the Eastern Scheldt basin open or closed;
3) Incremental adaptations that eventually may result in transformational adaptations

Pivoting SLR impacts and adaptation options

The data presented in Figure 5.1 suggests a trend where, as the sea-level rise, more decisive ATP's occur for the Eastern Scheldt. From a SLR of 1 m onwards, a combination of pivotal SLR impacts and adaptation decisions emerges. One of the most important adaptation decisions that comes into play is whether to keep the Eastern Scheldt open or closing it off. This adaptation decision is driven by several developments at play. Firstly, frequent and prolonged closures of the Eastern Scheldt barrier require (major) adaptation from an ecological perspective and for certain economic sectors such as the mussel and oyster industry (Haasnoot et al., 2018a; Zandvoort et al., 2019). The future path to be pursued in these sectors, whether it is the preservation of current values or a transition towards adaptation, necessitates the choice between an open or closed Eastern Scheldt barrier.

Nevertheless, pivoting adaptation decisions may arise earlier for the Eastern Scheldt. Starting from a SLR of 0.22 m, several failure mechanisms may arise for the Eastern Scheldt barrier and surrounding levees. These ATP's demonstrate different levels of impact, predominantly requiring incremental adaptations, such as raising and reinforcement of the levees. However, in some cases incremental adaptation can accrue to result in transformational adaptation (IPCC, 2022). One such example is when the reinforcement of Eastern Scheldt levees or the Eastern Scheldt barrier can be so substantial that transformational actions become necessary or more appealing. Such a situation, where (multiple) incremental adaptations force a transition to transformative adaptations, is of great importance for the Eastern Scheldt as it may lead to a shift in the priority of the decisiveness of ATP's and therefore may lead to alternative adaptation strategies as the future unfolds.

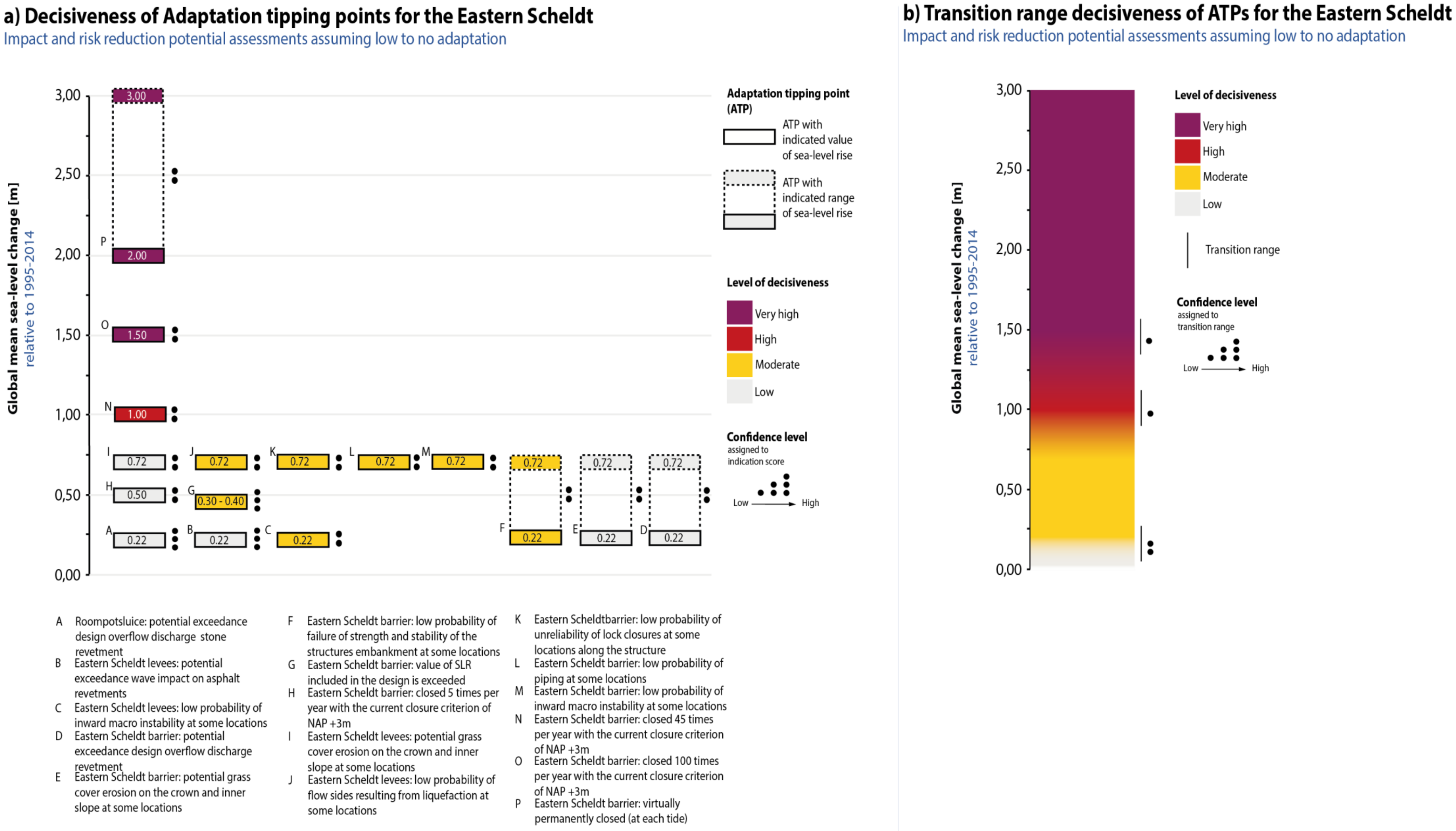

Figure 5.1 **Panel a):** Overview of the collected Adaptation Tipping Points (ATP's) for the Eastern Scheldt basin with at the y-axis the global mean sea-level change in meter relative to 1995-2014 (no value for the x-axis). ATP's are depicted in a rectangle (with indicated value) or two rectangles (with indicated range) with the colours indicating its level of decisiveness that was based on the impact and risk reduction potential assessments assuming low to no adaptation. Each rectangle is assigned to a letter corresponding with a description at the bottom of the figure. Moreover confidence levels in the assigned level of decisiveness are indicated through black bullets. *For instance: ATP A (Roompotsluice: potential exceedance design overflow discharge stone revetment) is likely to occur at a sea-level rise of 0.22 m and has a low level of decisiveness, with a high confidence level*. **Panel b):** transition range of the level of decisiveness for the Eastern Scheldt with a confidence level assigned to the transition range.

Table 5.1 Overview of the ATP's indicating the SLR of occurrence, a description and the indication scores for its risk and risk reduction potential with an explanation and confidence levels in the given score (medium or high). In some cells, additional information is provided (in italics). Indication scores are depicted in grey/coloured that correspond to their level of decisiveness (grey: 'low', yellow: 'moderate', red: 'high' and purple: 'very high').

<table>
<tr><th>SLR [m]</th><th>Description</th><th>Risk</th><th>Risk reduction potential</th></tr>
<tr><td rowspan="3">0.22</td><td rowspan="3">Roompotsluice: storm conditions may lead to an exceedance of the maximum design overflow discharge capacity of the stone revetment (Witteveen+Bos, 2017)</td><td>Low</td><td>Incremental adaptations</td></tr>
<tr><td colspan="2">High confidence</td></tr>
<tr><td>The revetment serves as a protective "layer", preserving wave impact from causing soil erosion and washout (Deltares, 2015)

Provided timely action is taken, these are limited consequences that are somewhat acceptable</td><td>For instance, through the replacement of the revetment accordingly to the current strategy (Deltares, z.d.)</td></tr>
<tr><td rowspan="3">0.22</td><td rowspan="3">Eastern Scheldt levees: wave impact on asphalt revetments may lead to damage to the revetment (Witteveen+Bos, 2017)</td><td>Low</td><td>Incremental adaptations</td></tr>
<tr><td colspan="2">High confidence</td></tr>
<tr><td>The revetment serves as a protective "layer", preserving wave impact from causing soil erosion and washout (Deltares, 2015)

Provided timely action is taken, these are limited consequences that are somewhat acceptable</td><td>For instance, through the replacement of the revetment accordingly to the current strategy (Deltares, 2015).</td></tr>
<tr><td rowspan="3">0.22</td><td rowspan="3">Eastern Scheldt levees: a low probability of inward macro instability at some locations along the levees, that could occur after a SLR of 0.72 m (Witteveen+Bos, 2017)</td><td>High</td><td>Incremental adaptations</td></tr>
<tr><td colspan="2">Medium confidence</td></tr>
<tr><td>Instability during subsequent high-water events can potentially lead to a levee breach (Deltares, z.d.)</td><td>For instance, through levee reinforcements accordingly to the current strategy (Deltares, z.d.)

Reinforcement of the barrier can be so substantial, transformational actions are needed/ more appealing</td></tr>
<tr><td rowspan="3">0.22 - 0.72</td><td rowspan="3">Eastern Scheldt barrier: storm conditions may lead to an exceedance of the maximum design overflow discharge capacity of the stone revetment and may potentially lead to instability of the revetment at some locations (Witteveen+Bos, 2017)</td><td>Low</td><td>Incremental adaptations</td></tr>
<tr><td colspan="2">Medium confidence</td></tr>
<tr><td>The revetment serves as a protective "layer", preserving wave impact from causing soil erosion and washout. The strength of a levee is (largely) dependent on the stability of the revetment that covers the dike body (Deltares, 2017; Witteveen+Bos, 2017)</td><td>For instance, through the replacement of the revetment accordingly to the current strategy (Deltares, z.d.)</td></tr>
</table>

		Provided timely action is taken, these are limited consequences that are somewhat acceptable	
0.22 - 0.72	Eastern Scheldt barrier: storm conditions may lead to grass cover erosion on the crown and inner slope at some locations (Witteveen+Bos, 2017)	**Low** *Medium confidence* The revetment serves as a protective “layer”, preserving wave impact from causing soil erosion and washout (Deltares, 2017; Deltares, 2015) *Provided timely action is taken, these are limited consequences that are somewhat acceptable*	**Incremental adaptations** For instance, through the replacement of the revetment accordingly to the current strategy (Deltares, z.d.)
0.22 - 0.72	Eastern Scheldt barrier: a low probability of failure of strength and stability of the structure’s embankment at some locations, that could occur after a SLR of 0.22-0.72 m (Witteveen+Bos, 2017)	**High** *Medium confidence* Instability during subsequent high-water events can potentially lead to a failure of the barrier (Deltares, z.d.)	**Incremental adaptations** For instance: through reinforcing the Eastern Scheldt barrier (Deltares, z.d.) *Reinforcement of the barrier can be so substantial, transformational actions are needed/ more appealing*
0.30 - 0.40 *including an additional safety margin for settlement of the underlying ground*	Eastern Scheldt barrier: the 0.4 m value of SLR included in the design is exceeded (De Jong et al., 2022)	**High** *High confidence* The rise in sea-level introduces several potential failure mechanisms to occur earlier than anticipated during the design phase (Witteveen+Bos, 2017)	**Incremental adaptations** For instance: through reinforcing barrier (Deltares, z.d.) *Replacement of the barrier can be so substantial, transformational actions are needed/ more appealing*
0.50	Eastern Scheldt barrier: closed 5 times per year with the current closure criterion of NAP +3m (Haasnoot et al., 2018a)	**Low** *Medium confidence* Frequent and prolonged closures are undesirable from an ecological perspective and for certain economic sectors such as the mussel and oyster industry (Haasnoot et al., 2018a; Zandvoort et al., 2019)	**Incremental adaptations** For instance: by increasing the closing level (NAP+3 m) *Might involve raising/widening the levees (max circa 200 km) accordingly to the current strategy (Haasnoot et al., 2018a)*
0.72	Eastern Scheldt levees: storm conditions may lead to grass cover erosion on crown, inner	**Low** *Medium confidence*	**Incremental adaptations**

	and outer slope at some locations (Witteveen+Bos, 2017)	The revetment serves as a protective "layer", preserving wave impact from causing soil erosion and washout (Deltares, 2015; Deltares, 2017) *Provided timely action is taken, these are limited consequences that are somewhat acceptable*	For instance, through replacement of the revetment accordingly to the current strategy (Deltares, z.d.) *Reinforcement of the barrier can be so substantial, transformational actions are needed/ more appealing*
0.72	Eastern Scheldt levees: storm conditions may lead to an elevated risk and low probability of flow sides resulting from liquefaction at some locations along the structure (Witteveen+Bos, 2017)	**High** *Medium confidence* Flow sides resulting from liquefaction during subsequent high-water events can potentially lead to a failure of the levee (Deltares, z.d.)	**Incremental adaptations** For instance, through reinforcing the Eastern Scheldt barrier (Deltares, z.d.) *Reinforcement of the barrier can be so substantial, transformational actions are needed/ more appealing*
0.72	Eastern Scheldt barrier: a low probability of unreliability of lock closures at some locations along the structure, that could occur after a SLR of 0.72 m (Witteveen+Bos, 2017)	**High** *Medium confidence* In the event of potential unreliability of closure, increased pressure on the levees surrounding the Eastern Scheldt, with potential collapse/ breach (Witteveen+Bos, 2017)	**Incremental adaptations** For instance, through replacing the concerned locks of the Eastern Scheldt barrier (Deltares, z.d.) *Replacement of the barrier can be so substantial, transformational actions are needed/ more appealing*
0.72	Eastern Scheldt barrier: a low probability of piping at some locations along the structure, that could occur after a SLR of 0.72 m (Witteveen+Bos, 2017) Eastern Scheldt barrier: a low probability of inward macro instability at some locations along the structure, that could occur after a SLR of 0.72 m (Witteveen+Bos, 2017)	**High** *Medium confidence* Forming and occurrence of piping and/or instability during subsequent high-water events can potentially lead to a collapse/breach of the barrier (Witteveen+Bos, 2017; Deltares, z.d.)	**Incremental adaptations** For instance, through reinforcing the barrier (Deltares, z.d.) *Reinforcements (for piping, macro instability and perhaps other potential failure mechanisms) can be so substantial that transformational actions are needed/ more appealing*
1.00	Eastern Scheldt barrier: closed 45 times per year with the current closure criterion of NAP +3m (Haasnoot et al., 2018a)	**Low** *Medium confidence* Frequent and prolonged closures are undesirable and may require some adaptation from an ecological perspective and for certain economic sectors such as the mussel and oyster industry (Haasnoot et al., 2018a; Zandvoort et al., 2019)	**Transformational adaptations** Levee reinforcements (height + width) could be so substantial (costs, required space, etc.) (Haasnoot et al., 2018a) that an alternative type of investment may become more appealing

1.50	Eastern Scheldt barrier: closed 100 times per year with the current closure criterion of NAP +3m (Haasnoot et al., 2018a)	**High**	**Transformational adaptations**
		Medium confidence	
2.00 - 3.00	Eastern Scheldt barrier: virtually permanently closed (at each tide) (Haasnoot et al., 2018a)	Frequent and prolonged closures (or even permanently closure) of the Eastern Scheldt basin necessitates substantial adaptation from an ecological perspective and for certain economic sectors such as the mussel and oyster industry (Haasnoot et al., 2018a; Zandvoort et al., 2019)	With the current strategy, the Eastern Scheldt will become a closed system for a long (continuous) period. Transformational actions are needed to maintain an open system (Haasnoot et al., 2018a). *Not only decisive for this region, but also for other, as the Dutch water system in the future might more rely on the Eastern Scheldt (Deltaprogramma, 2020)*

5.2 The Volkerak-Zoommeer

In this thesis, three ATP's were found for the Volkerak-Zoommeer, related to the developments concerning the usage of the water storage in the Volkerak-Zoommeer and the reduced discharge capacity of the Bathse spuisluis. In the short-term, these ATP's are expected to be manageable with incremental adaptations, assuming low to no adaptation. Transformational adaptations may be needed after a SLR of 1.0 m (*low confidence*).

Figure 5.2 panel a provides an overview of the level of decisiveness of these ATP's, while the rationale behind the score is detailed in **Table 5.2**. The data in Figure 5.2 panel a suggests a trend where the decisiveness of the ATP's increases from a SLR of 1.00 m. However, considering that this thesis collected two ATP's for the Haringvliet, the confidence level for this transition is low.

Table 5.2 Overview of the ATP's indicating the SLR of occurrence, a description and the indication scores for its risk and risk reduction potential with an explanation and medium confidence levels in the given score. In some cells, additional information is provided (in italics). Indication scores are depicted in grey/coloured that correspond to their level of decisiveness (grey: 'low' and yellow: 'moderate').

SLR [m]	Description	Risk	Risk reduction potential
0.50	The discharge capacity of the Bathse spuisluis may reduce from 130 m^3/s to 100 m^3/s (Nolte et al., 2020)	**Low**	**Incremental adaptations**
		Medium confidence	
		Could potentially result in insufficient maintenance of the desired water level (NAP-0.10 and NAP+0.15 m) in the Volkerak-Zoommeer. However, it is not very likely this will lead to an exceedance of the maximum water level (NAP+0.5 m) (Nolte et al., 2020; Van der Heijden et al., 2023)	Minor adjustments to the operational water management may be needed and are expected to be sufficient (Nolte et al., 2020), For instance, the use of the Krammersluizen as additional water outlet (Geerse et al., 2017).
0.60	The probability of using the water storage in the Volkerak-	**High**	**Incremental adaptations**
		Medium confidence	

	Zoommeer increases to 1 in 25 years compared to the current 1 in 1400 years (Kind et al., 2019; Nolte et al., 2020)	With further SLR, the probability of using the water storage in the Volkerak-Zoommeer increases, leading to a shift from a temporary (emergency) measure to a more frequent occurrence, resulting in structural implications for its various uses (Kind et al., 2019)	Minor adjustments to the operational water management may be needed and are expected to be sufficient (Nolte et al., 2020), For instance, the use of the Krammersluizen as additional water outlet (Geerse et al., 2017).
1.00 – 1.25	The discharge capacity of the Bathse spuisluis may reduce from 130 m^3/s to 70 m^3/s (Nolte et al., 2020)	**High**	**Incremental adaptations**
		Medium confidence	
		Insufficient discharge capacity may result in a higher probability of extreme water levels in the Volkerak-Zoommeer (Geerse et al., 2017). Moreover, to reduce flood risk in the Rijnmond region, the storage capacity of the Volkerak-Zoommeer should be fully available (Vrouwfolder Waterberging VZM, 2012)	In the event that the measure "water storage VZM" is not operational: reducing the water intake through the Volkeraksluizen (Nolte et al., 2020). In the event that the measure is operational: alternative outlets may be used such as the Krammersluizen or the construction of an outlet in the Oesterdasm (Geerse et al., 2017; De Millieueffectrapportage, 2014)

5.3 The Haringvliet

In this thesis, two ATP's were found for the Haringvliet, related to the design level of the Haringvlietdam. A major task for the Haringvliet will be the reinforcement or raising (incremental adaptations) of the Haringvliet barrier. However, in the context of SLR and decreased discharge and storage capacity, transformational actions may be worth considering (Kind et al., 2019).

Figure 5.2 panel b provides an overview of the level of decisiveness of these ATP's, while the rationale behind the score is detailed in **Table 5.3**. The data in Figure 5.2 panel b suggests a trend where the decisiveness of the ATP's increases from a SLR of 1.00 m. However, considering that this thesis collected two ATP's for the Haringvliet, the confidence level for this transition is low.

Table 5.3 Overview of the ATP's indicating the SLR of occurrence, a description and the indication scores for its risk and risk reduction potential with an explanation and medium confidence levels in the given score. In some cells, additional information is provided (in italics). Indication scores are depicted in yellow that correspond to a moderate level of decisiveness.

1.00	A storm event with a recurrence interval of 1:100 years results in a water level increase exceeding the design height of the Haringvliet barrier (Haasnoot et al., 2018a; Kind et al., 2019) *Based on the inner sluice gate design level of NAP +5 m*	**High**	**Incremental adaptations**
		Medium confidence	
		Increased risk of exceedance – current safety standard 1:4000. Consequently, increased flood risk for the Rijnmond region (Leggerdocument Dijkringverbindende	By reinforcing or raising the barrier, the barrier can withstand higher water levels (Kind et al., 2019) *Reinforcement of the barrier can be so substantial,*

		Waterkering Haringvlietdam, 2009) *"Exceeding the design level in the current condition of the barrier does not necessarily mean that the barrier fails or collapses" (Kind et al., 2019)*	*transformational actions are needed/ more appealing*
2.00	A storm event with a recurrence interval of less than 1:10 years results in a water level increase exceeding the design height of the Haringvliet barrier (Haasnoot et al., 2018a; Kind et al., 2019) *Based on the inner sluice gate design level of NAP +5 m*	**High**	**Incremental adaptations**
		Medium confidence	
		Increased risk of exceedance – current safety standard 1:4000. Consequently, increased flood risk for the Rijnmond region (Leggerdocument Dijkringverbindende Waterkering Haringvlietdam, 2009) *"Exceeding the design level in the current condition of the barrier does not necessarily mean that the barrier fails or collapses" (Kind et al., 2019)*	By reinforcing or raising the barrier, the barrier can withstand higher water levels (Kind et al., 2019) *In the context of SLR and decreased discharge and storage capacity, a different distribution of the Rhine discharge may be worth considering (transformational adaptations)*

5.4 The Bernisse-Brielse Meer system

In this thesis, three ATP's were found for the Bernisse-Brielse Meer system, related to the salinisation of the water inlets at Bernisse and Spijkenisse. On the short-term, this can likely be addressed through incremental adaptations. However, if the Spijkenisse inlet is no longer suitable and the Bernisse inlet experiences prolonged salinisation, an alternative water supply for the Brielse Meer will be needed.

Figure 5.2 panel c provides an overview of the level of decisiveness of these ATP's, while the rationale behind the score is detailed in **Table 5.4**. The data in Figure 5.2 panel c suggests a trend where the decisiveness of the ATP's increases from a SLR of 0.40 and 2.00 m. However, considering that this thesis collected two ATP's for the Haringvliet, the confidence level for this transition is low.

Table 5.4 Overview of the ATP's indicating the SLR of occurrence, a description and the indication scores for its risk and risk reduction potential with an explanation and medium confidence levels in the given score. In some cells, additional information is provided (in italics). Indication scores are depicted in grey/coloured that correspond to their level of decisiveness (grey: 'low', yellow: 'moderate' and purple: 'very high').

0.25	It is unclear whether the Spijkenisse inlet is a sufficient alternative (Haasnoot et al., 2018a)	**Low**	**Incremental adaptations**
		Medium confidence	
		However, the Bernisse inlet is available (Haasnoot et al., 2018a)	It may be necessary to explore options for increasing the supply of freshwater by expanding existing freshwater buffers and routes (Deltabeslissing zoetwater, 2014)
0.40	Salinisation of the Spui at the Bernisse inlet is expected to	**High**	**Incremental adaptations**
		Medium confidence	

	occur more frequently and to a greater extent (Haasnoot et al., 2018a)	It is unclear whether the Spijkenisse inlet is a sufficient alternative in case of prolonged salinisation of the Bernisse inlet (Haasnoot et al., 2018a)	It may be necessary to explore options for increasing the supply of freshwater by expanding existing freshwater buffers and routes (Deltabeslissing zoetwater, 2014) *It may be required to change these routes and use alternative routes (transformational)*
2.00	The Spijkenisse inlet is expected to be no longer suitable for alternative water supply	**High**	**Transformational adaptations**
		Medium confidence	
		An alternative water supply for the Brielse Meer is desired/needed, however Spijkenisse does not seem to be a functional alternative anymore (Haasnoot et al., 2018a)	Providing freshwater supply by expanding freshwater buffers and exploring alternative water supply routes (Deltabeslissing zoetwater, 2014)

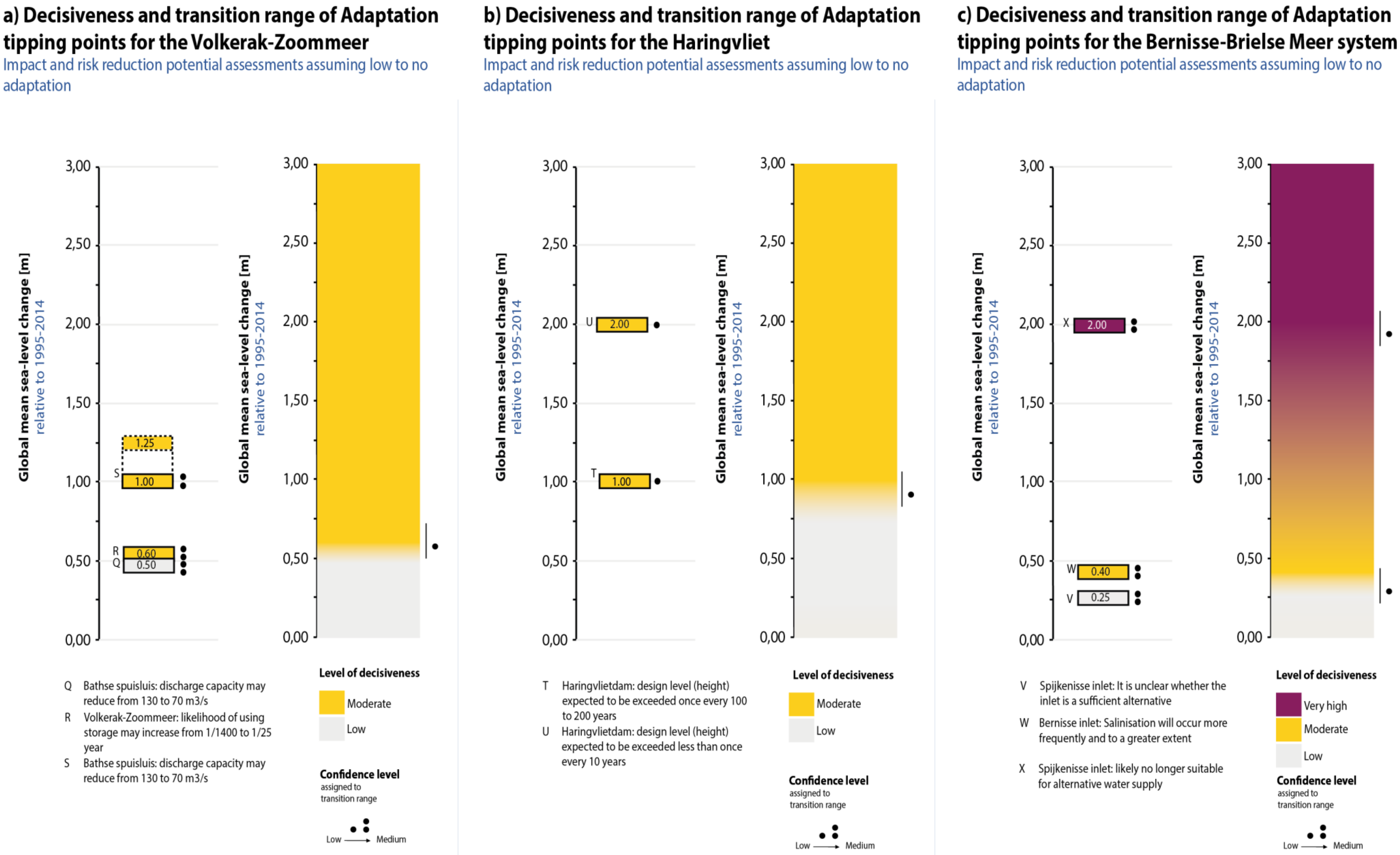

Figure 5.2 **Panel a):** Overview of the collected Adaptation Tipping Points (ATP's) for the Volkerak-Zoommeer with at the y-axis the global mean sea-level change in meter relative to 1995-2014 (no value for the x-axis). ATP's are depicted in a rectangle (with indicated value) or two rectangles (with indicated range) with the colours indicating its level of decisiveness that was based on the impact and risk reduction potential assessments assuming low to no adaptation. Each rectangle is assigned to a letter corresponding with a description at the bottom of the figure. Moreover confidence levels in the assigned level of decisiveness are indicated through black bullets. *For instance: ATP Q (Bathse spuisluis: discharge capacity may reduce from 130 to 70 m^3/s) is likely to occur at a sea-level rise of 0.50 m and has a low level of decisiveness, with a medium confidence level.* The transition range of the level of decisiveness for the Volkerak-Zoommeer with a confidence level assigned to the transition range. **Panel b):** Overview of the Haringvliet. **Panel c):** Overview of the Bernisse-Brielse Meer system.

6. Results: Adaptation decisions for the Eastern Scheldt

As SLR risk increases over time, different adaptation pathways can be followed to contain this risk. These adaptation pathways lead towards the different adaptation strategies as described in the Delta Program (Protect-open; Protect-closed, Accommodate, and Seaward). This section highlights two main findings regarding adaptation pathways and decisions for the Eastern Scheldt basin[1]:

1) Potential "regret" and "no-regret" measures, with a particular focus on the choice between an open or closed Eastern Scheldt basin;
2) The relevance of external ATP's for the Eastern Scheldt basin, with specific attention to the Maeslant barrier in the Nieuwe Waterweg

Evaluation of adaptation strategies

After the construction of the closable Eastern Scheldt barrier, a direction towards a "Protect-open" strategy has been pursued. However, to ensure the protection of the sandy coast, flood risk and freshwater supply as the sea-level rises, there are several moments for transition towards other adaptation strategies. An overview of different adaptation strategies that can be combined and sequenced to contain SLR risk for a period of time in the Eastern Scheldt is visualised in an adaptation pathway map (**Figure 6.1**). One potential moment for transition is in anticipation of the exceedance of the SLR design value of the Eastern Scheldt barrier at a SLR of 0.30 – 0.40 m. Remaining on the "Protect-open" strategy would require an increase in current closure level (NAP + 3m) of the barrier and raising and reinforcement of the old sea levees. A shift towards alternative directions can also be pursued: "Protect-closed" (*e.g., by increasing the height or overflow resistance of the barrier*), "Accommodate" (*e.g., by experimenting with land elevation*) or a direction towards "Seaward" (*for instance, by claiming new land areas above sea-level in the North Sea off the Dutch or Belgian coast*). To carefully consider these transition moments and prevent "regret measures", timely anticipation is essential. There are multiple examples for such "regret measures". For instance, investing extensively in reinforcement or replacement of the Eastern Scheldt barrier, followed by a later transition to a "Seaward" strategy, which may have limited added value given the substantial costs and potential societal impact. Such a situation, where transition becomes very expensive, has a high societal impact, or becomes no longer feasible due to insufficient time, is referred to as a "lock-in" situation (Haasnoot et al., 2022; Hanger-Kopp et al., 2022).

The adoption of measures that offer flexibility to supplement them with other measures in response to further SLR, can be regarded as "low-regret" measures (Haasnoot et al., 2022). For instance, increasing the closure level of the Eastern Scheldt barrier ("Protect-open" strategy) offers the possibility to further investigate or test (large-scale) measures that can be followed later on, e.g., a transition towards an "Accommodate" strategy. However, these follow-up measures should be timely implemented. Further raising the surrounding old sea levees (circa 200 km), is a large investment in which implementation requires additional surface area (Haasnoot et al., 2018a). At a certain point, the levees surrounding the Eastern Scheldt may be raised and widened to such an extent that modifications to the existing infrastructure may become necessary and is therefore technically or spatially not feasible anymore, or socially not accepted. In this case, a lock-in situation may be reached.

[1] *As noted in the Methodology (section 3.1), this basin is chosen as, in this thesis, the most ATP's and pivotal impacts of SLR were found here*

External ATP's related to choices concerning the Maeslant barrier

Initially, this research primarily focused on ATP's that may occur within the Eastern Scheldt basin (internal ATP's). However, external developments related to choices concerning the Nieuwe Waterweg and the Maeslant barrier were found to be highly relevant for the adaptation decisions in the Eastern Scheldt and could not be excluded from the overall analysis. The Nieuwe Waterweg is a major branch of the Rhine-Meuse Delta that discharges it water into the North Sea. The Maeslant barrier, which can be closed during storm surges, facilitates shipping activities in the Nieuwe Waterweg and provides flood protection for the Rijnmond-Drechtsteden region. In response to SLR, various long-term strategies are being considered for this region as part of the delta decision for the Rhine-Meuse Delta (Deltaprogramma, 2020). In the event of a possible closure or failure of the Maeslant barrier, redirecting river discharges to the Eastern Scheldt may become necessary. The use of the Eastern Scheldt basin for water retention and river water discharge may require changes to the adaptation strategies to be followed. To drain the excess water from the rivers to the North Sea following a "Protect-closed" strategy, a large pumping capacity is required (De Bruijn et al., 2022). In case of using the Eastern Scheldt basin for river water storage, the Eastern Scheldt barrier needs to be closed at a minimum level to optimise the storage capacity and facilitate the discharge of river water into the Eastern Scheldt (Witteveen + Bos, 2017). An "Protect-open" strategy may therefore not be feasibly anymore and could require a transition towards another adaptation strategy.

Adaptation pathways for the Eastern Scheldt

Route-map of adaptation options and tipping points

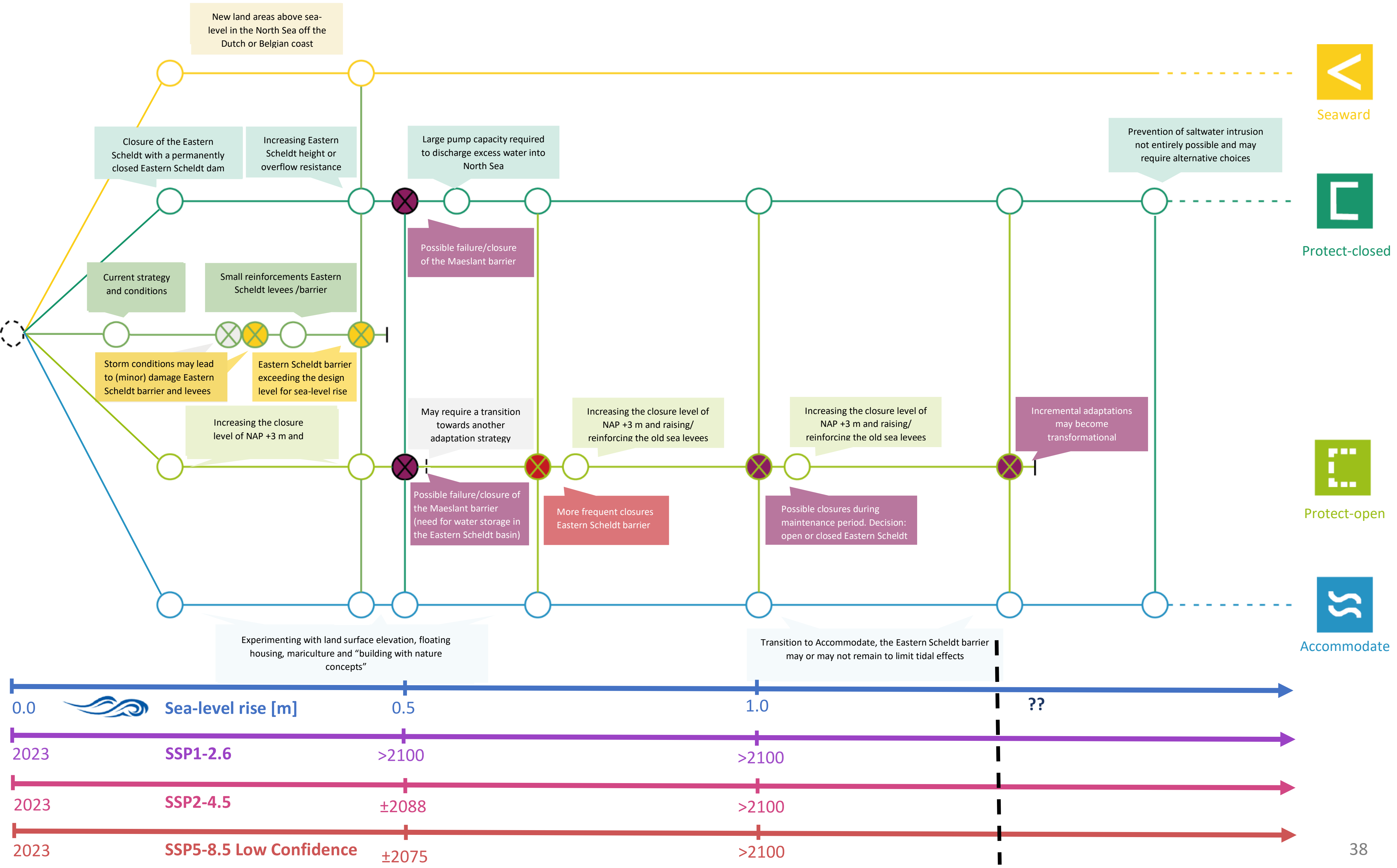

Figure 6.1 Adaptation Pathway map for the Eastern Scheldt. These pathways offer different options that can be combined and sequenced to contain SLR in m relative to 2023 (depicted in the blue arrow underneath the map) risk for a period over time (depicted in the coloured arrows underneath the map for the SSP scenarios: SSP1-2.6 (purple), SSP2-4.5 (pink) and SSP5-8.5 Low (red)). From current conditions (SLR of 0 m- left), different pathways can be followed (to right) that lead to the four solution directions, with “Protect-closed” depicted in blue/green; “Protect-open” depicted in light green (upper right); “Seaward” depicted in yellow (bottom left) and “Accommodate” depicted in blue (bottom right). Adaptation Tipping Points (ATP’s) are indicated by coloured dots (with a cross) that indicate the level of decisiveness (grey: ‘low’, yellow: ‘moderate’, red: ‘high’ and purple: ‘very high’). Possible transitions in anticipation of these ATP’s are indicated through lines that end in a dot on a pathway towards another direction. In case a lock-in situation is reached and transition is required, a black line was used.

7. Discussion

This thesis presents an approach to determine the decisiveness of ATP's, based on a risk- and risk reduction potential assessment. In this section, a reflection on this approach is presented, the main benefits and limitations are mentioned, and input for further refinement of the method is provided.

Reflection on the method and results

In this thesis, one particular way of defining decisiveness was chosen, using a risk- and a risk reduction potential assessment. This approach resulted in a list of ATP's with assigned indication scores for their decisiveness, therefore achieving the research objective. However, the way "decisiveness" is defined has a substantial influence on the outcomes. Other definitions or extensions of the given definition could lead to a different set of results. It would be interesting to explore if a different or more encompassing definition of "decisiveness" can be determined and how this would influence the set of decisive ATP's.

To assess ATP's using the method presented in this thesis, ATP's and potential measures were collected for the Southwestern Delta case study. In this thesis, the focus was laid on three themes, so inevitably it does not present the complete picture. Nevertheless, the main aim of this thesis is to test and demonstrate the usability of the developed method. This was primarily done for the Eastern Scheldt basin, as the most ATP's were found for this basin. Moreover, the approach was used on three other basins. When applying the approach, an indication score was assigned to each ATP based on a single judgment that was supported through literature. Results of this approach show that this approach can help in reducing the set of ATP's to a subset of decisive ATP's, which could give insights into pivoting impacts and adaptation options. However, in these individual judgements, a certain level of uncertainty is involved. Other studies, including those conducted by the IPCC (Mastrandea et al., 2010) use "Uncertainties Guidance" to indicate the reliability level of the presented results. Within this research, a similar indication is used representing the levels of reliability. These confidence levels were also assigned through individual judgments. However, it could be interesting to explore multiple judgments that may provide variations in the assigned confidence levels or even the set of decisive ATP's. Therefore, setting up a team of specialists, each following a similar approach based on their expertise, knowledge and supporting literature could further provide valuable insights.

As the aim of this thesis is to individually assess ATP's and determine their decisiveness, ATP's were given an indication for their risk reduction potential in terms of either incremental or transformational adaptations. However, "in some cases incremental adaptation can accrue to result in transformational adaptation" (IPCC, 2022). A limitation of this thesis is that the indication scores as used in this approach do not include such a potential for transition between incremental and transformational adaptations. Nevertheless, this aspect has been thoughtfully considered and is addressed in this method through a description providing the possibility for such transitions.

In this research the DAPP approach is used. Such an approach supports decision making by regarding adaptation strategies, as a set of measures over time. Other approaches, for example Robust Decision Making and Adaptive Policy Making are used for dealing with deep uncertainties in making adaptive plans. These differ from the DAPP approach as they "aim at reducing vulnerability in the largest possible range of conditions" (*static robustness*), while DAPP "plan to change over time, in case conditions change" (*dynamic robustness*) (Walker et al., 2013). Moreover, to evaluate on adaptation solutions, other approaches are also used, for instance multi-criteria analysis or cost-benefit analysis (Johnston et al., 2014; Danh & Kai, 2014). Both methods have strong and weak points. For example, multi-criteria analysis and cost-benefit analysis focus on single solutions for single problems, while DAPP consider a wide range of scenarios and adaptation options and therefore better deal with uncertainties. Moreover, cost-benefit analysis provides quantitative comparison of possible measures and presents a preferred strategy, while DAPP does not quantitatively provide these insights. Previous research has demonstrated combined approach, with the benefit that this can give quantitative insight in what strategies have higher costs than others (de Ruig et al., 2019; Haasnoot et al., 2020c). Such a method could be used in a follow-up study to gain a better understanding of the advantages and disadvantages of the adaptation pathways.

Academic contribution and recommendations for further research

The systematic approach presented in this thesis combines previous studies related to Adaptation Tipping Points (ATP'S) (Kwadijk et al., 2010; Haasnoot et al., 2013) and offers an approach that can help to determine the decisiveness of ATP's and therefore could give insights into pivoting impacts and adaptation options. This can be used as a supportive tool to determine the priority of decisions that have to be made in anticipation of future SLR.

In the case of the Southwestern Delta, mainly risks and measures directly related to the management objectives for the sandy coastline, flood risks and freshwater supply were considered. However, other indicators influencing decisions are for example ecology, agriculture and recreation. In case of available data, the approach presented in this thesis can be extended to encompass these additional criteria. For example, in recent years, several studies have been conducted that address the potential risks of SLR for the intertidal area and ecology (Witteveen + Bos, 2017; Zandvoort et al., 2019) and propose measures to reduce these risks (Ronde et al., 2013) within the Eastern Scheldt. Such studies can be used for assessment when ecological criteria are included in the approach presented in this thesis.

This research is based on ATP's identified in existing reports, or documented in a database, within the scope of this thesis. It is recommended to further investigate whether the identified ATP's present the complete picture and consider the possibility of identifying additional ATP's. For instance, within the timespan of conducting this thesis, no ATP's were found in existing literature for the Westerschelde and the Grevelingen. It should be examined whether this is accurate and provides a complete overview of all ATP's in the area. Additionally, with these potential new insights, it is recommended to conduct a follow-up study that examines all sub-areas of the Southwestern Delta collectively, using the method developed in this thesis, rather than separately as it was done in this thesis. Nevertheless, the main aim of this thesis is to test and demonstrate the usability of the developed method.

In the coming decades, developments arising from other transitions, such as the energy transition, housing ambitions, and agricultural developments are expected (IPCC, 2022). These developments may influence the solution space for adaptation to SLR, either by providing opportunities (synergies) or possibly cause conflicts, for instance in terms of investments or required space. Further research focusing on synergies and conflicts between these transitions can be of great value in gaining an improved understanding of the solution space for adaptation to SLR.

Insight into pivotal decisions could provide short-term action and avoid regret measures. For decision-making, a subsequent step to creating an adaptation pathway map is to focus on translating the adaptation pathway map into a plan of action. This involves deciding which pathways or set of pathways to follow or should remain open for future developments and what that implies for short-term actions. For these selected pathways, timelines for planning and implementation, including the time devoted to ideation, planning and execution, can be examined.

8. Conclusion

The aim of this thesis was to address the following research questions:

(1) *Which ATP's and potential adaptation measures may the Southwestern Delta experience with increasing SLR, focussing on the management targets here for the sandy coastlines, flood risks and freshwater supply?*

For the Southwestern Delta case, ATP's were collected and used for four (sub)basins, including the Eastern Scheldt basin, the Volkerak-Zoommeer, the Haringvliet and the Bernisse-Brielse Meer system. In general, the main effects for the Eastern Scheldt basin were found to be the closing frequency of the Eastern Scheldt barrier and the decreasing functional lifetime of both the Eastern Scheldt barrier and the levees surrounding the Eastern Scheldt. Adaptation measures were found for the solution directions of "Protect-closed", "Protect-open", "Seaward" and "Accommodate". For the Volkerak-Zoommeer, the main effects were found to be the use of the Volkerak-Zoommeer as a water buffer and the discharge capacity of the Bathse spuisluis. Moreover, ATP's for the design height of the Haringvlietdam and salinisation of the inlets Bernisse and Spijkenisse were found.

(2) *How can we determine decisive ATP's and what are decisive ATP's for the Southwestern Delta?*

This thesis describes a structured methodology for collecting, assessment and prioritisation of Adaptation Tipping Points (ATP's) and uses the Dynamic Adaptive Policy Pathway (DAPP) approach to present potential adaptation pathways that can be followed to overcome ATP's. With the systematic approach as used in this thesis, ATP's can be assigned an indication score in a risk and risk reduction potential assessment. These indication scores are presented in a manner providing explicit references for each statement. Uncertainty in these indication scores is represented through confidence levels. Through this approach this thesis was able to collect a subset of decisive ATP's for the four (sub) basins, with a particular focus on the Eastern Scheldt basin as most ATP's were collected for this basin. From a sea-level rise (SLR) of 1.00 m onwards, most decisive ATP's for the Eastern Scheldt basin, were found with the increasing closure of the Eastern Scheldt barrier. On the short term, SLR challenges in the Eastern Scheldt basin can predominantly be addressed by incremental adaptations. However, for the long-term, transformational adaptations are required or more appealing. In some cases, incremental adaptations may result in transformational adaptations.

(3) *Which decisive adaptation decisions will lead to the greatest reduction in the solution space?*

Adaptation decisions were considered for the Eastern Scheldt basin, as the most ATP's and pivotal impacts were found here. From the adaptation pathway map, it can be seen that several adaptation decisions need to be made for the Eastern Scheldt. Decisive adaptation decisions are found early in the pathways and are also strongly influenced by choices concerning the Maeslant barrier in the Nieuwe Waterweg. Additionally, the adaptation decision to keep the Eastern Scheldt open or closed is recognised as one of the most decisive adaptation decisions. This choice likely arises before a SLR of 1.00 m. Extensive investments in adaptation strategies such as "Protect-open" or "Seaward" may eventually lead to lock-in situations as transition towards another strategy becomes expensive or has high societal impact or due to insufficient time.

Results of the approach as presented in this thesis show that this approach can help in reducing the set of ATP's to a subset of decisive ATP's, which could give insights into pivoting impacts and adaptation options. Moreover, using the DAPP approach, adaptation pathways were regarded as a set of measures over time. Conducting follow-up research on identifying ATP's, specifically for the Southwestern Delta, is strongly recommended. Furthermore, to decide which pathways or set of pathways to follow, it is strongly recommended to gain quantitative insights in the costs and benefits of the set of adaptation pathways. This can be done using combined approach of DAPP with a cost-benefit framework. In addition, timelines for planning and implementation can be examined.

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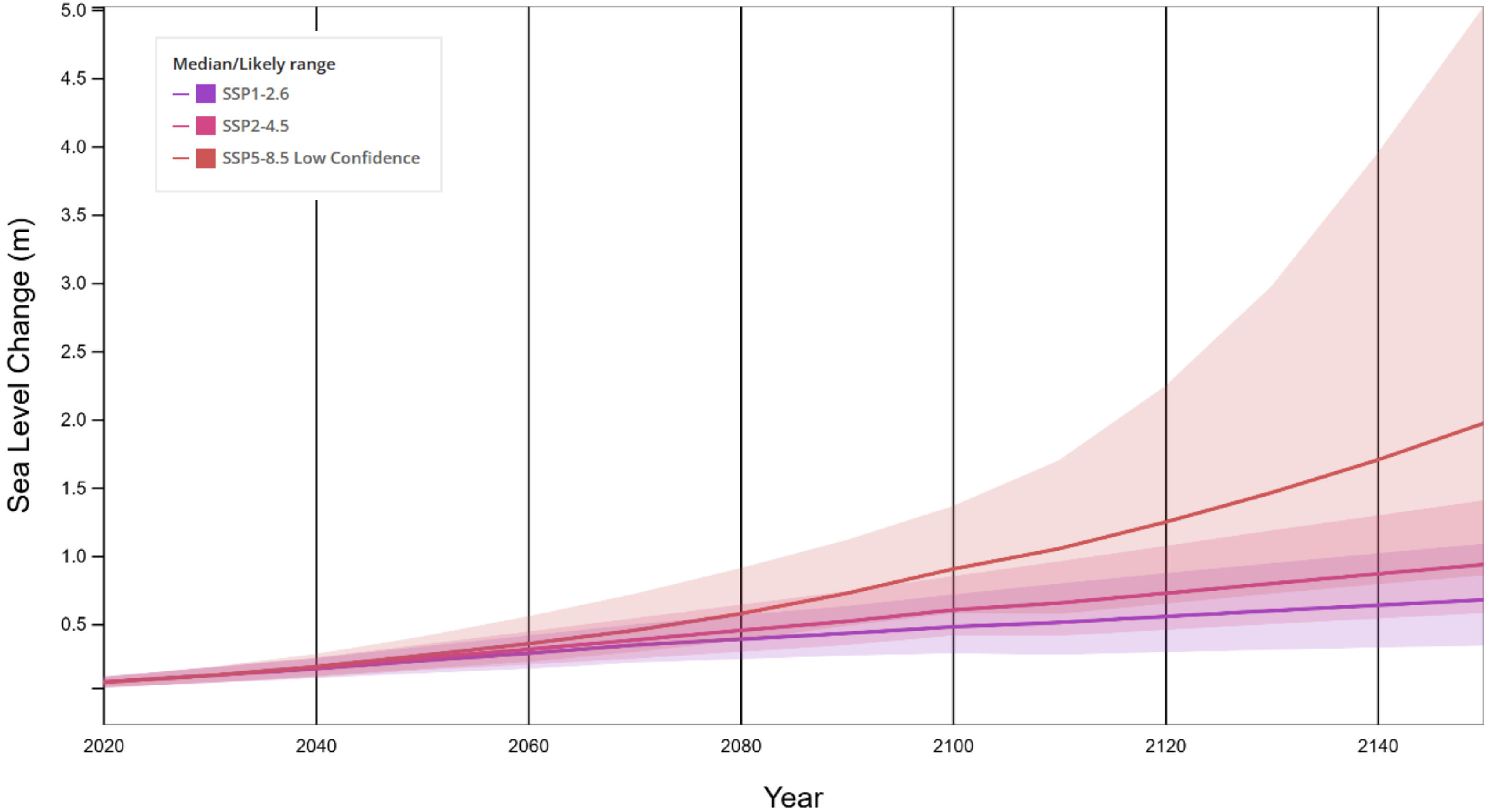
Appendices

Appendix I Sea-level scenarios IPCC



Sea level change for SSP scenarios: SSP1-2.6. SSP2-4.5 and SSP5-8.5 Low Confidence (IPCC AR6 Sea Level Projection Tool, z.d.). Projections are relative to a 1995 2014 baseline.

Appendix II Informed Consent Forms

INFORMED CONSENT FORM (INTERVIEW)

In this study we want to learn about adaptation tipping points in the context of adaptation to long-term sea-level rise. Participation in this interview is voluntary and you can quit the interview at any time without giving a reason and without penalty. Your answers to the questions will be shared with the research team. We will process your personal data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act). Please respond to the questions honestly and feel free to say or write anything you like.

I confirm that:

- I am satisfied with the received information about the research;
- I have no further questions about the research at this moment;
- I had the opportunity to think carefully about participating in the study;
- I will give an honest answer to the questions asked.

I agree that:

- the data to be collected will be obtained and stored for scientific purposes;
- the collected, completely anonymous, research data can be shared and re-used by scientists to answer other research questions;

I understand that:

- I have the right to see the research report afterwards.

Do you agree to participate? X Yes ~~o No~~

Signature:

Dr.ir. G.H.P. Oude Essink

INFORMED CONSENT FORM (INTERVIEW)

In this study we want to learn about adaptation tipping points in the context of adaptation to long-term sea-level rise. Participation in this interview is voluntary and you can quit the interview at any time without giving a reason and without penalty. Your answers to the questions will be shared with the research team. We will process your personal data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act). Please respond to the questions honestly and feel free to say or write anything you like.

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- the data to be collected will be obtained and stored for scientific purposes;
- the collected, completely anonymous, research data can be shared and re-used by scientists to answer other research questions;

I understand that:

- I have the right to see the research report afterwards.

Do you agree to participate? o Yes o No

Signature:

21-4-'23

Arno Nolte