A design of the Delta21 sea defence using the adaptive pathway approach

by S. Versteeg

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Master thesis v2.0

By

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Cover page: conceptual drawing of the Delta21 project site by Esmée van Eeden

"God created the earth, but the Dutch created the Netherlands"

Acknowledgement

In front of you is the thesis ‘A design of the Delta21 sea defence using the adaptive pathway approach’, written to obtain the title of Master of Science in Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences of the Delft University of Technology. This thesis could not have been written without the help and support of my committee, colleagues at Witteveen+Bos, family, friends and girlfriend.

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Also I would like to thank Huub Lavooij and Leen Berke, the initiators of the Delta21 project, for giving me the opportunity to write my thesis about a part of this project while also giving me complete freedom in terms of content. I truly believe that innovative ideas like Delta21 can contribute in the development of the way in which we manage water in the Netherlands, in order to keep the Netherlands safe and liveable in the future.

Last I want to thank my parents, friends and girlfriend for supporting me through encouragement, constructive criticism and suggestions.

I hope you have as much fun reading this thesis, as I had creating it!

Stanley Versteeg
Kamerik, January 2023

Summary

Besides global warming, climate change is expected to result in (among others) an increased number of extreme precipitation events and a rising sea level. In the future, this can be the cause of an increased number of high river discharge events in combination with high water levels on the North Sea, which goes hand in hand with an increased risk of flooding in the Netherlands when no suitable counter measures are taken.

One of the projects which seeks to deal with climate change and improve flood prevention for the Netherlands is the Delta21 project. By combining a sea defence, energy storage lake, pumping station, overflow structure and storm surge barrier, the Delta21 project increases safety against flooding while providing a sustainable way for temporary energy storage.

The rate of climate change is difficult to predict and therefore accompanied by uncertainty. As the lifetime of projects in civil engineering generally is in the order of 50 to 100 years, the change of boundary conditions over the lifetime of the structure is prone to uncertainty as well. Apart from socio-economic developments, climate change plays a major role in the potential change of boundary conditions in the case of the Delta21 project. One of the main uncertainties which has a significant effect on flood safety is in the rate of sea level rise.

The most extreme sea level rise scenario predicts a rise in sea level of up to 5 meters during the 100 year lifetime of the sea defence, which also causes an increase of the design wave height at the toe of the sea defence.

It is not desired to create a very conservative design which is able to withstand the most extreme climate change scenarios, as this would mean that the new structure is over-engineered when the most extreme scenario does not occur. This causes the necessity to modify the Delta21 sea defence in order to meet the flood safety requirements in the future, in the case that more sea level rise than originally designed for occurs.

The objective of the thesis is to find the characteristics of the design of the Delta21 sea defence while considering the uncertainties and possible consequences of climate change. The method used to include the uncertainties of climate change during the design process is the adaptive pathway approach.

The adaptive pathway approach is originally created to be applied to, and modify, existing systems. However, by first creating various concept designs with the use of the classic design approach and using these as input, the approach can be used in the evaluation of these design concepts.

With the use of the Dutch WBI2017 guideline, three conceptual designs for a sea dike were created for the failure mechanism of overtopping. These design variants form the base situation in the adaptive pathway approach and are considered the existing situation while applying this methodology.

The base design variants are created to meet the safety requirements until up to 1 meter of sea level rise, however due to the uncertainty of climate change larger amounts of sea level rise can occur in the future. The change in boundary conditions requires adaptation of the earlier created base design situation, therefore various adaptation options are designed to modify this design to the new circumstances. Each of these adaptation options can mitigate the effects of a certain amount of sea level rise, using the adaptive pathway approach this is visualised in an adaptive pathway scheme.

By mutually comparing the adaptive pathways in the same pathway scheme, the preferred adaptation method per base design variant is selected. The selection of the preferred pathway is conducted via an evaluation on environmental cost indicator, direct construction costs, the impact of the adaptation

on the neighbouring Natura2000 area and the overall flexibility in adaptability. This process is repeated parallel for the three earlier created base design variants for the Delta21 flood defence and results in a preferred method of adaptation for each of these base design variants.

After determining the preferred adaptation strategy per design variant, the preferred design variant for the Delta21 sea defence is selected by a lifetime evaluation under the influence of sea level rise. In this evaluation the characteristics of the initial design variants, their preferred pathways and their corresponding evolution over the lifetime serve as input.

The three base design variants have different preferred methods of adaptation to (up to five meters of) sea level rise. When comparing the variants over the total lifetime of the sea defence, this gives a different image compared to an evaluation of only the situation at the beginning of the lifetime. The design variant which has the preferrable non-adapted design situation, does not necessarily have the best characteristics when comparing the same design variants after adaptation, for cases in which more sea level rise occur.

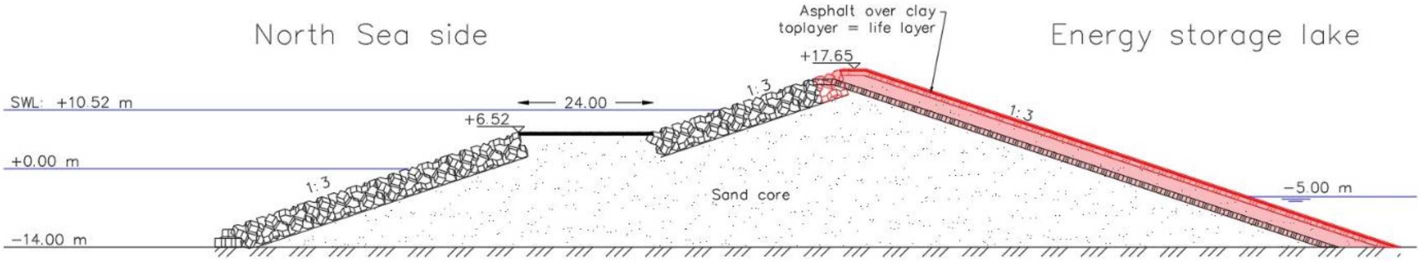
From this evaluation it turns out that the preferred conceptual design of the Delta21 sea defence has an initial crest level of NAP + 16 m and a 24 meters wide berm at storm surge level NAP + 6.52 m. The 1:3 outer slopes are covered with concrete Xbloc armour units. The inner slope is initially protected by a clay layer topped by a life layer, which makes the allowable overtopping discharge under design conditions 5 l/s/m.

This design is created for 1 meter of sea level rise. Under the influence of climate change this design can most efficiently be modified to mitigate the effects of up to five meters of sea level rise in two steps:

1. First the inner slope can be reinforced by applying an asphalt layer on top of the inner clay layer, this increases the allowable overtopping discharge under design conditions to 125 l/s/m and mitigates the effects of up to 3.9 meters of sea level rise.

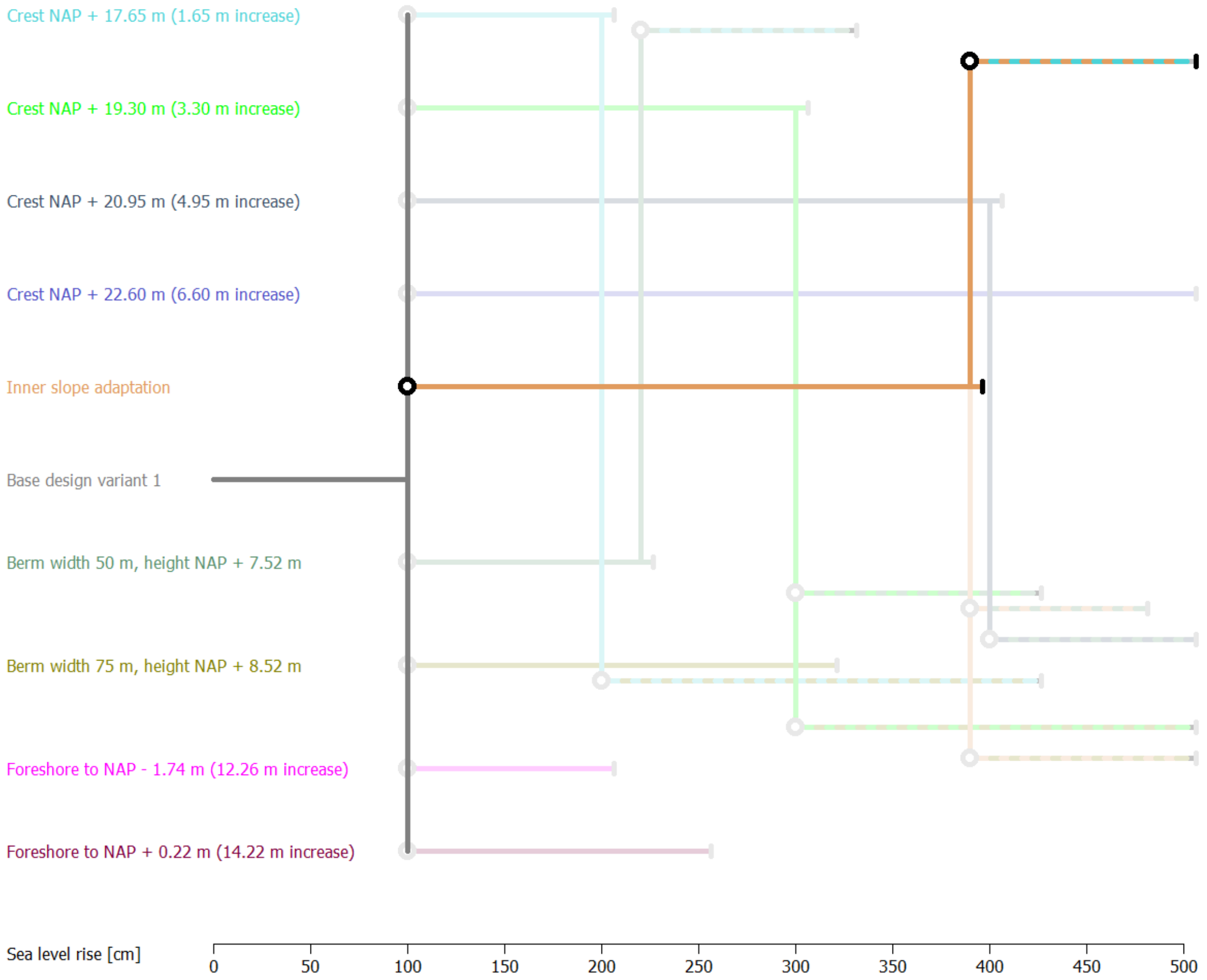
2. When more than 3.9 meters of sea level rise occurs, the crest level can be increased with 1.65 meters to NAP + 17.65 m. This combination of steps mitigates the effects of up to 5 meters of sea level rise.

The fully adapted sea defence and the adaptive pathway of this adaptation strategy are presented underneath.



The adapted Delta21 sea defence with inner slope adaptation and a crest level increase to NAP + 17,65 m (geometry after adaptation indicated in red, base geometry in black)

The study has shown that the adaptive pathway approach can be used as a structured methodology to consider the uncertainties and consequences of climate change even during the early design stages for the Delta21 sea defence. More research is necessary to prove that this methodology can also be applied to soft sea defences and other design cases.



The preferred adaptive pathway for the Delta21 sea defence under the influence of sea level rise. This is indicated with the thick, full colour line.

Contents

1. Introduction

1.1 Background

The Netherlands are located in a delta formed by the rivers Rhine, Meuse, Ems and Scheldt which all end in the North Sea. The dynamic behaviour of the flow of water caused necessity of protective measures in coastal zones and low-lying areas to prevent constant flooding of valuable areas. Around 1000 AD the first dikes as we know them were put up on a larger scale (Voorendt, 2015).

Nowadays, the Dutch government spends 7 billion Euros a year to keep water management and flood protection of the Netherlands at a very high standard (Rijkswaterstaat, 2019). In present day the threat of water still exists and is increasing due to the effects of climate change and land subsidence. Precipitation in the catchments of the rivers is getting more intense, while at the mouths sea levels are rising due to melting arctic ice and thermic expanse (KNMI, 2021). Consequence of these changes is that expenses for flood defence are rising, and therefore an eye is kept out for other methods of flood prevention in order to keep the Netherlands dry. It is still uncertain how much and at what rate the sea level will rise and precipitation will increase under the influence of climate change.

One project currently under development is the Delta21 program, a comprehensive plan which seeks to be an addition in the energy transition as well as being a solution for the flood safety of the Netherlands. The Delta21 program roughly consists of a storm surge barrier and an energy storage lake constructed in the North Sea between Maasvlakte 2 and the island of Goeree-Overflakkee, the location can be seen in Figures 1 and 2. When high discharge conditions occur during storm surge at the North Sea the storm surge barrier next to the lake will be closed to prevent influence on the water levels in the Haringvliet. During high discharge conditions of the rivers Rhine and Meuse, water can be let into the lake using an overflow construction, after which the water is discharged into the North Sea using a pumping station.

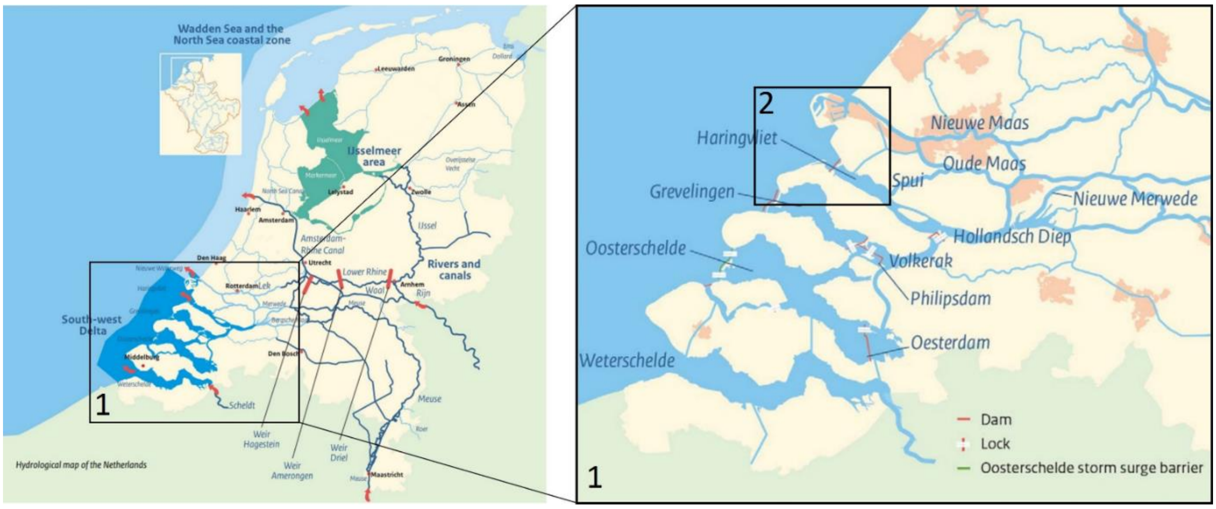


Figure 1 Overview of the Netherlands and the South-west Delta (Rijkswaterstaat, 2019)

Figure 2 Overview project location Delta21, indicated as viewport 2 in Figure 1 (Altered from Google Maps)

One of the aims of Delta21 is to lower the water levels in the rivers and estuaries in the Southwest of the Netherlands during high discharge conditions. To accomplish this goal the water level at the mouth of the Southwest estuary, the Haringvliet, should be kept sufficiently low. Lowering this water level during high discharge conditions will cause the water level of the rest of the system to decrease as well, which reduces the necessity of enlarging the elevation of dikes in the rest of the system. A decreased water level in the Southwest delta would also cause a lower water level in the Rotterdam area, which reduces the amount of closures of the Maeslantbarrier.

The combination of the pumping station and storm surge barrier of Delta21 is crucial for keeping water levels in the river system low during high discharge and storm surge conditions. These low water levels are necessary when the dikes in the system are not reinforced. The storm surge barrier and pumping station are situated in the Delta21 sea defence, which reaches from the Maasvlakte 2 to the island of Goeree-Overflakkee and also forms the base of the energy storage lake. This sea defence is also a part of the primary flood defence of the Netherlands is assessed as being such.

The lifetime of projects in civil engineering generally is long, a lifetime of 100 years is not an exception and therefore the boundary conditions which are used to create designs for these projects can change significantly over the life span. Apart from socio-economic developments, climate change plays a major role in the potential change of boundary conditions in the case of the Delta21 project. The rate of climate change is difficult to predict and therefore accompanied by a lot of uncertainty.

Since flood protection and the possible consequences of climate change go hand-in-hand, the design process of the new Delta21 flood protection system is heavily influenced by the uncertainties of climate change. Dealing with uncertainty during designing is not an easy task and should therefore be taken seriously during the process, in this thesis this will be done by using the adaptive policy pathway approach during the design process.

1.2 Problem statement

The Delta21 initiative seeks to be a link in the chain of the energy transition and in the meantime it is a new approach in the defence against high water in the Netherlands. Using a sea defence created out of soil and several structures, the water levels in the Southwest delta of the Netherlands can be kept low during intensifying hydraulic conditions. Designs for the structures have already been created, however at this moment a design for a static variant of the sea defence does not exist and is to be created.

Although it is known that sea levels around the globe will rise in decades to come, the scale of this phenomenon is not yet known. Any new structure with a long lifetime (which is the case in many civil engineering projects) will have to deal with uncertain circumstances during the lifetime. For the Delta21 sea defence this uncertainty is mostly found in the rise of the sea level: the rate of climate change and the effects of this on both sea level rise and accompanying hydraulic conditions are not certain.

Based on the exploration of the problem in the previous sections, the following problem statement is formulated:

It is not known what the primary sea defence dividing the energy storage lake and the North Sea will look like. Since the rate and amount of sea level rise in the coming century is still very much uncertain, this uncertainty should be taken into account in the design process of said sea defence.

1.3 Objective and scope

The objective of the thesis is to find the characteristics of the conceptual design of the Delta21 sea defence while considering the uncertainties and possible consequences of climate change. These uncertainties will be taken into account by the use of the adaptive pathway approach.

Scope

This thesis focusses on the conceptual design of the (closure)dam as part of the Delta21 sea defence, the structures which are part of the overall project (the intake structure, storm surge barrier and turbine station) and the connections of the dike to these structures are not discussed in this thesis. The ecological effects and implications of sediment flows of the overall Delta21 project are not discussed in this thesis.

In the design of the sea defence only a static sea defence (or sea dike) is considered, dynamic systems, hybrid forms and structural elements are disregarded (this also holds for the adaptation options).

The design is created for the failure mechanism of overtopping. Top layer stability is only considered in the calculation of the dimensions of the interlocking armour units and placed stone revetment. The failure mechanisms upburst and piping and macro stability are disregarded in this thesis.

As it is a conceptual design, the transitions between the various revetment types is not taken into account. Also filter and toe constructions and the overall constructability are not considered.

Hydraulic loads on the defence differ at various locations along the 28.5 kilometers of new coastline as created by the Delta21 project. One project location with the maximum hydraulic load will be regarded in the design process. The coastline of the energy storage lake as is conceptualized by Esmée van Eeden (van Eeden, 2021) will be used as the location of the toe of the new Delta21 sea defence. The hydraulic boundary conditions are determined via extreme value analysis and the design process is conducted by the standard of the WBI2017 methodology. In line with the IPCC and KNMI reports, a maximum of 5 meters of sea level rise will be regarded during the 100 year lifetime of the Delta21 sea defence.

1.4 Research questions

In this thesis the aim is to come to a conceptual design of the Delta21 sea defence while considering the uncertainties and consequences of climate change by the use of the adaptive pathway approach. The research will be conducted using multiple research questions, the main question is the following:

What will a conceptual design of a static Delta21 sea defence look like bearing in mind the uncertainties and consequences of climate change and can the adaptive pathway approach be used to consider these uncertainties?

From this main question two distinct research questions can be determined, being:

- Q.1. How can the adaptive pathway approach be implemented in the process of creating a conceptual design for a new sea defence?
- Q.2. What design variant for the Delta21 sea defence is preferable, bearing in mind the possible consequences of sea level rise?

The answers to the main research question are found during the design process of the Delta21 sea defence, this process guided by the following questions:

- Q.3. What will possible variants of a conceptual design for a static Delta21 flood defence look like, using the classic design approach?
- Q.4. How do the boundary conditions change under the influence of climate change?
- Q.5. In what ways can the Delta21 flood defence design variants be altered in order to deal with the changing boundary conditions?

The answers of the last 3 questions are not presented in the conclusions, however they are presented in the report. The answer to Q.3 is found in Section 5.4, Q.4 in Section 4.3 and Q.5 in Chapter 6.

2. Methodology and thesis outline

This chapter describes the applied methodology during the design process of the Delta21 sea defence. The first section describes the overall methodology for this thesis, while the second section of this chapter further elaborates on the use of the adaptive pathway approach during the design process. The chapter is closed by the outline.

2.1 Methodology

The structure of the thesis and the different steps which are taken to come to the first conceptual design of a climate adaptive sea defence for the Delta21 project are elaborated in this section. In the first steps the background for the design process is provided, which form the base of the base conceptual designs and the various adaptation options.

In overview the full methodology can be schematized as shown in Figure 3 underneath.

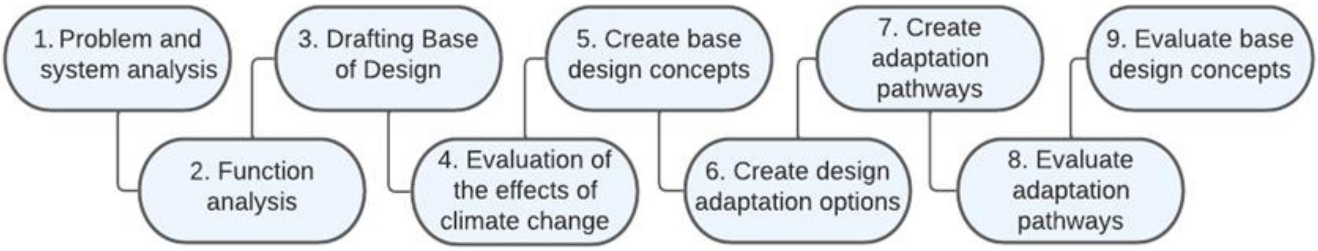


Figure 3 Schematization of design process

1) System analysis

In the Chapter 3 the system analysis is discussed. First climate change and the effects of this phenomenon on the Netherlands are treated, after which the workings and details of the Delta21 project are regarded. The next part of this section of the thesis is the evaluation of the flooding probability of the new Delta21 sea defence, which also forms a part of the base of design as treated in the next section.

The function analysis creates an overview of the principle, preserving and additional functions of the Delta21 project at first in order to create an overview of the most important points of focus. After this the same functions are determined separately for the Delta21 sea defence.

2) Setting up the base of design

This function analysis eventually leads to a list of requirements for the new sea defence, which forms the first part of the base of design. The other part of this section is the determination of the (hydraulic) boundary conditions. These boundary conditions are determined based partly on the flooding probability evaluation.

3) Evaluation of the effects of climate change on the base of design

The change of climate results in a rise in sea level which causes the hydraulic conditions as part of the base of design to change. In this step of the methodology the effects of climate change on the boundary conditions are determined. Steps 2 and 3 together form the base of design.

4) Creation of base design concepts

The use of the adaptive pathway approach asks for a base situation which can be altered in order to deal with changing boundary conditions. The first step in the process is therefore the creation of these base design concepts. Because of the differences between the design concepts the adaptability will differ as well. The base concepts are created with a base level of 1 meter sea level rise in mind.

5) Inventory of potential adaptation options

The base design variants of the Delta21 sea defence are designed for 1 meter of sea level rise. As a consequence of climate change the sea level and other hydraulic boundary conditions will change. During this step the different options for adapting the sea defence will be discussed, including the limitations per adaptation method and the degree of adaptability in the future.

6) Creation of adaptation pathway schemes

Step 6 handles the creation of adaptive pathways which are created using the adaptation methods as described in the previous step and the base design concepts of step 4 as base. The adaptive pathway approach, and the way these pathways will be created and evaluated is explained in Section 2.2 below.

7) Evaluation of the adaptation pathway schemes

Each of the base design variants can be altered to (up to) 5 meters of sea level rise in various different ways. By evaluating these pathways for each of the three design concepts separately, the preferred adaptive pathway can be determined for each of the base design variants.

8) Evaluation of base design concepts

The last step of the thesis is the evaluation of the three base design concepts and the determination of the preferred base design concept of the Delta21 sea defence. This is done by evaluating the three base design concepts and their different options of adapting to sea level rise.

2.2 The adaptive pathway approach

Steps 6 to 8 of the above described methodology make use of the adaptive pathway approach which originally is a methodology for making well-informed decisions in the face of large uncertainties. This methodology is used as a tool to see the effect of different adaptation methods for the base concept design to counter the effects of changing boundary conditions. The evaluation of the created pathway schemes is conducted in step 8 of the methodology which is schematized underneath in Figure 4.

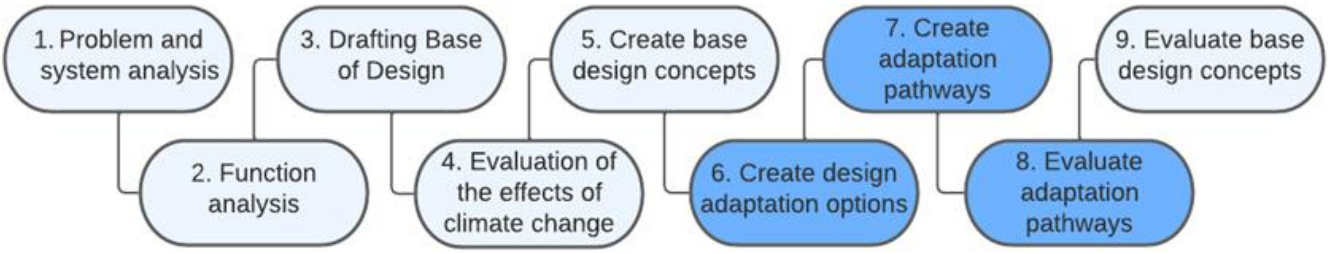


Figure 4 Steps in the methodology which make use of the adaptive pathway approach

First the general principle of the adaptive pathway approach is described, after which the specific use of this approach in this thesis is elaborated on.

The principle of the adaptive pathway approach

During decision making often large uncertainties arise, the adaptive pathway approach is a methodology for decisionmakers to create a set of possible actions based on external developments over time. These external developments can vary: some examples are new technologies, economic developments and climate change (which is the main driver in this thesis).

Because of the longevity of the lifetime of civil engineering structures like a sea defence, the conditions in the future are hard to predict. For economic reasons it is not desired to create a very conservative design which is able to withstand the most extreme scenarios, as this would mean that the new structure is over-engineered when the most extreme scenario does not occur. This creates the desire for the structure to be able to adapt to changing circumstances, see also van Gent, 2019 (van Gent, 2019).

In the adaptive pathway approach, pathway schemes are created which show the different options to adapt an existing situation to changing conditions. An example of such a scheme is presented underneath in Figure 5. The schematisation of the adaptive pathways makes use of adaptation actions and tipping points.

Adaptation actions

An action is defined as the moment an adaptation is applied. In the case of the Delta21 sea defence, the base situation is designed for 1 meter of sea level rise. When this amount of sea level rise occurs, the sea defence has to be adapted in order to mitigate the effects of larger amounts of sea level rise. At that moment, multiple adaptation options can be applied during the adaptation action. In the adaptive pathway scheme the use of an adaptation option is schematized as an action, the symbol of which is a circle as shown underneath in Figure 5.

In the pathway scheme the mitigated amount of sea level rise is indicated by a coloured bar. When two actions are used in a combination, the combined effect is indicated as a multi-coloured bar as is also presented in Figure 5 below.

Adaptation tipping points

The tipping point of an adaptation is the moment at which the adaptation option is no longer effective. For example an amount of crest level increase, which mitigates the effects of 1 meter of sea level rise and is not effective anymore when that amount of sea level rise has occurred. This means that further adaptation of the sea defence is necessary in case larger amounts of sea level rise occur.

An example of this can be seen in Figure 5 underneath. Here adaptation option 1 mitigates the effect of 1 extra meter of sea level rise (2 meters in total), the tipping point is indicated as a vertical mark at the end of the adaptation path. In this example a combination is made with adaptation option 3, which further adapts the sea defence to counter up to 5 meters of sea level rise.

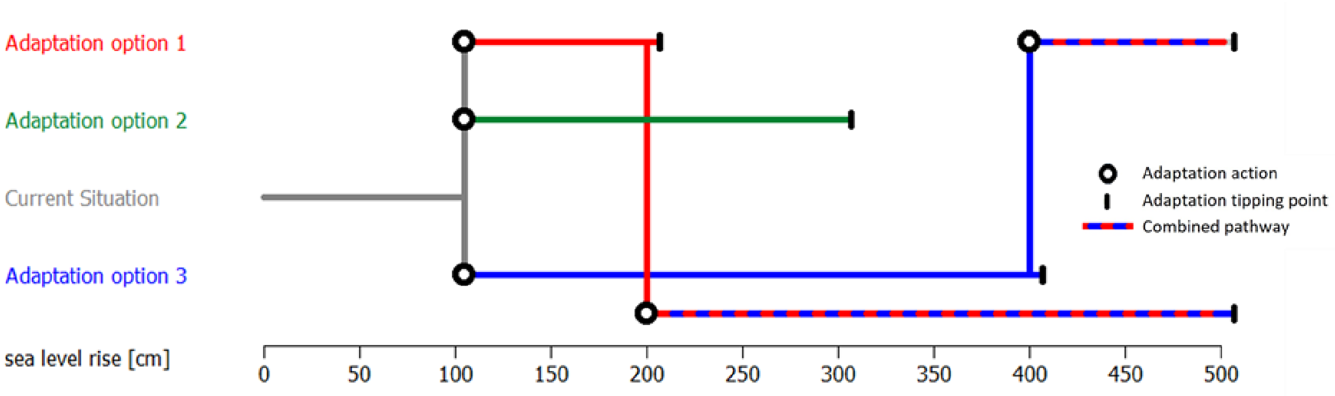


Figure 5 example of an adaptive pathway scheme

The adaptive pathway approach as part of the design methodology for the Delta21 sea defence

In this thesis the adaptive pathway approach will be used in design decision making for the conceptual design of the Delta21 sea defence. Usually an adaptive pathway scheme starts with an existing (or current) situation, which is not present in the case of the Delta21 project. Therefore the thesis starts with the creation of three design concepts for the sea defence, these concepts form the basis for three adaptive pathway schemes.

The creation of the base design concepts is not part of the original methodology of the adaptive pathway approach, however it is a very necessary step to be able to use the adaptive pathway scheme in the creation of conceptual designs.

The adaptive pathway approach is applied to the three base design concepts and the process of this approach can be described in multiple steps:

1. The influence of climate change on the base of design is be evaluated. The changing boundary conditions are used to create adaptation methods which counter the effects of sea level rise in step 2 of this methodology. This evaluation can be found in the base of design.

2. For the Delta21 sea defence multiple adaptational measures are developed, these measures have their own tipping point and can be combined to create adaptive pathways.

3. The adaptation measures as treated in step 2 of this process will be used to create adaptational pathways. These couple the adaptational measures to the changing boundary conditions due to climate change.

4. Using four evaluation criteria, the adaptive pathway schemes are evaluated. The outcome of this evaluation is the selection of a preferred adaptation method for each of the three base design variants. The four evaluation criteria are:

    - Environmental costs indicator
    - Direct construction costs
    - Change in toe location
    - Flexibility of Adaptability

    The way the values for these evaluation criteria are determined is elaborated in Chapter 8. The preferred pathway will be determined by a combined argumentation using the criteria above.

5. The last step of the adaptive pathway approach is the selection of the preferred base design concept for the Delta21 sea defence. For this evaluation and selection the same criteria will be used as during above mentioned step 4.

Previous research making use of the Adaptive Pathway Approach

The adaptive pathway approach is a methodology which is used in policy making by (among others) Rijkswaterstaat for a few years at the time of writing this thesis. The use of the adaptive pathway approach is still rather unexplored in combination with civil engineering structures, multiple students have created a thesis about the use of the adaptive pathway approach in combination with civil engineering structures. It is also a topic which is being explored by professional researchers in the Netherlands. Some studies after the approach are mentioned in Table 1 below:

Author	Topic
M. Haasnoot	Exploring pathways for sustainable water management in river deltas in a changing environment (Haasnoot, Middelkoop, Offermans, van Beek, & van Deursen, 2012)
M.R.A. van Gent	Climate adaptation of coastal structures (van Gent, 2019)
K.P.J. Hogeveen	Climate Adaption of Rubble Mound Breakwaters (Hogeveen, 2021)
T. Vrinds	Adaptive design of flood defence systems (Vrinds, 2021)
L. Rowbottom	Reliability based adaptation of port infrastructure against climate change (Rowbottom, 2021)
D. Huijsman	Adaptation of marine locks against sea level rise (Huijsman, 2021)

Table 1 Studies after the use of the adaptive pathway approach in civil engineering

Above mentioned studies focus on the adaptation of existing structures to changing circumstances.

The use of the adaptive pathway approach is originally set for existing situations, this thesis however aims to use the adaptation pathway approach in the creation of a conceptual design for a new sea defence.

The methodology will be used in the evaluation of the three conceptual designs for the Delta21 sea defence. By the use of the adaptive pathway approach the adaptability to changing boundary conditions is the future can be evaluated. That way the outcome of the adaptive pathway approach will be used in the selection of the preferred conceptual design for the sea defence.

2.3 Thesis outline

In this thesis a conceptual design for the adaptable Delta21 flood defence is presented. In order to get to this design the engineering design cycle is utilized combined with the use of the adaptive pathway approach. The outline of the thesis follows the thesis methodology as described in Sections 2.1 and 2.2.

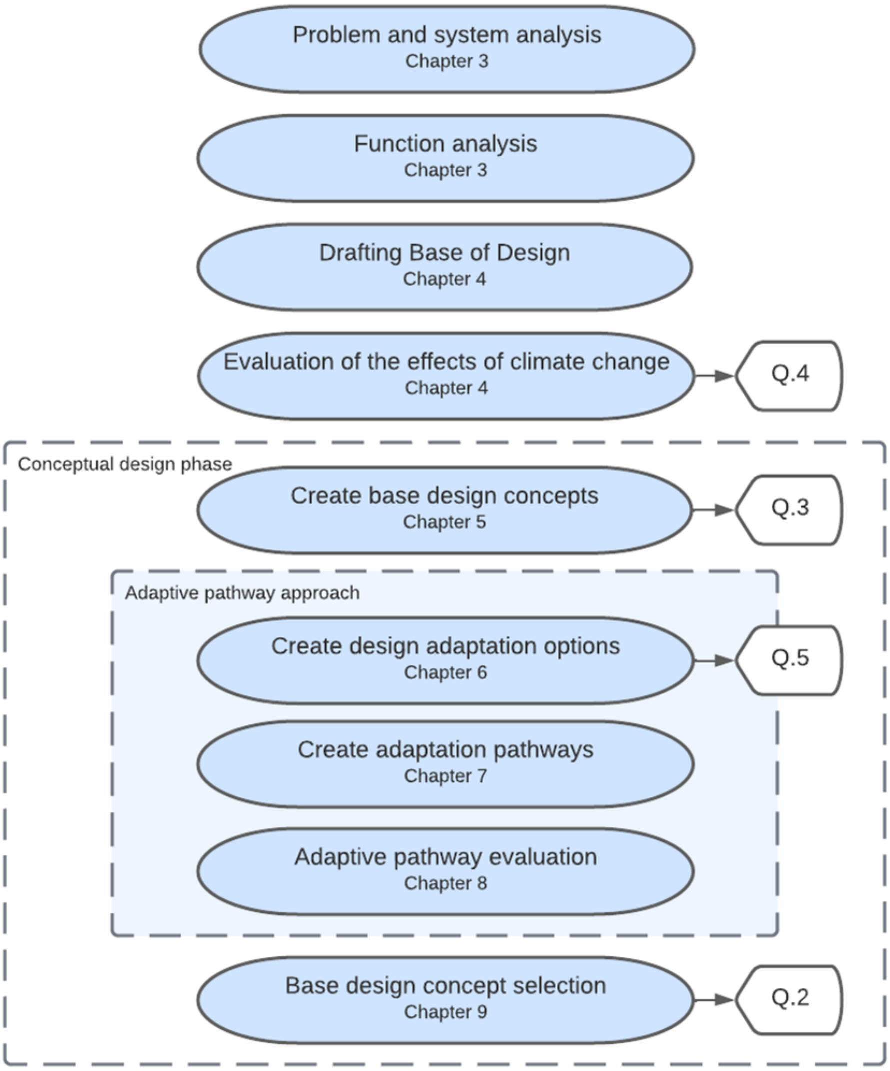


Figure 6 Schematised thesis outline

Chapter 3 describes the problem-, system- and function analysis, after which Chapter 4 draws the base of design. In this base of the design, also the influence of climate change on the boundary conditions is assessed which forms the answer to research question 5.

With the use of this base of design the first design concepts are created in Chapter 4, the outcome of this chapter is also the answer to research question 4.

The adaptive pathway approach is utilized in Chapters 6 to 8, in which adaptation options are created to form adaptation pathways. The preferred adaptive pathway per base design variant is selected as the last part of this approach.

Chapter 9 selects the preferred conceptual design of the Delta21 sea defence, after which the research discussion and conclusion are presented in Chapters 10 and 11 respectively.

3. System analysis

This chapter describes the first phase two steps of the methodology: the problem, system and function analysis. The aim of this stage is to define the problem and describe the background of the project. This is accomplished by looking at the background of the problem (climate change), describing a part of the possible solution (the Delta21 project) and elaborate on the position of the Delta21 project in the Dutch flood defence system.

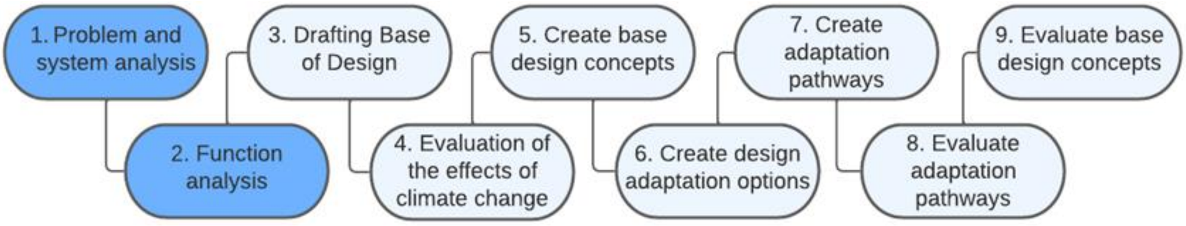


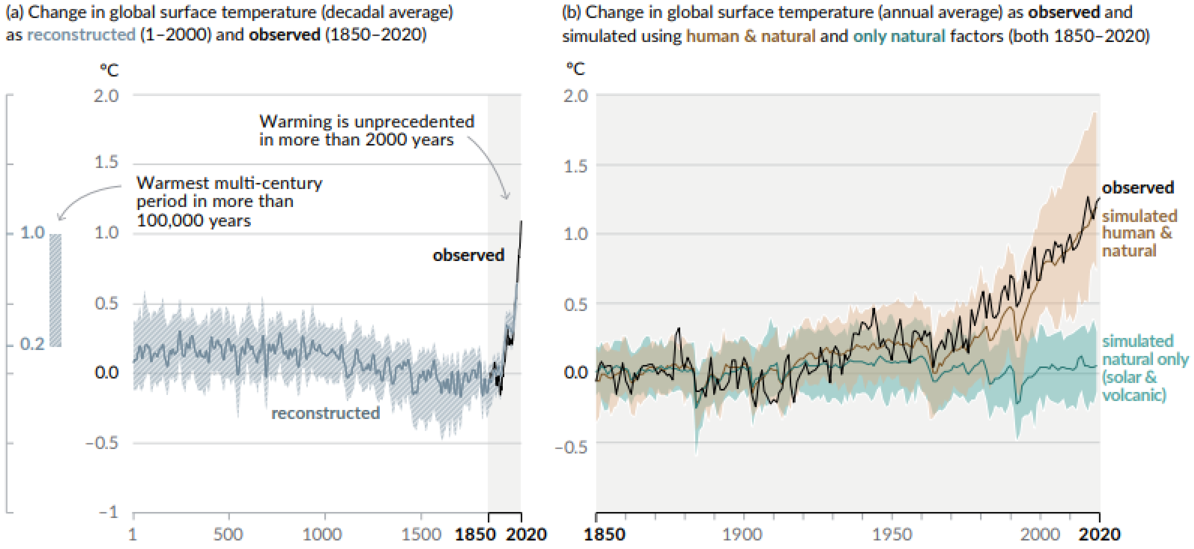
Figure 7 Position of the problem and system analysis in the thesis methodology

As climate change is one of the main drivers of the Delta21 project, this is discussed first. Subsequently, the flood protection for the Dutch South-western Delta is considered. Section 3.2 describes the Delta21 project in terms of its three core values: flood protection, energy storage and nature conservation.

3.1 Climate change and implications for the Dutch coastal zone

3.1.1 Global climate change

The climate is constantly changing, both through natural variation and human contribution. The rise of temperature is caused by the rising amount of greenhouse gasses in the atmosphere, this increase is directly related to human activity (IPCC, 2021). Emissions due to traffic, industry, energy production and agriculture are still growing. In 2019 the atmospheric CO_2 concentrations were higher than at any time in at least 2 million years (IPCC, 2021). The release of greenhouse gasses in the form of carbon dioxide and methane cause a heat trapping effect which has global warming as direct consequence.


(a) Change in global surface temperature (decadal average) as reconstructed (1–2000) and **observed** (1850–2020)

(b) Change in global surface temperature (annual average) as **observed** and simulated using human & natural and only natural factors (both 1850–2020)

Figure 8 Changes in global surface temperature relative to 1850–1900 (IPCC, 2021)

The increase in temperature leads to an increase of the volume of water in the oceans due to thermal expansion of water, the melting of ice sheets and glaciers and an increase in precipitation. These effects are expected to accelerate when the temperature increases more and therefore sea level will continue to rise in the coming century (IPCC, 2021). Thermal expansion is cause for 50% of the total sea level rise between 1971 and 2018, while ice loss from glaciers and ice sheets contributed 42%.

The loss of ice from these places increased by a factor 4 between 1992-1999 and 2010-2019. Due to rising global temperature thermal expansion and ice-loss are expected to rise in the future (IPCC, 2021).

Globally the mean-sea level has increased with approximately 20 centimetres between 1901 and 2018 with an average rate of 1.7 mm per year, however between 2006 and 2018 the average change of water level was 3.7 mm per year (IPCC, 2021). It is certain that sea levels will rise further over the next decades and centuries, however the rate at which this happens is not yet known. Global average estimates differ from 0.28 meters (low-end SSP1-1.9) to 1.01 meters (high-end SSP5-8.5) between 2018 and 2100 (IPCC, 2021), these numbers are higher than previously estimated in former IPCC reports. For the year 2150 the expected sea level rise is even higher: global average estimates differ from 0.37 meters (low-end SSP1-1.9) to 1.88 meters (high-end SSP5-8.5) between 2018 and 2150 (IPCC, 2021). The uncertain process of ice-sheet collapsing could cause sea level rise to be at least 2 meters is 2100 and 5 meters in 2150.

For these scenarios, the SSP1-1.9 scenario requires an almost immediate net stop in the emission of greenhouse gasses. The SSP3-2.7 and SSP5-8.5 scenarios represent a scenario in which the current emission behaviour continues (IPCC, 2021).

Sea level rise is not the only effect of rising global temperatures, with every increase of temperature the changes in extreme weather are also becoming larger. This means that dry periods become longer but periods of heavy precipitation also increase, which has consequences for the way this water is directed to sea (IPCC, 2021). At a global scale it is estimated that heavy daily precipitation events increase by 7% for every degree of global temperature rise (Fowler, Lenderink, Prein, & al., 2021). Climate change can cause more intense precipitation events and earlier melting of snow due to the higher temperatures. For seasonal rivers which rely on snowfall this means a higher peak in winter and a longer dry period in summer. However for rivers which discharge through the year it means that peaks in discharge get larger and longer (Doell & Müller Schmied, 2012).

3.1.2 Implications for the Netherlands

The consequences of climate change are felt all over the world, this also holds for the Netherlands. The Intergovernmental Panel on Climate Change (IPCC) is doing research on climate change and the consequences it has for the entire planet. In the Netherlands, the Royal Netherlands Meteorological Institute (KNMI) are translating this research to the effects climate change will have for the Netherlands specifically. For every new report the IPCC publishes, the KNMI brings a new analysis. The latest of these reports are the AR6 from IPCC and the “Klimaatsignaal ’21” from KNMI based on IPCC reports and own research. In this section sea level rise and the consequences of this, changes in river discharge and changes in hydraulic conditions are regarded.

Sea level rise

The design of flood protection measures is highly dependent on the water levels at sea. As a consequence of the warming of the Earth’s atmosphere, water levels on the oceans have started to rise. Between 2006 and 2018 the average rate of rise was 3.7 mm per year (KNMI, 2021), (IPCC, 2021), this is however difficult to see on the North Sea because of local effects of wind variation and currents.

As the North Sea is connected to the large system of oceans and seas which stretches all around the globe, sea level rise will without a doubt have consequences for the Dutch coast as well. Depending on emission rates of greenhouse gasses the climate will also change at different rates. This also means that the amount of sea level rise depends on emission rates, which causes bandwidths for the amount of expected sea level rise in the decades to come. It is expected that in the year 2050, the sea level will be between 14 and 47 centimeters higher compared to the 1995-2014 (KNMI, 2021). For the year 2100 the sea level will rise between 35 and 121 centimeters compared to 1995-2014 (KNMI, 2021).

However these numbers will get larger when the Antarctic ice caps get unstable and start collapsing, this scenario is still highly uncertain which causes great insecurities in the estimation of overall sea level rise in coming decades (Haasnoot, et al., 2018). Instability of the ice caps would mean that this ice will start melting a lot faster, contributing to a higher rate of sea level rise.

It is very likely that 1 meter sea level rise is present between 2090 and 2140, however the collapse of ice sheets could cause 1 meter of sea level rise by the year 2070. In this case 2 meters of sea level rise can already be expected by the year 2090 (KNMI, 2021).

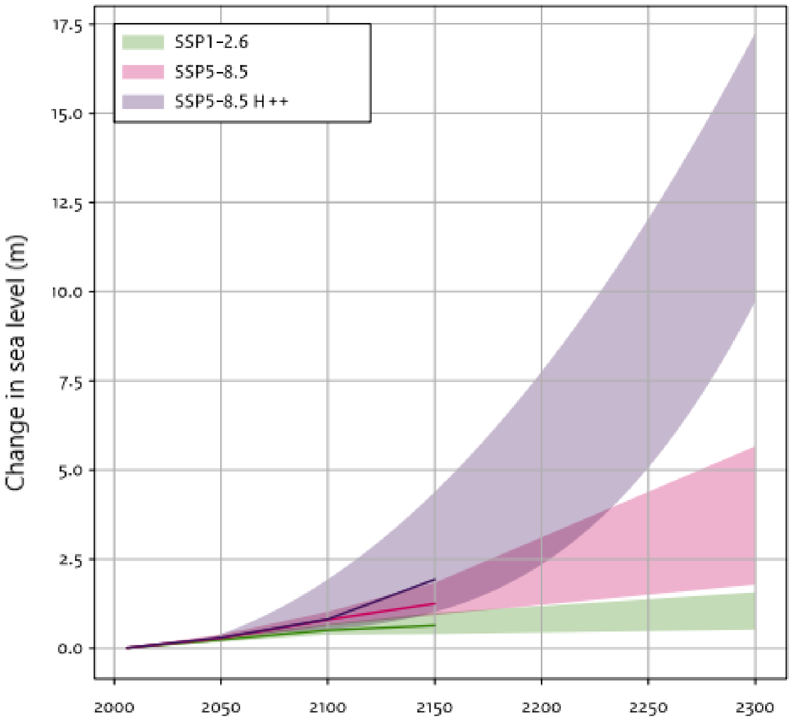


Figure 9 Changes in sea level for different temperature ranges (KNMI, 2021).

In Figure 9 above, scenario SSP5-8.5 H++ implicates the scenario in which there is no change in current behaviour and ice sheets are collapsing rapidly. The bandwidths shown in above figure are 67% for each scenario, however the changes for a separate scenario differ as well.

For the year 2150 the bandwidths per scenario are the following:

Scenario	Bottom of 67% bandwidth	Top of 67% bandwidth
SSP1-2.6	0.5	1.0
SSP5-8.5	1.0	2.0
SSP5-8.5++	1.0	5.0

Table 2 The 67 percent bandwidth sea level rise values in 2150 (IPCC, 2021)

The year 2150 is regarded as the end of the 100 year lifetime of the Delta21 sea defence.

All expected sea level rise numbers are higher than expected in the KNMI and IPCC reports as published in 2014.

Consequences of sea level rise

The rise of water levels at the coast will have large consequences for flood protection in the Netherlands. A study by Deltares shows different consequences for various amounts of sea level rise, the rate at which the water level increases does not necessarily have influence on these consequences (Haasnoot, et al., 2018). These consequences impact both the coastal foundation as well as flood safety.

Consequences for sand suppletion

When the sea level rises 40 centimetres compared to the water level in 1995 already 3 to 4 times the amount of sand suppletion will be necessary to let the coast grow along with the rise of sea level. A rise of more than 1 meter (which is quite possibly expected to happen at the end of this century) requires 25 times the current annual amount of sand suppletion in order to let the coast keep up with sea level rise (Haasnoot, et al., 2018).

Closure of storm surge barriers

A higher water level at sea also means that the closing criterium of the Maeslantbarrier and Oosterschelde barrier will be reached more often. A rise of 40 centimetres causes the Maeslantbarrier to close once every 4 years and the Oosterschelde barrier once every three years. A rise of 1 meter increases the frequency of closure even further: the Maeslantbarrier will be closing 3 times every year, while the Oosterschelde barrier has to close 45 times per year (Haasnoot, et al., 2018).

For sea level rise above 1 meter the frequencies get even larger. It is expected that both barriers will have to be closed almost permanently when sea level rise increases to 2 meters (Haasnoot, et al., 2018).

Dike reinforcement

The rise of sea levels will cause the necessity of higher crest levels of sea dikes in order to prevent damage by overtopping (Haasnoot, et al., 2018). On top of an elevated still water line, depth induced breaking waves will also grow due to the elevated water level which asks for even larger increases in crest height.

Hydraulic conditions

The water level in the oceans and seas is not the only factor which has an influence on the design of flood defense systems. Other hydraulic conditions as wave and wind conditions and the frequency and intensity of storm events also play a role in this process.

Since 1950 the wind climate in the Netherlands and the North Sea have a great year-to-year variability and since the 90s there is a small decrease in wind force (KNMI, 2021). The newest generation of climate models show a very small variation in wind velocities in the coming decades. It is expected that the change in maximum wind velocity is 0.35 m/s or 2% of the average annual maximum, which is considered to be an insignificant increase (KNMI, 2021), (Haasnoot, et al., 2018).

Set-up caused by wind is therefore also not expected to increase significantly over the coming decades. However, the highest water levels are still expected to increase a lot due to sea level rise.

River discharge

Besides rising sea levels, changing river discharge is a hydrologically relevant effect of climate change. The two main rivers flowing in the Dutch Southwest Delta are the Rhine and the Meuse. The Meuse mainly discharges rainwater and corresponds to a precipitation surplus (van Vliet & Zwolsman, 2008), whereas the Rhine discharges both rainwater and meltwater.

In the future, higher winter temperatures will mean less water being stored as snow and ice, causing the Rhine to also discharge mainly rainwater (Deltaprogramma, 2022).

The amount of extreme precipitation events are in line with the moisture content of the atmosphere, this holds for every type of precipitation (IPCC, 2021). In the Netherlands the moisture content in summer rises between 3-7% per degree of global average temperature rise (KNMI, 2021). It is expected that the amount of heavy rainfall events in this season also rises at the same rate, causing higher and more frequent peak river discharges. Climate models show that the amount of low intensity rainfall events (less than 10 mm per hour) is decreasing, however high intensity rainfall events (more than 50 mm per hour) are increasing in frequency (KNMI, 2021).

Since the 1950s, low precipitation periods are becoming more common. This leads to a larger frequency of periods of low water in the rivers. However trends and computer models both also show that the frequency of very high precipitation events also increases. The combination of both trends shows that it is expected that both the frequencies of high and low water events on rivers will increase.

It is expected that river discharges will increase in the future for both the rivers Rhine and Meuse. The river Rhine currently has a maximum discharge of 16.000 m^3/s which is expected to increase to 20.000 m^3/s (Hegnauer, Kwadijk, & Klijn, 2015). High discharge in the river Meuse is expected to increase from 3800 m^3/s to 4600 m^3/s in the coming decades (Reuber, Schielen, & Barneveld, 2005). Most of the water from the Rhine will flow to the North Sea via the Haringvliet estuary.

Conclusions for the future of the Southwest delta of the Netherlands

As climate changes the sea levels are rising and precipitation events will get more extreme. Combination of this causes an increase in the frequency of high water closure events for the Maeslantbarrier and Oosterschelde barrier. As theses frequencies increase normative conditions will occur more often, with the direct effect that even larger waves or higher water levels will also occur more often.

In the future both the Maeslantbarrier and Oosterschelde barrier will have to close more often, constraining the direct river discharge into the North Sea. When this happens in combination with a high discharge event on the rivers Rhine and Meuse, the water levels in these rivers will increase rapidly. The current policy of dealing with these issues, even after the Room for the River programme, will be to raise the dike crest levels in the entire estuary which will be a costly operation.

3.2 Delta21

3.2.1 An overview of the Delta21 project

The combination of rising sea levels and heavier rainfall will require ongoing measures to provide the Netherlands with sufficient protection against flooding. Several of these measures which are being implemented or are nearing completion in the Netherlands are the Room for the River programme and the “Hoogwaterbeschermingsprogramma (HWBP)” (Deltaprogramma, 2022).

The Delta21 programme is a new plan to provide a future-proof solution for flood prevention. This project, located in the Haringvliet estuary to the south of Maasvlakte 2, aims to be part of the flood protection of the south-western delta of the Netherlands, while at the same time serving as an energy storage lake and providing for nature restoration and preservation. Roughly speaking, the plan consists of three main goals: flood protection, energy storage and nature conservation and restoration in the area.

Delta21 is a concept which combines flood protection with sustainable energy storage, this concept is applicable on many locations all over the earth. The current plans of Delta21 in the mouth of the Haringvliet estuary can therefore also be seen as a case study which will eventually apply for numerous locations, this is described at the end of this section.

A proposed lay-out of the project can be seen in Figure 10.

Figure 10 Lay-out of the Delta21 project

In the figure above:

1: Delta21 sea defence
2: Turbine station
3: Overflow construction
4: Storm surge barrier
5: Tidal lake
6: Energy storage lake
7: Haringvliet Barrier
8: Maasvlakte 2
9: Maeslantbarrier

3.2.2 Flood protection

The Delta21 project is an alternative for the continuous reinforcements of the dikes in the Southwest delta. During high water on the North Sea a storm surge barrier keeps this water out, however when discharge and water levels on the rivers are high this water can be discharged using a turbine station.

The main goal of the project is to keep water levels in the rivers low, even during storm surge and high discharge conditions. Currently the Haringvliet barrier and Maeslantbarrier are closed during extreme storm surge events, which blocks the free outflow of the Nieuwe Waterweg and Haringvliet into the North Sea.

Current situation

In the present situation, the moment of closure of the Maeslantbarrier is dependent on water levels at Rotterdam and Dordrecht, once the water level is at NAP+3.0m at Rotterdam or NAP+2.9 m at Dordrecht this barrier is closed. Once closed the barrier protects until a storm surge level of NAP+4.5 m at sea. The possibility of failure of the Maeslantbarrier is once every 100 closures (Rijkswaterstaat, 2012). Since closure levels occur once every 10 or 20 years the Maeslantbarrier has a failure probability of 1:1000 to 1:2000, being a crucial part of the Dutch sea defence this probability is large (it is located in a dike ring with a failure probability of 1:10.000) .

In the case of high river discharges during a long storm surge event, the water levels on the river can get increase rapidly. When this is the case the Maeslantbarrier can float for a short duration, letting river water out to sea. This however brings extra risk to the functionality of the structure.

Delta21 functionality

Delta21 is primarily formed by a sea defence of approximately 28.5 kilometres long, including structures like the turbine station and storm surge barrier. During high water at sea the storm surge barrier will be closed in order to prevent high water to come in to the estuary. During high discharge events on the rivers the intake structure for the energy storage lake will be fully opened, enabling the turbine station (with a capacity of 10.000 m^3/s) to keep the water levels in the Haringvliet estuary and at Rotterdam and Dordrecht at a maximum water level of NAP + 2.5 m. The goal for Delta21 is to guarantee a 10.000 year return period for exceedance of the NAP + 3.0 m water level at Dordrecht (Lavooij & Berke, 2019). This means that the level of closure for the Maeslantbarrier will only be reached during extreme storm events, lowering the probability of failure for the Maeslantbarrier and at the same time reducing the failure probability of the dikes in the delta.

The full process to guarantee water safety in the Dutch Southwest delta is schematized underneath in Figure 11.

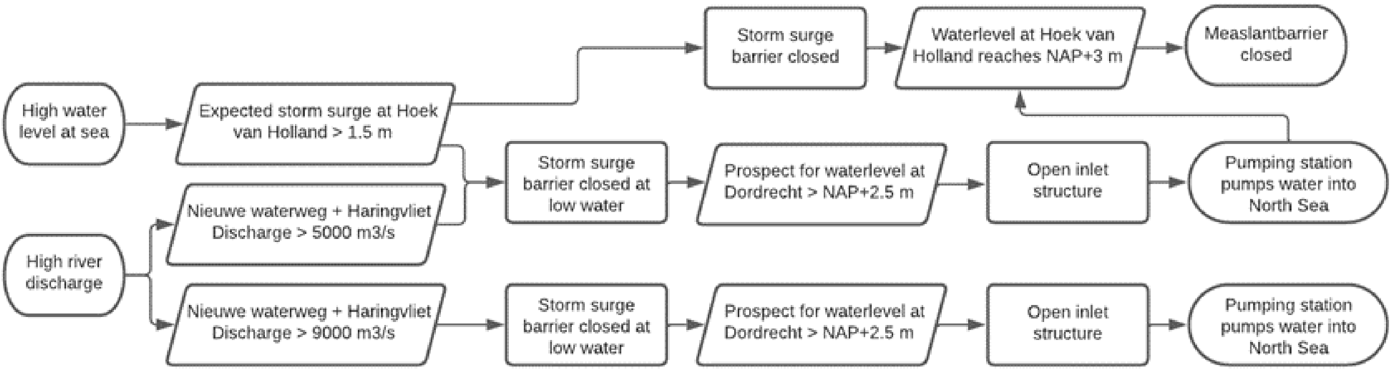


Figure 11 Schematization of the Delta21 structure operational processes

3.2.3 Energy storage lake

The fast rate of climate change is mostly driven by greenhouse gasses in the atmosphere, these gasses are emitted by human actions (for energy supply, transport, industry, etc.). In recent years other, more sustainable, ways for generating energy are sought in the so-called energy transition. Delta21 will contain an energy storage lake which will function as a “green battery” by the use of hydro power.

Wind and solar energy are the most used renewable energy sources in the Netherlands (CBS, 2022). These ways of generating energy are dependent on natural circumstances and therefore highly variable. During high wind conditions or cloudless, sunny days an energy surplus is generated. Consequence is that during these times more energy is generated than consumed which causes a part of this energy to be lost. By creating an energy storage lake the Delta21 project seeks to be a solution for storing this energy. During periods of high energy production by renewable energy sources the energy storage lake can be drained using a pumping station, total drainage of the lake takes 12 hours during which 600 million cubic meters of water are moved. During times of energy demand the lake can be filled with water from the North Sea via the same pumping station in which the pumps will function as turbines, functioning as hydropower generators.

The energy storage lake will have a surface area of approximately 40 km^2 and the water level will drop 17.5 meters (a water column between NAP - 22.5 m and NAP - 5 m is used for energy storage) in a 12 hour period.

The full process of the use of the energy storage lake is schematized in Figure 12. In this schematization water level fluctuations due to flood safety purposes as described in Section 3.2.1 are not taken into account.

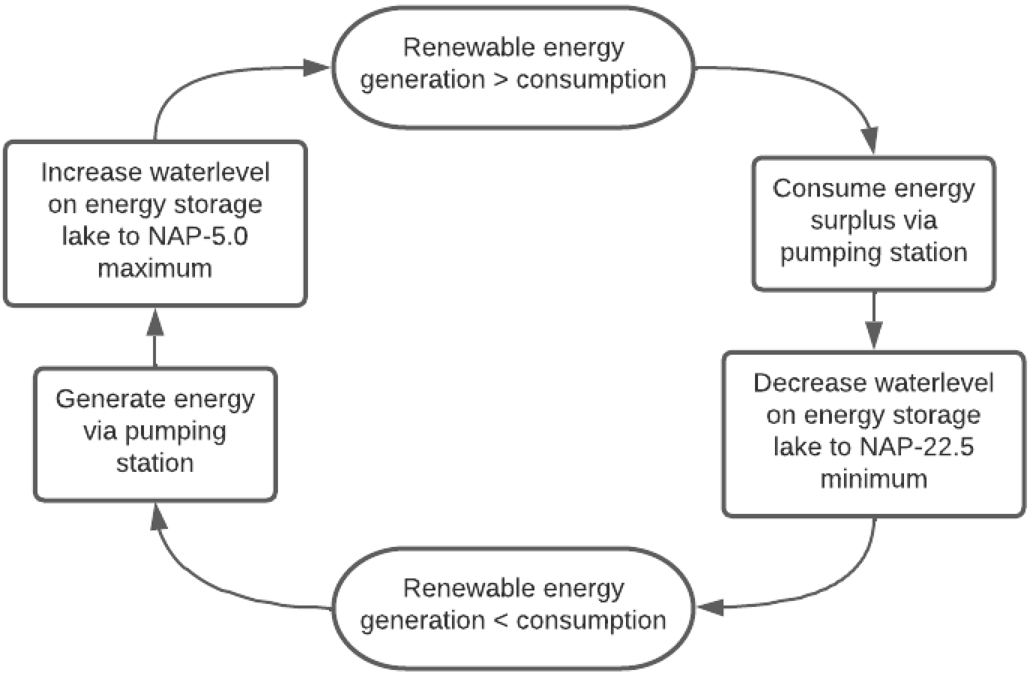


Figure 12 Schematization of processes in the use of the energy storage lake (purely for energy storage purposes)

3.2.4 Nature conservation and recovery

The third goal of the Delta21 project is the conservation and recovery of nature in the Haringvliet estuary. After the construction of the Dutch Deltaworks, the border between salt and fresh water in the estuary was located at the Haringvliet sluices. This caused a loss of fish migration between the North Sea and the Dutch rivers on top of the loss of the brackish water biotope which was present in the area. As an attempt to bring this biotope back the so-called “kierbesluit” was implemented in 2019 (Rijkswaterstaat, 2022).

During high tide the Haringvliet sluices are opened slightly, which enables salt water to flow into the Haringvliet. This measure enables migratory fish to enter the Haringvliet. With the “kierbesluit” an area of brackish water was brought back into the Haringvliet estuary, this functions as a breading area for different kinds of fish (Reeze, et al., 2020).

Implementation of the Delta21 project means that the Haringvliet sluices can be opened permanently, this will have positive effects on the biodiversity in the region as fish migration and the brackish biotope can be fully restored.

Delta21 and Natura2000

The Delta21 project site is located in a Natura2000 area in front of the Dutch coast as is presented underneath in Figure 13.

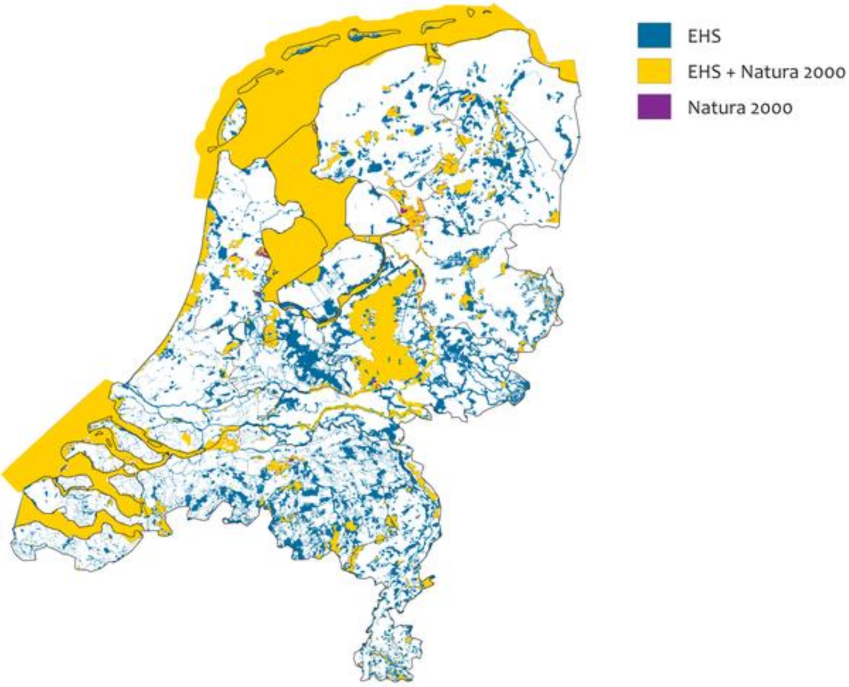


Figure 13 Natura2000 areas in the Netherlands (Rijksoverheid, 2007)

Building a project of this size in a Natura2000 area does involve a lot of obligations and requirements which are included in legislations. However, it does also provide a lot of opportunities for the Delta21 project in (among others) the form of water safety, the return of salt tides and fish migration but also for the construction of the tidal lake and energy storage lake (Delta21, 2018).

3.2.5 Delta21 as a universally applicable concept

The plans for the Delta21 project are not only applicable in the Haringvliet estuary: every estuary around the world with similar characteristics can be altered to apply the plan concerning flood safety and energy storage.

The main reason the Delta21 project is universally applicable is the fact that it is build up out of different components which are possible to be combined under various circumstances. The energy storage lake is applicable in every estuarine environment and depending on the situation, flood safety can be guaranteed by the use of the storm surge barrier and process management of the storage lake.

Using the different components, the Delta21 project concept is applicable on numerous locations under which the Elbe river in Germany, Thames river in London and the Hudson river in New York. It is also applicable for bays and estuary like the ones in Jakarta, Hull and Venice. In the Delta21 exploration phase, case studies have been conducted for 18 locations all around the globe (Delta21, 2020).

3.2.6 Delta21 in line with the Maasvlakte 2 sea defence

Since the Delta21 project reaches into the North Sea stretching out from Maasvlakte 2, some characteristics of the Maasvlakte 2 sea defence can be taken into account in the design of the sea defence of the Delta21 project. Because of the fact that the water depth and orientation of the Maasvlakte 2 sea defence are the same as those for the Delta21 sea defence, the hydraulic conditions at the toes are the same as well. Even though the hinterland and the water safety requirements of both the defences differ, some characteristics can be used when designing the Delta21 sea defence.

One of the wishes of Huub Lavooij and Leen Berke (initiators of the Delta21 project) for the Delta21 sea defence is that the crest level is in line with Maasvlakte 2, which is between NAP + 13 m and NAP + 16 m (Loman, Hofland, Van de Biezen, & Poot, 2012).

3.2.7 Previous research on Delta21

In the past couple of years multiple students have done research regarding the Delta21 project. These studies covered a large variety of subjects, from the economic feasibility to the ecological impacts of such a large project. Studies have also been done of the erosion and sedimentation of the (new) coast and Maasvlakte 2 and of the influence of rapid drawdown on dike stability.

Also structural designs have been made regarding the overflow into the energy storage lake, the new barrier which closes the Haringvliet and the turbine station. However a design of the sea defence dividing the energy storage lake and the North Sea has only been created as a sandy variant.

The effects of the Delta21-project on the alongshore sediment transport and erosion

This study, by Detmar Dieleman, focused on the sediment transport along the new coastline of the Delta21 project. In order to do this first a model-0 was created using the coastline of Maasvlakte 2 using UNIBEST, this was done in order to verify the different variables used in the modelling of the area. The verification of the model-0 was done by comparing the results of the created UNIBEST model to the measured erosion numbers in the PUMA model and the actual coastal nourishment volumes in the area.

After this assessment a UNIBEST model was created using the coastline of the Delta21 project. This model showed characteristics of along shore transport of the new coastline, which appeared to be the same as that of the Maasvlakte 2 land reclamation. Significant erosion was visible at the western bend of the project, where in both Northern and Southern direction 0.4 million m^3/year sediment was lost using a grain size of 370 µm. Based on the modelled years and conditions, between 0.4 and 1.2 million m^3/year of sediment will erode for this grain size. This is similar to the erosion patterns of Maasvlakte 2.

For a smaller grain size (a comparison was made for D_{50} = 140 µm) the occurring erosion was 2 – 2.5 times larger. The grainsize of 140 µm is approximately the grain size present in the soil which will be dredged from the energy storage lake.

Influence of rapid drawdown on dike stability

In this thesis by Steve van Adrichem, the main goal was to research the influence of the rapid drawdown in the energy storage lake on the stability of the slopes of the lake. The study was carried out using both numerical models and scale models.

The influence of rapid drawdown on dike stability was researched for a dike constructed fully out of sand, with a slope of 1:20.

First centrifugal and full scale tests were carried out and used to verify a PLAXIS2D model. In the next stage of the thesis this model was used to create a computational model of the Delta21 closure dam. The conclusion of this modelling phase was that, for a fully sandy dike with slopes of 1:20 the stability was sufficient.

In this research however, the application of other soil types and layers and the use of a revetment were not regarded. Therefore the outcome of this thesis is only applicable for a fully sandy sea defence.

Theses regarding the design of Delta21 structures and sea defence

As mentioned, multiple students have created designs for the structures which are a part of the Delta21 project. The outcomes of these designs have no effect on the design of the Delta21 sea defence and will therefore simply be mentioned but not elaborated. The most recently published design MSc. thesis topics and author at the time of writing this thesis are mentioned in Table 3 underneath.

Thesis author	Topic
P.R.I. Onwuachu	The new Haringvliet barrier (Onwuachu, 2021)
Loïc Jacquemin	Delta21: Improved Design of the Pump-turbine station (Jacquemin, 2021)
D.H. Donkers	Conceptual Design of the Spillway into the Energy Storage Lake of Delta21 (Donkers, 2021)
J.L. van Dam	Ontwerp duinenrij energie-opslagmeer (van Dam, 2020)

Table 3 Most recent MSc. thesis topics and authors for Delta21 structure designs

One thesis research does influence the design of the Delta21 sea defence, namely the thesis written by Esmée van Eeden: “A new dynamic landscape for the Haringvliet” (van Eeden, 2021). The shoreline as determined in this research is regarded as the toe of the Delta21 sea defence in this thesis.

3.3 Sea defence flooding probability

Flood protection is the number one priority in the design of the sea defence of the Delta21 project, in this subsection the safety requirement for the sections of the sea defence is discussed. First the global protection strategy for the Netherlands is described, followed by possible failure mechanisms for sea defences and a description of the way flood defence reliability is determined. Using the safety strategy, location of the flood defence and coupling these to possible failure mechanisms, the flood safety requirement for the new sea defence are determined.

3.3.1 Protection against flooding in the Netherlands

In the Dutch water law the flooding probability is describes as "the chance of loss of water retaining capacity of a dike section, causing the area protected by the dike section to be flooded, resulting in fatalities or substantial economic damage" (Rijksoverheid, 2022).

Since the first of January 2017, the Dutch protection standard for all Dutch flood protection infrastructure is determined in the "*Wettelijk Beoordelings Instrumentarium 2017 (WBI2017)*" (Rijkswaterstaat, 2016). In this method it is determined that fatalities due to flooding should have a 10^{-5} chance of occurring per individual per year.

To accomplish this, the Dutch primary flood protection system is divided in different sections which are all assigned an individual flooding probability, the sections in the region of the Delta21 project including flooding probabilities are shown in Figure 14.

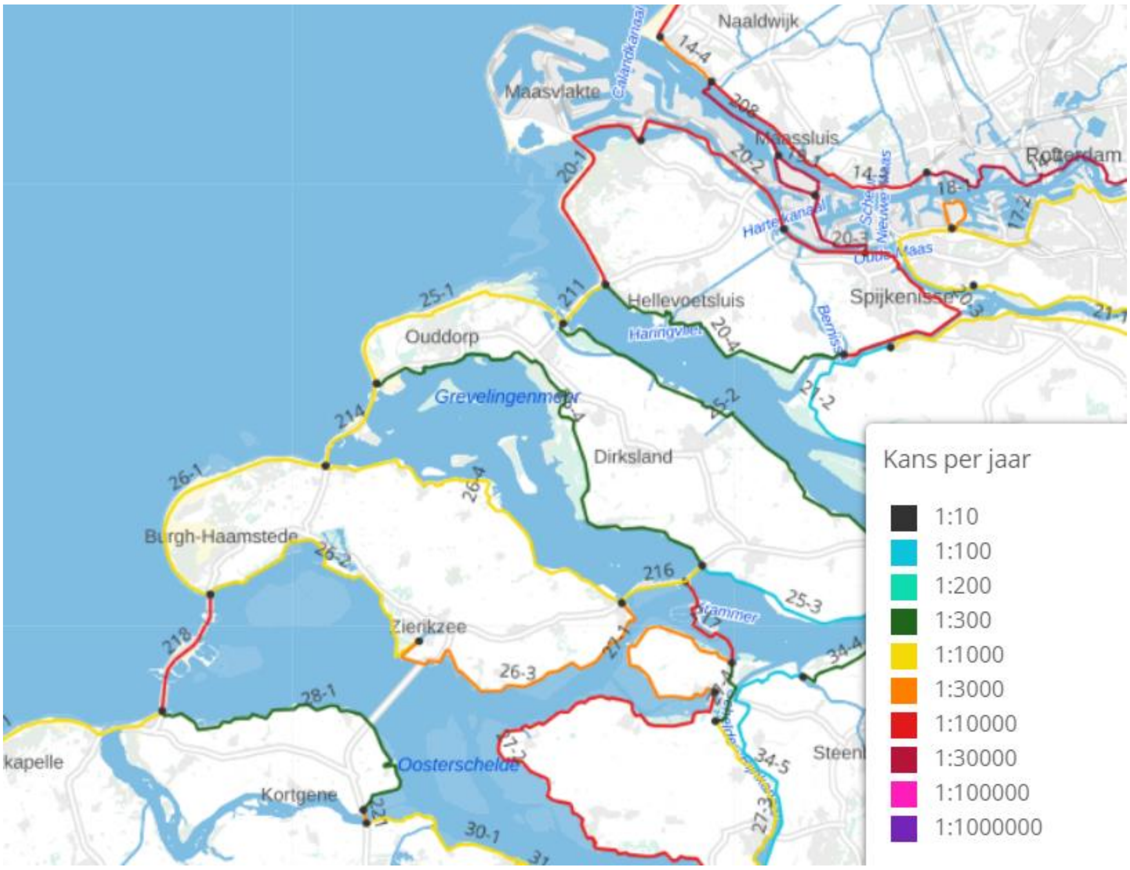


Figure 14 Flooding probability of the various flood defence segments in the Dutch Southwest Delta (taken from waterveiligheidsportaal.nl) (Waterveiligheidsportaal, 2022)

Because of the lengthy nature of the larger dike segments (as shown in Figure 14), the character of these can be different on various locations along the segment. Think about the presence of structures in a section or different soil profiles and hinterlands. Therefore the indicated dike sections are divided in smaller sections of which the flooding probabilities are assessed individually. These smaller sections can be regarded as a series of which the flooding probabilities together convert to the overall flooding probability of the main dike section.

This means that the flooding probability of a dike section is not dependent on the reliability of a single element but depends on the reliability of all elements combined. Some sections however do consist of one single element, like the Haringvliet barrier as indicated with section number 211 in Figure 14 which has a flooding probability of 1:1000.

3.3.2 Failure mechanisms

The flooding probabilities of the individual section elements are to be determined by the use of different failure mechanisms related to the dike section. In these failure mechanisms a distinction is made between those for structures and for dikes specifically. In this thesis a design is made for a hard sea defence (or sea dike), therefore the failure mechanisms for structures will not be discussed here.

Failure mechanisms for hard sea defences

- Overflow or overtopping
- Upburst and piping
- Macro instability (both inwards and outwards)
- Damaged revetment and erosion

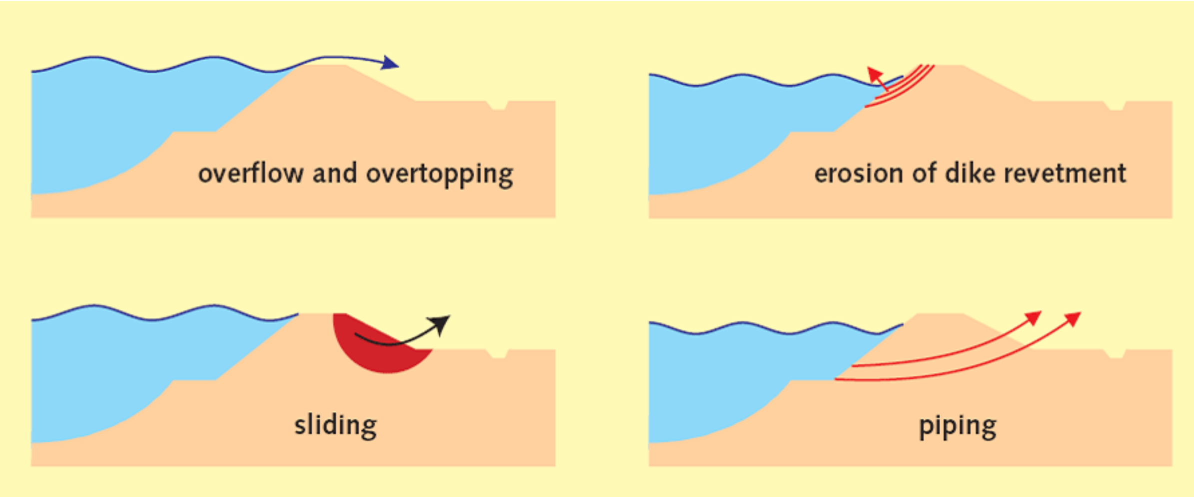


Figure 15 failure mechanisms for dikes (FLOODsite, 2022)

As described in the scope of this thesis, only the failure mechanism of overflow and overtopping is regarded in this phase of the conceptual design of the Delta21 sea defence.

Failure budget distribution in WBI2017

Above mentioned failure mechanisms play a role in the design and review of different dike sections, but not every failure mechanism is valued the same in the process. In the WBI2017 procedure the distribution of importance of failure mechanisms in the determination of the flooding probability is given, these values are shown in Table 4 below. The original table for the failure budget distribution in the WBI2017 gives different budgets for sea dikes and soft sea defences (dunes). Table 4 below only shows the failure budget distribution for sea dikes.

Type of sea defence	Failure mechanism	Contribution to failure
Dike	Overtopping	24%
	Upburst and piping	24%
	Inward macro instability	4%
	Damaged revetment and erosion	10%
Structure	Failure of closure	4%
	Piping	2%
	Constructive failure	2%
Dune	Dune erosion	10%
Other		20%
Total		**100%**

Table 4 Failure mechanisms and accompanying contribution to the over-all flooding probability of the dike section (Rijkswaterstaat, 2016)

The values given in Table 4 above will be used to determine the maximum failure probability per failure mechanism for the sea defence section in Section 3.3.4 below.

3.3.3 The Delta21 sea defence as primary flood defence

The new sea defence formed by the Delta21 project will form a new line of protection against both high water on the Rhine and Meuse as well as high water at the North Sea. The Delta21 project will be a replacement for the water retaining function of the Haringvliet Barrier, which will therefore no longer be considered a primary sea defence in the region.

The total length of the sea defence of the Delta21 project is 28.5 km. This stretch of sea defence consists of 2 structures and 3 stretches of sandy coast or dike as indicated in figure 16.

Figure 16 overview of the new sea defence sections

It can be seen that only the outer edge of the Delta21 project is considered to be a primary sea defence. In this sea defence the following sections can be determined:

1. Section 1: 13.5 kilometres
2. Turbine station: 3 kilometres
3. Section 2: 7 kilometres
4. Storm surge barrier: 1 kilometre
5. Section 3: 4 kilometres

The section indicated by the red dotted line in Figure 16 will not have a water safety function and is therefore not included as sea defence. This body of soil is only in use to create a division between the energy storage lake and the tidal lake.

The new Delta21 sea defence will change the protection strategy of the hinterland as discussed in Section 2.3.1. Part of the advantages of the Delta21 project is that the dikes in the Dutch Southwest delta do not have to be reinforced further in the future, this means that the full protection against high water from the North Sea will be guaranteed by the new sea defence. The Delta21 project will replace the Haringvliet barrier, which currently has a flooding probability of 1:1000 as shown in Figure 14. Therefore the flooding probability of the entire Delta21 project will be 1:1000 as well.

3.3.4 Determination of the Delta21 sea defence failure probability per failure mechanism

Using the “Handreiking ontwerpen met overstromingskansen” (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017) the flooding probability for the new sea defence is determined.

First the failure probability per cross-section for the separate sections of the Delta21 sea defence is determined via the lengthwise distribution of the sections over the full sea defence, which is P_{max} in Formula 1 underneath. After this the failure probability per failure mechanism per cross-section of the sea defence is determined using the following formula (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017):

$$P_{dem,cs} = \frac{P_{max} * \omega}{N} \tag{1}$$

In which:

$P_{dem,cs}$ = The failure probability per failure mechanism per cross-section of the sea defence

P_{max} = The maximum flooding probability for the dike segment per year

ω = maximum contribution of the failure mechanism in the failure probability (as given in Table 4)

N = The length-effect factor [-]

The full calculation and methodology per failure mechanism can be found in Appendix A, in Table 5 underneath the failure probabilities for the different failure mechanisms are shown for sections 1, 2 and 3, the structures in the sea defence are considered in Appendix A as well.

Failure mechanism	**Section 1**			**Section 2**			**Section 3**		
	ω	N	$\mathbf{P_{dem,cs}}$	ω	N	$\mathbf{P_{dem,cs}}$	ω	N	$\mathbf{P_{dem,cs}}$
Overtopping	0.24	2	5.36E-5	0.24	2	2.94E-5	0.24	2	1.68E-5
Upburst and piping	0.24	19	5.65E-6	0.24	10.3	5.69E-6	0.24	6.3	5.31E-6
Inward macro instability	0.04	9.91	1.80E-6	0.04	5.62	1.74E-6	0.04	3.64	1.54E-6
Damaged revetment and erosion	0.1	14.5	3.07E-6	0.1	8	1.84E-6	0.1	4	1.05E-6

Table 5 Maximum failure probability $P_{dem,cs}$ (1/year) per failure mechanism per section of sea defence

3.4 Function analysis

The Delta21 project will fulfil multiple functions in the Dutch Southwest delta. The functions of a system are divided in three different groups: principle, preserving and additional functions. Principle functions are the main objectives fulfilled by the project, preserving functions are aimed to remove or mitigate negative effects caused by the system. Additional functions are those that bring positive effects but are not part of the original function of the new system.

Principle functions of the Delta21 project:

1. Providing flood protection for the Dutch Southwest delta
2. Storing electrical energy in the form of hydrodynamic energy (green battery function)

Preserving functions:

3. Enabling outflow of rivers into the North Sea
4. Enabling tidal exchange between the North Sea and the Haringvliet estuary
5. Providing a sailing route for vessels to navigate between the North Sea and the Haringvliet
6. Restauration of ecological system behind the Haringvliet sluices
7. Enabling salt water intrusion in the tidal lake to (re)create a brackish biotope

Additional functions:

8. Provide space for recreational use

It is no coincidence that above mentioned functions largely coincide with the three main goals of the Delta21 project: providing flood safety, (sustainable) energy storage and nature conservation and restauration. The first two of these goals are the main functions of the Delta21 project, while the conservation and restauration of nature will be a consequence of the processes induced by the new environment.

Function analysis for the Delta21 sea defence

For the sea defence the function analysis will look different, since this part of the project will have the necessity to enable other parts of the Delta21 project to work. The main function of the new sea defence will be the provision of flood protection for the Dutch Southwest delta, however due to it being a division between the North Sea and the energy storage lake it also plays a large role in the energy storage function.

Principle functions of the Delta21 sea defence:

1. Providing flood protection for the Dutch Southwest delta against storms at the North Sea
2. Enable the water level in the energy storage lake to fluctuate between NAP - 5.0 m and NAP - 22.5 m

Preserving functions:

3. The location of the Delta21 sea defence should not disturb longshore sediment transport in the region.

Additional functions:

4. Provide space for recreational use
5. Provide accessibility for (maintenance) vehicles

4. Base of design

In this chapter the program of requirements and boundary conditions used in the design for the Delta21 sea defence are treated, together these form the base of design.

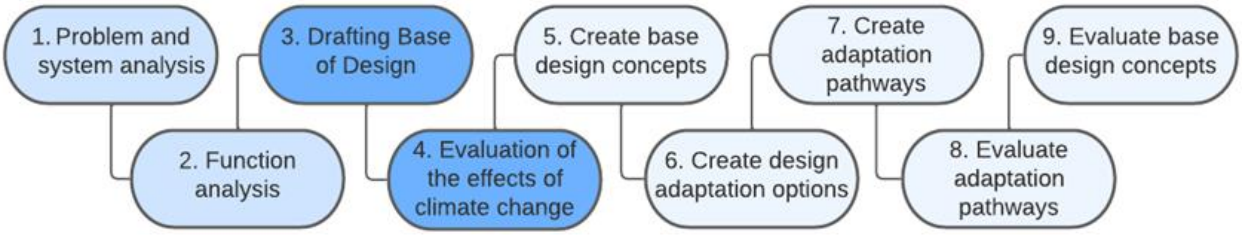


Figure 17 Position of the base of design in the thesis methodology

4.1 Program of requirements

The requirement program describes the main requirements of the Delta21 sea defence, coupled to the functions as described in the function analysis in Section 3.4. These requirements are partly derived from the function analysis, as well as stated by Huub Lavooij (initiator of the Delta21 project).

R 1. The new sea defence of the Delta21 project should provide flood safety for the Dutch Southwest delta

The entire Delta21 project has a maximum flooding probability of 1:1000, for the separate sections the flooding probabilities are determined in Section 3.3.4. The conceptual design on cross-section level will be created using the requirements for section 1, which has a maximum flooding probability of 1:2109 per year (as is determined in appendix A). For the failure mechanism of overtopping this means that the sea defence is designed for wave conditions with a return period of 18656 years.

R 2. The water level behind the sea defence should be able to fluctuate

To guarantee the functionality of the Delta 21 project, the water level behind the sea defence must be able to fluctuate. In practice the fluctuation of the water level will be between NAP - 5.0 meters and NAP - 22.5 meters during normal conditions and is facilitated by giving the slope of the energy storage lake a 1:20 angle (van Adrichem, 2021).

R 3. The sea defence should be accessible for (maintenance) vehicles

The sea defence will not be used to create a new connection between Maasvlakte 2 and the main land of the province of Zeeland, however it should be accessible for maintenance vehicles via a crest or berm of sufficient width.

R 4. The sea defence should be integrated into the landscape

Currently the project location is located in open sea, which makes this a tough requirement to meet and verify. The Delta21 sea defence will reach into the North Sea from the Maasvlakte 2, here a sea defence is present with maximum crest heights between NAP + 13 m and NAP + 16 m. Since no restrictions in crest height are given and a lack of space is not an issue, it seems logical to have crest heights in line with those present at Maasvlakte 2. Therefore crest heights until NAP + 16 m are considered.

4.2 Boundary conditions

In this chapter the boundary conditions which are necessary in the design of the sea defence are determined. First the location and orientation of the new coastline are concluded, at the same time this also plays a large role in the bathymetry in front of the new coastline.

Next the wave characteristics (height and period) will be determined, concluding with occurring water levels and the possible maximum fetch induced wave height as a final check.

4.2.1 Location, coastline and bathymetry of the sea defence

The new coastline corresponding to the Delta21 project plans reaches into the North Sea from the Maasvlakte 2. In Figures 18 and 19 this coastline has been projected onto the bathymetry as subtracted from the navionics web-app. This bathymetry corresponded to the Vaklodingen measurements in the area next to the Maasvlakte 2.

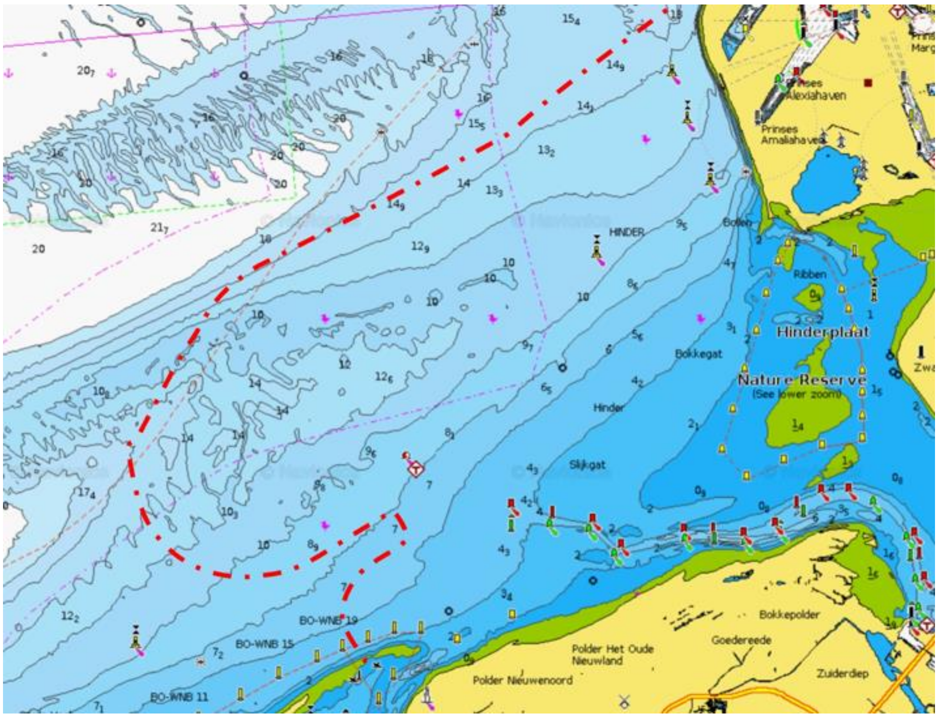


Figure 18 Bathymetry of the North Sea bed at the location of the new coastline of the Delta21 project (indicated as a red dotted line) (taken and altered from https://webapp.navionics.com)

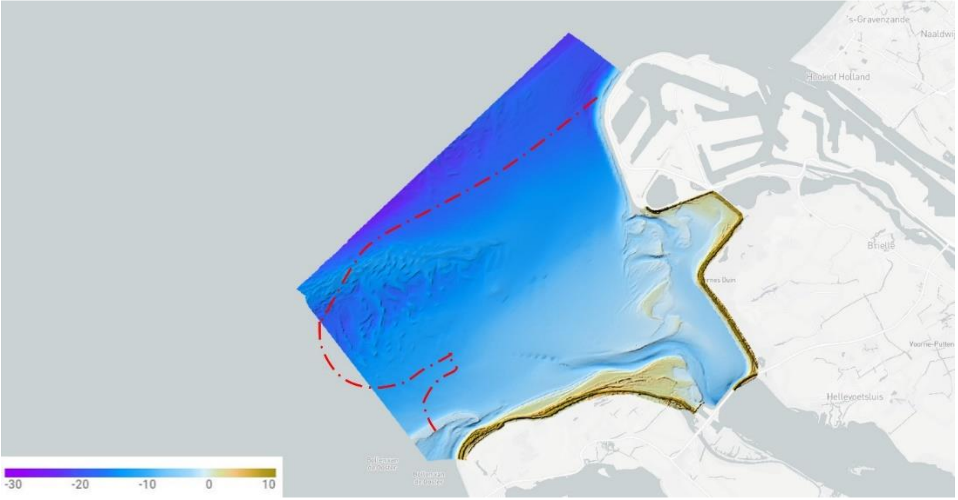


Figure 19 The new coastline projected on the Vaklodingen bathymetry

As can be seen in Figures 18 and 19 the bed level on the location of the new Delta21 coastline is between 5 and 16 meters below NAP with the largest stretch of defence having a current water depth of 14 meters.

4.2.2 Hydraulic conditions

The hydraulic conditions will be determined using both Hydra-NL and the peak-over-threshold method. Hydra-NL is part of WBI2017 and it is a probabilistic model which calculated the probabilistic statistics corresponding to the hydraulic loads on flood defences in the Netherlands. The program combines pre-calculated results from SwanOne models with probabilistic characteristics of the wave conditions for different locations on the Dutch flood defence system. The Hydra-NL database however is only sufficient for hard sea defences, the sandy system is not included in the database.

Water levels

The design water level is determined by combining occurring water levels with expected sea level rise during the lifetime of the sea defence. As is described in Section 2.1.2, it is very likely that 1 meter of sea level rise occurs during the lifetime of the sea defence. In Hydra-NL the water levels for the year 2023 are determined, for all climate scenarios this means that an 8 centimeter sea level rise is included in the calculation results (Deltares, 2018). In order to include 1 meter of sea level rise to come to the design water levels for the lifetime of the sea defence an extra 92 centimeters are added to the number acquired from Hydra-NL. The hereby gotten design water levels are shown in Tables 6 and 7.

AT HARINGVLIET BARRIER:

Return period [years]	**100**	**300**	**1000**	**3000**	**10000**	**30000**	**100000**
Water level [m+NAP]	4.86	5.18	5.55	5.90	6.31	6.69	7.11

Table 6 design water level corresponding to their return periods including 1 meter of sea level rise

AT OUDDORP BEACH:

Return period [years]	**100**	**300**	**1000**	**3000**	**10000**	**30000**	**100000**
Water level [m+NAP]	4.78	5.09	5.45	5.79	6.18	6.55	6.97

Table 7 design water level corresponding to their return periods including 1 meter of sea level rise

An example for the time series of a storm with a return period of 10000 years is created using the program “Waterstandsverloop” and is shown in Figure 20. As can be seen the water level increases gradually during the storm period and reaches the maximum water level during high tide.

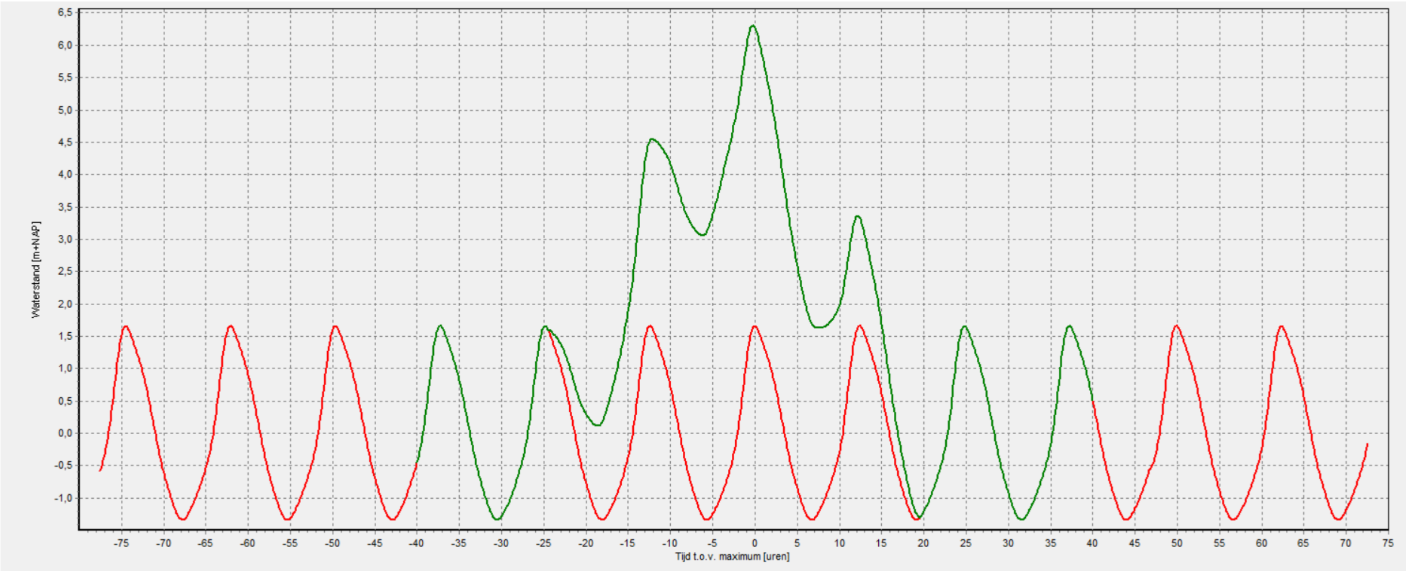


Figure 20 Time series of a storm with a return period of 10000 years. In red the normal tidal sequence is indicated, in green the water level increase during the storm period is indicated.

Wind characteristics

Since the design conditions for the Delta21 sea defence are dependent on stormy conditions, the behaviour of these storms is important for the determination of the design wave height. The two most important factors regarding wind are the wind velocity and direction. Both the characteristics play a role in the creation of wind waves and are determined with the use of Hydra-NL.

In the consideration of the wind characteristics the data associated with both the Haringvliet barrier as well as Ouddorp beach were examined, both datasets show the same behaviour. During high energy conditions only wind directions between 300 and 330 degrees North play a large role, which would mean onshore wind normal to the coast.

The wind speeds differ for different return periods, however they only differ slightly for the locations of the Haringvliet barrier and Ouddorp beach. The wind speeds for the different return periods are shown in Table 8 underneath.

Return period [years]	**100**	**300**	**1000**	**3000**	**10000**	**30000**	**100000**
Wind velocity [m/s]	26.2	28.3	30.5	34.9	37	39.2	41.9

Table 8 Wind velocities for different return periods

Wave characteristics

The occurring wave height and period are very dependent on the near-shore bathymetry because of the influence of processes as depth induced breaking and shoaling. Because the coastal zone in front of the Delta21 project does not yet exist it is not possible to extract occurring wave heights from the Hydra-NL database. Therefore an extreme value analysis for waves in deep water conditions at the Europlatform was carried out, after which SwanOne was used to model the propagation of waves from deep water conditions to future near shore conditions. The full extreme value analysis for the deep water waves can be found in Appendix B, in Table 9 below the final wave conditions at the toe of the new sea defence are presented.

Return period [years]	**100**	**300**	**1000**	**10000**	**30000**	**100000**
H_s [m]	6.68	6.95	7.21	7.75	7.97	8.19
T_p [s]	12.42	12.77	13.12	13.71	13.95	14.20

Table 9 design wave characteristics for multiple return periods

Above mentioned wave heights at the toe of the sea defence are the current wave conditions at the location of the Delta21 project. However in these numbers the change in foreshore due to the construction of the project is not yet taken into account.

4.2.3 Water level deviation at the energy storage lake

The Delta21 sea defence will defend the southwest delta of the Netherlands against high water at the North sea. However at the other side of the defence another body of water is present: the energy storage lake. From this lake the sea defence is under influence of a very large water level deviation and fetch generated waves.

Water level deviation

This lake is mainly characterised by a large withdraw of water in a short amount of time: the water can deviate between NAP – 5,00 m and NAP – 22,50 m in a timeframe of 12 hours, which means the water level can drop at a maximum rate of 1,46 meters per hour. As is described in the Msc thesis “Influence of rapid drawdown on dike stability” by Steve van Adrichem (van Adrichem, 2021) it is advised that the slopes of the energy storage lake to the sea defence will have to be 1:20 in order to guarantee dike stability under the influence of this large water level deviation. This in not necessarily the slope of the inner slope of the sea defence, but should be the slope of the energy storage lake.

4.3 Influence of climate change on the hydraulic boundary conditions

The boundary conditions as described in Section 4.2 form the foundation of the base design concepts which are the base of the adaptative pathway approach. In decades to come the boundary conditions which form part of the base of design will change due to climate change. In this section the effects of climate change on the boundary conditions are described, the altered boundary conditions will form the base for Chapter 6.

Concerning the Delta21 sea defence, the rise of sea level is the most important consequence of climate change. An elevated sea level does not only result in a greater water depth, it also has an influence on the wave size at the toe of the new sea defence.

It is assumed that the return periods and wave heights for deep water waves at the location of the Europlatform will not alter due to climate change. This assumption is supported by the fact that wind velocities will not increase significantly due to the changing climate (KNMI, 2021) (IPCC, 2021), causing fetch induced waves to be of equal size in both situations. On top of that the assumption is made that the return periods for high water on the North Sea will also stay the same due to the same reasoning.

In Appendix B the influence of sea level rise for wave propagation to the new coastline of the Delta21 project is calculated. The results of this are shown graphically in Figure 21.

In this figure the bottom green line projecting 1 meter of sea level rise shows the wave heights as used in the base situation. The orange, grey, yellow and blue lines indicate the wave heights which will occur for two, three, four and five meters of sea level rise respectively. As can be seen, the wave heights at the toe of the sea defence increase when the sea level elevation increases.

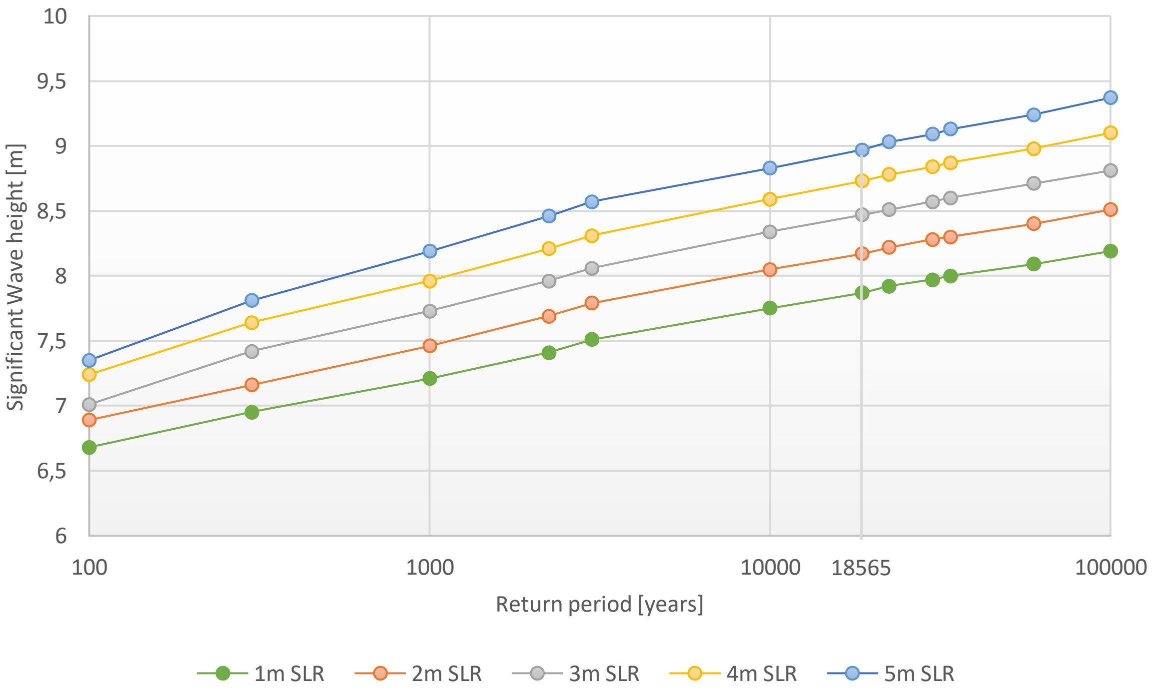


Figure 21 The influence of sea level rise on the significant wave height at the toe of the sea defence

In the graph above the wave heights corresponding to all return periods as determined in Appendix A are presented. The design of the Delta21 sea defence will be created for design wave conditions with a return period of 18565 years.

Table 10 shows the wave heights corresponding to a return period of 18656 years for different amounts of sea level rise, this return period is used to design the sea defence on the failure mechanism of overtopping.

Water depth at toe [m]	Storm surge level [NAP+m]	Amount of sea level rise [m]	Significant wave height [m]
20.52	6.52	1 (base scenario)	7.87
21.52	7.52	2	8.17
22.52	8.52	3	8.47
23.52	9.52	4	8.73
24.52	10.52	5	8.97

Table 10 Significant wave heights with a return period of 18656 years for different amounts of sea level rise

Up to five meters of sea level rise are taken into account, as this is the amount of sea level rise which can occur under great uncertainty for the worst emission scenario during the 100 year lifetime of the Delta21 sea defence as described in Section 3.1.2 (IPCC, 2021).

4.4 Overview of the base of design

The Delta21 sea defence is created for design conditions with a return period of 18565 years as is determined in Appendix A. The most important characteristics from the base of design for the design of the Delta21 sea defence are listed underneath in Table 11.

Sea level rise scenario	Parameter	Value	Unit
All	North Sea bed level	-14	[m+NAP]
	Return period for overtopping	18656	[years]
	Wave angle with the coast	90	[°]
1 meter of sea level rise	Still water level (SWL)	6,52	[m+NAP]
	Significant wave height at toe (H_s)	7,87	[m]
	Wave period at toe (T_p)	12,82	[s]
2 meters of sea level rise	Still water level (SWL)	7,52	[m+NAP]
	Significant wave height at toe (H_s)	8,17	[m]
	Wave period at toe (T_p)	13,06	[s]
3 meters of sea level rise	Still water level (SWL)	8,52	[m+NAP]
	Significant wave height at toe (H_s)	8,47	[m]
	Wave period at toe (T_p)	13,30	[s]
4 meters of sea level rise	Still water level (SWL)	9,52	[m+NAP]
	Significant wave height at toe (H_s)	8,73	[m]
	Wave period at toe (T_p)	13,50	[s]
5 meters of sea level rise	Still water level (SWL)	10,52	[m+NAP]
	Significant wave height at toe (H_s)	8,97	[m]
	Wave period at toe (T_p)	13,69	[s]

Table 11 Overview of the most important values of the base of design for the design of the Delta21 sea defence

5. Generation of base sea defence concepts

The first step in the creation of the conceptual design for the Delta21 sea defence with the use of the adaptation pathway approach is the generation of the base sea defence design concepts which form the base of the adaptation pathways. In this chapter these base concepts are created that meet the overtopping requirement, which is the fifth step of the methodology as described in Section 2.1 and shown in Figure 22 underneath.

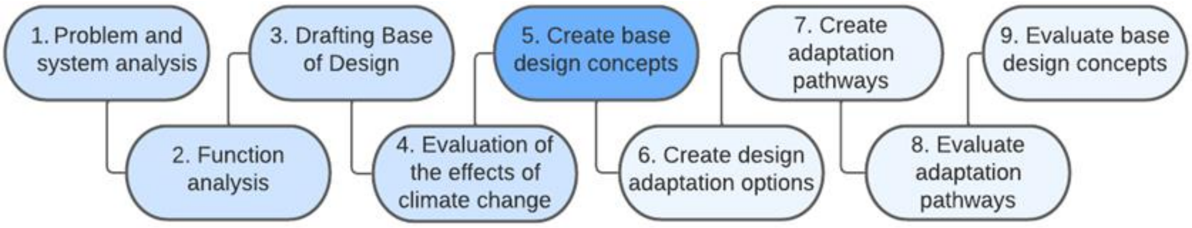


Figure 22 Position of this chapter in the thesis methodology

Firstly the design parameters for the creation of the design concepts are determined, after which multiple design concepts are formed and verified to three additional requirements. This leads to 3 different design variants which are elaborated in Section 5.3, these designs meet the requirements of overtopping, accessibility and a fluctuating water level as proposed in Section 4.1.

5.1 Inventory of design parameters

The conceptual designs for the Delta21 sea defence are created using overtopping as the leading failure mechanism to give shape to the geometry and composition of the dike. This section describes the parameters which play a role in the design of the sea defence. In Section 5.2, multiple design concepts are created by varying these parameters. The full design process is described in Appendix C: Static sea defence design.

The overtopping of the Delta21 sea defence is calculated using the deterministic overtopping formulas as given by Van der Meer in the Technical Report Wave Run-up and Wave Overtopping at Dikes (van der Meer, 2002).

$$\frac{q}{\sqrt{gH_s^3}} = \frac{0.067}{\sqrt{tan\alpha}} * \gamma_b * \xi_{m-1,0} * \exp\left(-4.3 * \frac{R_c}{H_s} * \frac{1}{\xi_{m-1,0}\gamma_b\gamma_f\gamma_\beta}\right) \tag{2}$$

With a maximum overtopping of:

$$\frac{q}{\sqrt{gH_s^3}} = 0.2 * \exp\left(-2.3 * \frac{R_c}{H_s} * \frac{1}{\gamma_f\gamma_\beta}\right) \tag{3}$$

In which:

q = $Average\ overtopping\ volume\ [m^3/s/m]$
H_s = $Significant\ wave\ height\ [m]$
R_c = $Crest\ height\ of\ the\ dike\ with\ respect\ to\ the\ storm\ surge\ level\ [m]$
α = $Outer\ slope\ angle$ [°]
$\xi_{m-1.0}$ = $Breaker\ parameter\ based\ on\ T_{m-1.0}$
$T_{m-1.0} = T_p/1.1$
γ_b = $Berm\ influence\ factor$ [-]
γ_f = $Roughness\ of\ elements\ on\ the\ slope$ [-]
γ_β = $Influence\ factor\ of\ angled\ wave\ attack$ [-]

The occurring amount of overtopping is influenced by the parameters present in formulas 2 and 3, these parameters are explained below.

The water depth at the toe of the sea defence is not a parameter in Formulas 2 and 3. When the wave height at the toe of the sea defence is depth-limited due to depth induced breaking, this is taken into account in the wave height. In the base design situation the foreshore is not shallow.

Berm influence factor

For the first conceptual design of the Delta21 sea defence it is assumed that the berm is situated at the height of the still water line as this is most effective as a counter measure against overtopping. Using the guidelines handed by EurOtop (Van der Meer, et al., 2018) the berm influence factor can be calculated using:

$$\gamma_b = 1 - r_b(1 - r_{dh}) \tag{4}$$

With:

$$r_b = \frac{B}{L_{berm}} \tag{5}$$

$$r_{dh} = 0.5 - 0.5\cos\left(\pi \frac{d_b}{R_{u2\%}}\right) \qquad (6) \qquad \text{for a berm above still water line}$$

$$r_{dh} = 0.5 - 0.5\cos\left(\pi \frac{d_b}{2 * H_s}\right) \qquad (7) \qquad \text{for a berm below still water line}$$

Otherwise, $r_{dh} = 1$ for berms outside the area of influence (between $2 * H_s$ below and $R_{u2\%}$ above the still water line).

In which:

r_b = relative berm length [-]
r_{dh} = height of the berm with respect to the still water line [-]
B = length of the berm [m]
L_{berm} = length of the slope (over two significant wave heights) including the berm [m]
d_b = distance between berm level and water level [m]
$R_{u2\%}$ = the 2% run-up [m]
H_s = Significant wave height [m]

Because of the fact that the berm is situated at the still water line in the first conceptual designs, $r_{dh} = 0$.

The berm is located at the storm surge level, however due to the effects of climate change the sea level will increase and therefore the berm will be located below the storm surge level over time (during storm conditions).

During this design phase a restriction in the value of γ_b (EurOtop describes that $\gamma_b > 0.6$) is disregarded as this restriction is not implemented due to a physical restriction but due to a lack of research data.

Roughness of elements on the slope and berm

In this case the outer slope of the sea defence is build up out of two slopes (the upper and lower slope) and a berm. Both slopes can be covered with different elements which do not have the same roughness. On top of that the top layer of the berm can have a different roughness as well. The roughness of the various different parts of the slope does not have an equal effect on the run-up and overtopping, in fact the roughness of the upper section has the most effect while the roughness of the lower slope has least effect (Chen, Van Gent, Warmink, & Hulscher, 2020).

The roughness coefficient for a slope with different elements can be calculated using the following formula (Van der Meer, et al., 2018):

$$\gamma_f = \frac{\alpha_1 * \gamma_{f1} * L_1 + \alpha_2 * \gamma_{f2} * L_2 + \alpha_2 * \gamma_{f3} * L_3}{\alpha_1 * L_1 + \alpha_2 * L_2 + \alpha_3 * L_3} \tag{8}$$

In which:

L_1 = length of slope until $-0.25z_{2\%}$ under the water line [m]
L_2 = length of the berm [m]
L_3 = length of slope until $+0.5z_{2\%}$ above the water line [m]
γ_n = roughness coefficient of the revetment on the part of the slope or berm [-]
α_n = influence factors of the position of the roughness elements on the overall slope [-]

The three different α_n factors are the influence factors of the position of the roughness elements on the overall outer slope ($\alpha_1 = 0.13$, $\alpha_2 = 0.22$ and $\alpha_3 = 0.65$). The roughness elements on the upper part of the outer slope have more influence on overtopping than the roughness elements on the lower slope and berm (Chen, Van Gent, Warmink, & Hulscher, 2020).

Using Formula 8 the roughness of the outer slope can be determined, however the use of material for the outer slope will have large consequences in this determination. For example the use of an asphalt top layer will result of a roughness coefficient of $\gamma_f = 1$ (van der Meer, 2002), but the use of Xbloc elements can result in an optimal roughness of $\gamma_f = 0.44$ (Delta Marine Consultants, 2018) for the slope on which the elements are placed.

Since the roughness of the entire outer slope is a function of roughness and the length of the separate sections of the front slope, the overall roughness depends on the width of the berm, top layer of the slopes and slope angles. Therefore the roughness coefficient differs for every considered design variant.

Influence factor of oblique wave attack

In the case that the wave attack obliquely incident to the sea defence, the wave run-up and therefore overtopping are reduced compared to a situation in which the waves are normally incident. However, in the case of the Delta21 sea defence the normative angle of wave attack is normally incident to the sea defence, therefore $\gamma_\beta = 1$.

Crest height

The crest height is the distance between the highest point of the dike and the design high water level (SWL) and plays a large role in the occurring amount of overtopping.

Slope angle

The last parameter which has an influence on the overtopping of the Delt21 sea defence is the slope angle of the outer slope.

5.2 Design concept creation and verification

When using overtopping as the main failure mechanism in designing the dike geometry, all variables as described in Section 5.1 can be used to create different design concepts. The basis of these concepts is the accepted amount of overtopping for design wave conditions as determined in requirement R.1. By combining the acceptable amount of overtopping with the design parameters from Section 5.1, various design concepts are created.

5.2.1 Determination of the acceptable amount of overtopping

The acceptable amount of overtopping is determined by various parameters on, and in the surroundings of, the sea defence. The first parameter is the material which is used to create the inner slope of the defence, however the presence and position of vehicles, people and material on and behind the dike can also influence the tolerable amount of overtopping.

In the case of the Delta21 sea defence it is assumed that there are no vehicles or people present on the sea defence during storm conditions. Therefore the tolerable amount of overtopping is solely determined by the material used to create the inner slope op the sea defence. For the Delta21 sea defence, two distinct variants are created:

1. the use of only a clay top layer with grass coverage
2. the use of clay and asphalt topped by a life layer

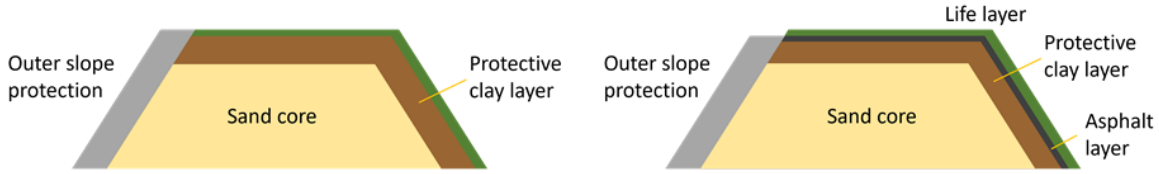


Figure 23 Schematic representation of crest types 1 and 2

1. The use of only a clay top layer with grass coverage

In this situation the inner slope of the sea defence is build up out of a clay layer which is covered in grass. Since the erodibility of the grass top layer is the only factor determining the allowable overtopping discharge, the allowable overtopping discharges according to the EurOtop Overtopping Manual is used. This document states that the maximum allowable overtopping discharge for well-kept, closed grass covers is 5 l/s/m (Van der Meer, et al., 2018). It is assumed that the grass-cover of the inner side of the Delta21 sea defence is closed and well-kept since this is a primary sea defence for the Netherlands.

2. The use of asphalt topped by a soil and grass layer.

When making use of an asphalt layer underneath a thin layer of soil and grass, the asphalt will prevent erosion of the inner slope and blocks UV-light from aging the asphalt layer.

At slope angles of 1:6 and less steep, overtopping discharges up to 1000 l/s/m can be handled (Deltares, 2015). However for dikes with a slope of 1:3 and steeper, only overtopping discharges until 125 l/s/m are tested (Deltares, 2015). At these discharges the asphalt top layer did not erode, therefore a maximum overtopping discharge of 125 l/s/m is assumed for the Delta21 sea defence.

Because of the large head of water over the dike, a clay layer is present underneath the asphalt layer to prevent large flows of water through the dike.

When assuming water coming in over sections 1, 2 and the turbine station, a total length of 23,5 kilometres will be overtopped. For an overtopping discharge of 125 l/s/m this means that 2937,5 m^3 of water enters the energy storage lake every second.

Since the turbine station capacity is 10.000 m^3/s and the energy storage lake has a larger capacity than necessary for the energy storage demand, this amount of overtopping can be discharged via and stored in the energy storage lake (Lavooij & Berke, 2019).

The 0,2 m life layer will increase the maximum crest level of the dike, this however is not an issue for the project as discussed with Delta21 initiators Huub Lavooij and Leen Berke. The increased crest level because of the life layer has no function in safety against flooding or reducing overtopping, therefore the level of the top of the asphalt layer is defined to be the crest level in this thesis.

5.2.2 Creation of overtopping-resistant design concepts

Using all parameters as mentioned in section 5.1, multiple overtopping-resistant designs of the Delta21 sea defence are created; using different slope angles, berm widths, crest heights, roughness elements and an inner slope lined with grass or asphalt. These designs are created using the overtopping requirements as indicated in Section 5.2.1 and the design choices as indicated below.

All possible design variants which are created using the mentioned variables can be found in Appendix D: Sea defence design concepts for overtopping.

Crest level

In the concept creation phase the crest height is not limited. In order to get a good image of all possible design geometries, the crest level of the sea defence is varied between NAP + 8 m and NAP + 25 m.

Berm

The berm (if present) is located at the still water level of NAP + 6.52 m is during normative storm conditions. The berm is covered in an asphalt layer which has a roughness coefficient of $\gamma_f = 1$ and the width is varied between 0 and 35 meters.

Lower and upper outer slope revetment

Two types of outer slope are considered, all of these consider a berm with an asphalt top layer. However the top layer (and therefore roughness) of the upper and lower slope differs:

1. An outer slope with both the upper and lower slope build up from interlocking armour units. In this thesis Xbloc are considered which have a roughness coefficient of $\gamma_f = 0.44$ (Delta Marine Consultants, 2018).

2. An outer slope fully covered in an asphalt top layer, the overall roughness for the entire outer slope will then be $\gamma_f = 1$ (Deltares, 2015).

The use of a placed block revetment is not considered to be a possible top layer material for the outer slope of the Delta21 sea defence as the required layer thickness would be 1.09 meters, which is unreasonably large. This is elaborated in Appendix C.

Lower and upper outer slope angle

The outer slope angle is varied between 1:1.5, 1:2, 1:3 and 1:4.

5.2.3 Concept verification

All generated conceptual design geometries can be found in Appendix D: Sea defence design concepts for overtopping. Three conceptual designs for the Delta21 sea defence are selected using three requirements:

1. *Maximum crest height*

This requirement is deduced from the program of requirements: requirement R.4, in combination with the information given in Section 3.2.5.

The Delta21 sea defence will reach into the North Sea from the Maasvlakte 2, here a sea defence is present with maximum crest levels between NAP + 13 m and NAP + 16 m. Since no restrictions in crest level are given by the Delta21 initiative and a lack of room for the sea defence is not an issue, it seems logical to have crest levels in line with those present at Maasvlakte 2. Therefore crest levels until NAP + 16 m are considered.

2. *Preferred slope angle per revetment type*

In this conceptual design phase only two types of revetments are regarded: asphalt and interlocking armour units.

For asphalt slopes the maximum slope angle is 1:3 for asphalt concrete in the water overpressure zone (Deltares, 2015). Therefore slopes steeper than 1:3 are disregarded from this design phase.

The use of concrete armour units requires steep slopes in order to get maximum stability for units with low weight (Delta Marine Consultants, 2018). For Xbloc the slope preferably is 2:3 (or 1:1.5) or steeper for maximum stability, however stability can also be guaranteed by applying heavier units for less steep slopes. In this study a maximum slope of 1:3 (using heavy units) is considered for the use of Xbloc, however a slope of 1:1.5 is preferred.

3. *Outer slope length*

Generally speaking, the costs for the sea defence can be reduced by reducing the amount of revetment. In the case of the Delta21 sea defence the outer slope will be fully covered in a revetment (either asphalt or concrete armour units). Therefore in this case the length of the outer slope is preferred to be small.

Using these three requirements to verify the design concepts, three different designs can are selected for the Delta21 sea defence. These designs are elaborated upon in Section 5.3 underneath.

5.3 Presentation of the base design concepts for the Delta21 sea defence

Three base design variants are created for the Delt21 sea defence, these are described in Sections 5.3.1 to 5.3.3 underneath.

5.3.1 Variant 1: an Xbloc outer slope and a clay and grass inner slope

The first design variant for the Delta21 sea defence is a dike of which the inner slope is protected by a clay layer topped with grass. It is assumed that the grass is in good condition and well-kept due to the primary status of the sea defence, therefore the tolerable amount of overtopping is 5 l/s/m (Van der Meer, et al., 2018).

Base design variant 1 has a crest level at NAP + 16 m and a berm with a width of 24 m at SWL (NAP + 6.52 m). The berm is topped with an asphalt layer with a roughness of $\gamma_f = 1$ and the slopes (with an angle of 1:3) are covered in interlocking armour units with an assumed roughness of $\gamma_f = 0.44$. The combined roughness of the outer slope is therefore $\gamma_f = 0.59$.

The total volume per meter length of this design variant is 3312 m^3/m and the length of the outer slope is 119 m.

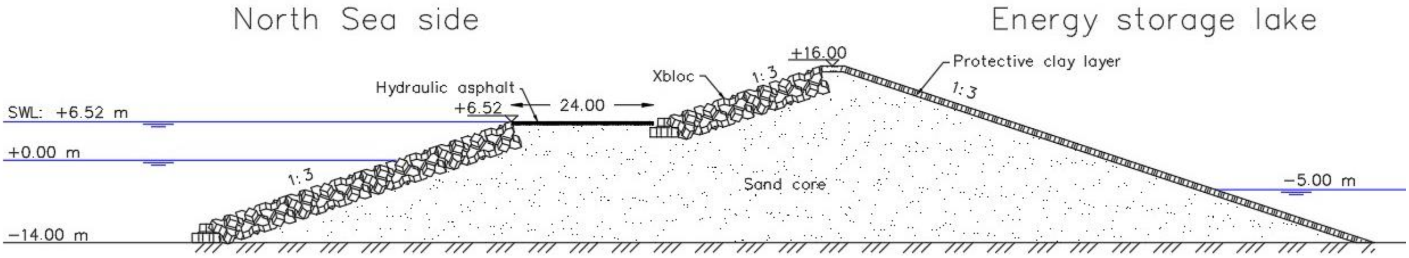


Figure 24 Sketch of static sea defence variant 1

5.3.2 Variant 2: an asphalted outer slope and an asphalt topped by grass inner slope

The second design variant for the Delta21 sea defence is a dike of which the inner slope is protected by a clay layer and asphalt layer, topped by a (aesthetic) life layer with grass of 0,2 m thickness. In this design the water safety function is fulfilled by the asphalt layer, the grass layer does not have a function in water safety other than protecting the asphalt against UV-radiation. The tolerable amount of overtopping is 125 l/s/m.

Base design variant 2 has a crest level at NAP + 16 m and a berm with a width of 22 m at SWL (NAP + 6.52 m). Both the berm and the slopes are topped with an asphalt layer with a roughness of $\gamma_f = 1$, the slopes have a slope angle of 1:3.

The total volume per meter length of this design variant is 3271 m^3/m and the length of the outer slope is 117 m.

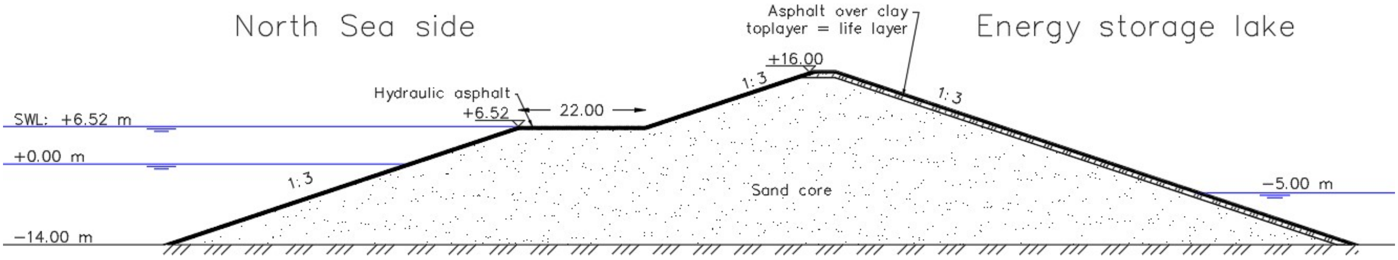


Figure 25 Sketch of static sea defence variant 2

5.3.3 Variant 3: an Xbloc outer slope and an asphalt topped by grass inner slope

The third design variant for the Delta21 sea defence also is a dike of which the inner slope is protected by a clay layer and asphalt layer, topped by a (aesthetic) life layer with grass of 0,2 m thickness. In this design the water safety function is fulfilled by the asphalt layer, the grass layer does not have a function in water safety other than protecting the asphalt against UV-radiation. The tolerable amount of overtopping is 125 l/s/m.

Base design variant 3 has a crest level at NAP + 16 m and a berm with a width of 23 m at SWL (NAP + 6.52 m). The berm is topped with an asphalt layer with a roughness of $\gamma_f = 1$ and the slopes (with an angle of 1:1.5) are covered in interlocking armour units with an assumed roughness of $\gamma_f = 0.44$. The combined roughness of the outer slope is therefore $\gamma_f = 0.66$.

The total volume per meter length of this design variant is 2617 m^3/m and the length of the outer slope is 77 m.

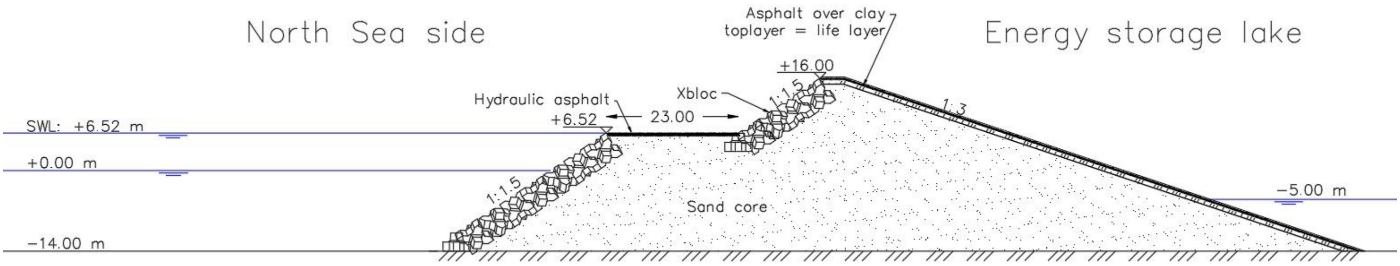


Figure 26 Sketch of static sea defence variant 3

5.4 Overview of the Delta21 sea defence conceptual design variants

Three separate conceptual design variants are created for the Delta21 sea defence, the details of each of the variants are shown in Table 12 underneath.

Design variant:		**Variant 1**	**Variant 2**	**Variant 3**
Crest height:	[m+NAP]	16	16	16
Crest width:	[m]	4	4	4
Berm width:	[m]	24	22	23
Berm height:	[m+NAP]	6,52	6,52	6,52
Slope angle:	[-]	1:3	1:3	1:1,5
Inner slope type:	[-]	Clay	Asphalt	Asphalt
Outer slope type:	[-]	Xbloc	Asphalt	Xbloc
Cross-sectional volume:	[m^3/m]	3312	3271	2617
Outer slope length:	[m]	119	117	77

Table 12 Overview of the characteristics of the conceptual design variants

The preferred conceptual design for the Delta21 sea defence will be selected via an evaluation on four criteria, this evaluation is presented in Chapter 9 and makes use of the adaptive pathway approach.

6. Creation of adaptation measures for the Delta21 sea defence

In this chapter the sixth step of the design methodology as shown in Figure 27 underneath are concerned. In Chapter 5, three conceptual designs for the Delta21 sea defence are created with only one meter of sea level rise in mind. However, during the 100 year lifetime of the structure, more sea level rise might occur. In order to cope with more sea level rise than originally designed for, the sea defence should be altered. This chapter handles the adaptational measures which can be applied for the Delta21 sea defence and form the adaptation actions in the adaptive pathway approach.

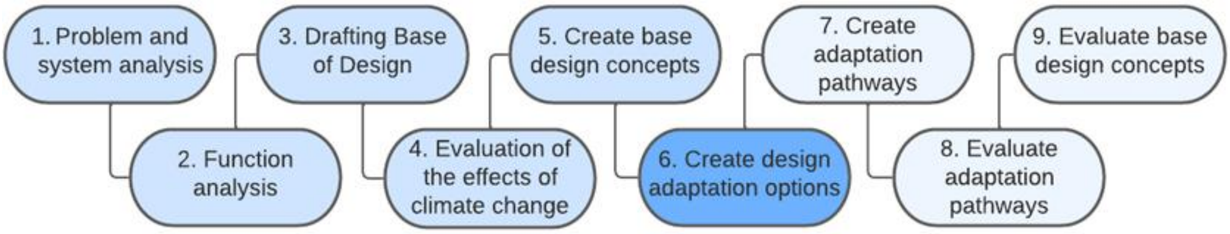


Figure 27 Position of this chapter in the thesis methodology

6.1 Selection of suitable adaptation measures

The conceptual designs for the Delta21 sea defence are created using overtopping as the leading failure mechanism. The rising sea level will bring new boundary conditions which imply more overtopping for the various base designs, in order to counter this phenomenon the sea defence designs will be altered. The parameters which can be changed in order to counter overtopping are the same parameters which are used in the creation of the three different base design variants and are regarded in Section 5.1 of this report.

From Function 2 on page 35 of this report, the following adaptation options can be deduced:

1. Crest level increase
2. Berm adaptation (which alters the berm reduction factor γ_b from Function 2)
3. Outer slope roughness increase (which alters the roughness coefficient γ_f from Function 2)
4. Inner slope strength increase (which increases the allowable overtopping discharge)
5. Outer slope angle decrease

Another way of decreasing the amount of overtopping is an increase in foreshore level (6), this will be the sixth adaptational measure which is regarded in the study for design adaptation options.

In this study, structural elements will not be regarded. This means that the application of crest walls and other structures will not be taken into account.

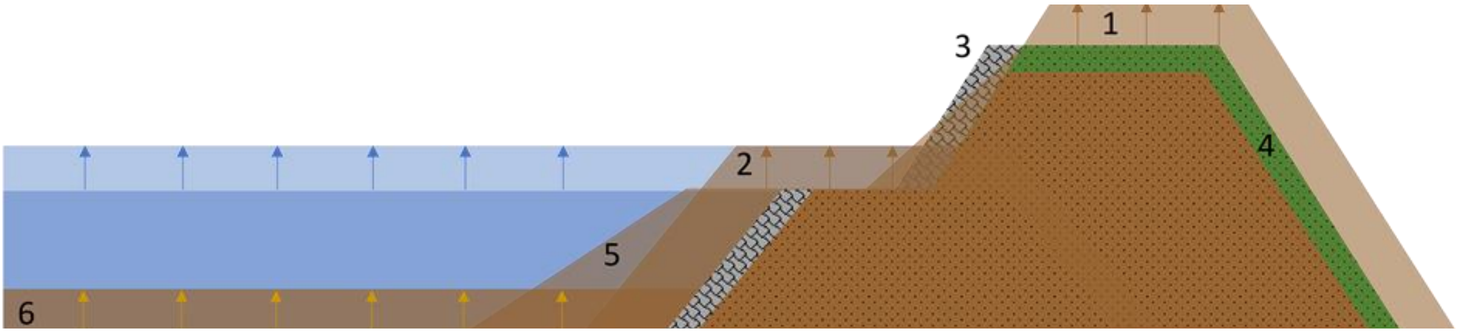


Figure 28 All possible adaptation options schematized in one figure

6.2 Application of adaptation options

The possible adaptation options for the Delta21 sea defence as mentioned in section 6.1 will be implemented differently for the three adaptation variants, due to the different geometries and characteristics of these variants. The way the adaptation options are applied for the three base design variants is discussed in Sections 6.2.1 to 6.2.6 underneath.

6.2.1 Crest height adaptation

A traditional method in dike reinforcement is increasing the crest height, this is also an option in the case of the Delta21 sea defence. This method is effective for all three base variants for the Delta21 sea defence.

The full derivation of crest level increase can be found in Appendix E: Adaptational measures for the Delta21 sea defence.

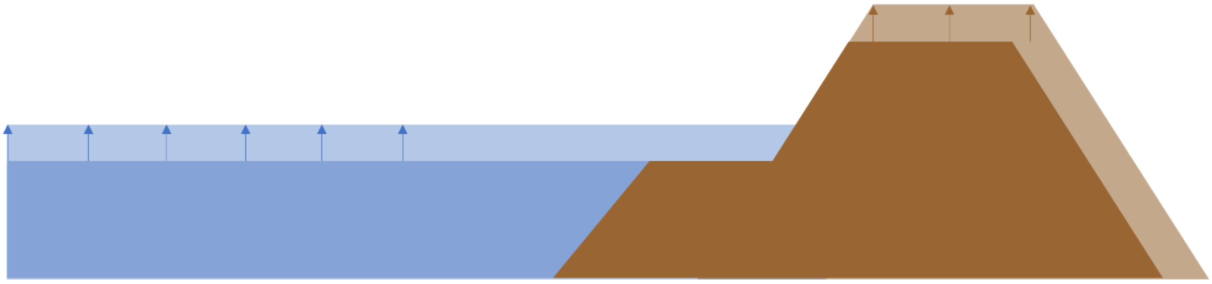


Figure 29 schematic representation of increasing the crest height on the sea defence

Application of crest level adaptation

The step sizes of crest level increase differ for each of the three base design variants. Every step of crest level increase has a tipping point of an extra meter of sea level rise, which means that an adaptation for 5 meters of sea level rise can be done in four steps of crest level increase for each of the variants.

The step sizes for the various design variants are shown underneath in Table 13.

Sea level rise [m]	Variant 1	Variant 2	Variant 3
2	1.65	1.75	1.95
3	3.30	3.50	3.90
4	4.95	5.25	5.85
5	6.60	7.00	7.80

Table 13 Amount of crest level increase (on top of the base NAP + 16 m crest level) for various levels of sea level increase

This adaptational measure does not imply difficulties for the application of other adaptational measures mentioned in this chapter and can therefore also be applied as a combination with those.

6.2.2 Berm adaptation

In the three base designs for the adaptive pathway schemes a berm is present to restrict the amount of overtopping. Just like the crest height can be adapted, the geometry of the berm can be adapted as well. In this adaptational measure the berm will be widened and the level will be increased.

The full derivation of berm adaptation can be found in Appendix E: Adaptational measures for the Delta21 sea defence.

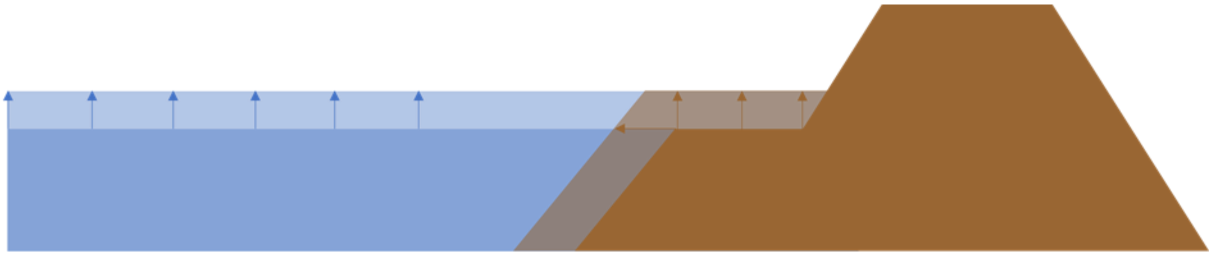


Figure 30 schematic representation of berm adaptation

Application of berm adaptation

The presence of a berm is integrated in the overtopping formula by the berm influence factor γ_b, which is a function of the berm width and the height of the berm with respect to SWL.

The influence of the berm is the largest when it is situated at SWL, however when the sea level rises this means that SWL rises as well. The length of the berm with respect to the wave length is the second parameters for the berm influence factor. The larger the wave length, the wider the berm has to be to dissipate wave energy. Therefore adaptation of the sea defence by altering the berm will be done by increasing the width and height of the berm.

Berm adaptation will be implicated in two steps for each of the three base design variants, the first step is a width increase to 50 meters, the second step increases the width to 75 meters. These steps have different tipping points for each of the variants, which are shown underneath in Table 14.

The berm level is increased to the storm surge level of the tipping point rounded to whole meters. The new berm level for each adaptation step is shown underneath in Table 14 as well.

	Variant 1		**Variant 2**		**Variant 3**	
Berm width	**Berm level**	**Tipping point**	**Berm level**	**Tipping point**	**Berm level**	**Tipping point**
[m]	[NAP+m]	[mSLR]	[NAP+m]	[mSLR]	[NAP+m]	[mSLR]
50 m	7.52	2.20	8.52	3.20	8.52	3.10
75 m	8.52	3.15	9.52	4.50	9.52	4.55

Table 14 Tipping points for berm width adaptation for the three base design variants

Berm adaptation implies no complications for the use of other adaptational measures and can therefore be used in a combination.

6.2.3 Slope roughness increase

The slope roughness is determined by the type of revetment and the elements used to create the top layer of the slope. In the case of the Delta21 sea defence the outer slope is created by three segments: the lower slope, berm and upper slope, which do not necessarily have the same roughness of the top layer.

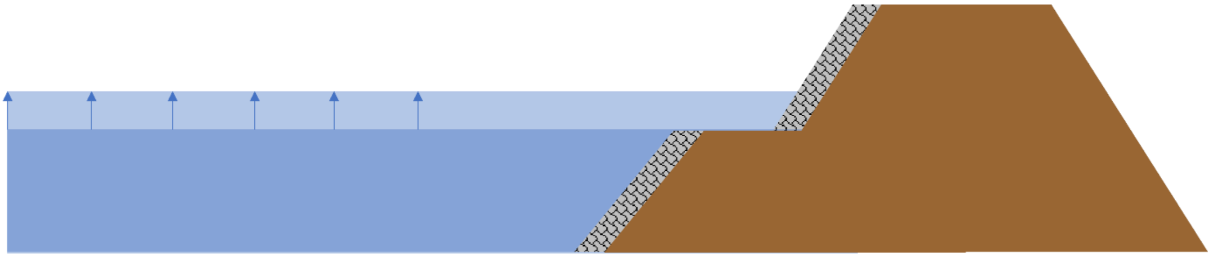


Figure 31 schematic representation of slope roughness adaptation

Application of outer slope roughness increase

As discussed in Section 5.2.2, two types of outer slope are considered, both consider a berm with an asphalt top layer. However the top layer of the upper and lower slope differ:

1. An outer slope fully covered in an asphalt top layer, the overall roughness for the entire outer slope will then be $\gamma_f = 1$ (Deltares, 2015).
2. An outer slope with both the upper and lower slope build up from interlocking armour units. In this thesis it is assumed that Xbloc are applied, which have a roughness factor of $\gamma_f = 0.44$ (Delta Marine Consultants, 2018).

Base design variant 1 and 3 both have an outer slope revetment created with concrete armour units and therefore above mentioned slope type 2. Design variant 2 is lined with asphalt and therefore has slope type 1. Transforming the outer slope from above mentioned slope type 1 to slope type 2 increases the roughness which decreases the occurring overtopping discharge.

This method of adaptation is only suitable for variant 2, which has a smooth outer slope and an inner slope with an asphalt layer below a clay and grass top layer. The smooth outer slope has a roughness coefficient $\gamma_f = 1$, this can be altered by applying interlocking armour units.

Applying this adaptation step to conceptual design variant 2 has the desired effect until 3.75 meters of sea level rise. Therefore 3.75 meters of sea level rise is the tipping point for this adaptation measure.

The use of concrete armour units is dependent on the steepness of the slope and cannot be performed for slopes milder than 1:3. Therefore this adaptation method cannot be applied in combination with the increase in slope angle as described in Section 6.2.5.

Application of this adaptational measure poses no further issues in combination with the other adaptational measures mentioned in this chapter.

6.2.4 Inner slope strength increase

Due to the erodibility of a grass top layer, a dike with only a clay and grass inner slope protection has a maximum overtopping discharge of 5 l/m/s. The maximum allowable overtopping discharge can be increase by applying asphalt on the inner slope to provide protection against erosion. In this case the inner slope protection will be build up as follows: a clay layer to provide protection against water pressure, an asphalt layer to prevent erosion and a life layer on top for protection against UV-light and aesthetics. Using this technique, the maximum allowable overtopping discharge is increased from 5 l/s/m to 125 l/s/m.

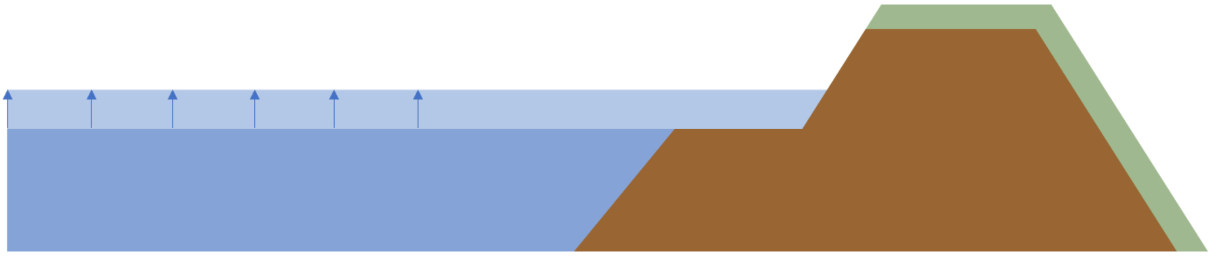


Figure 32 schematic representation of inner slope strength increase

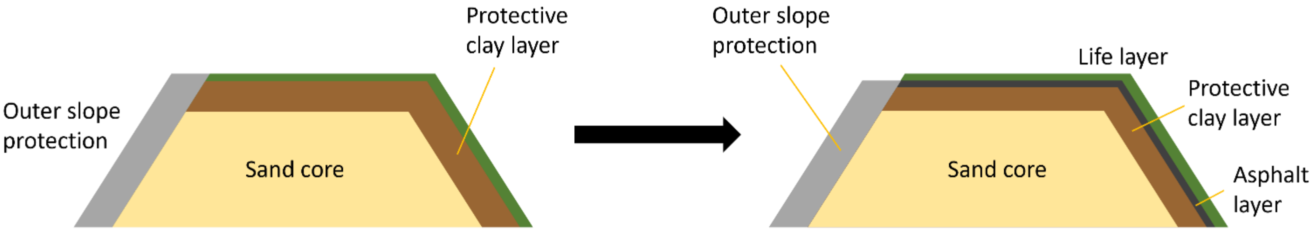


Figure 33 The new inner slope protection

Design variant 1 has an inner slope covered solely in grass, which means that this adaptation step can be applied once. This adaptational measure is not applicable for variants 2 and 3 since these base designs already include a reinforced inner slope. The tipping point for this adaptational measure can be found underneath in Table 15.

	Variant 1	**Variant 2**	**Variant 3**
Tipping point [mSLR]	3.90	N/A	N/A

Table 15 Tipping point for inner slope adaptation for the three base design variants

The use of this adaptational measure has no implications for the use of the other adaptational measures mentioned in this chapter and can therefore be combined.

6.2.5 Outer slope angle adaptation

Decreasing the slope angle (and thereby making the slope less steep) decreases the amount of overtopping. However the adaptation of slope angle has large consequences for the geometry of the dike as is schematized in Figure 34 underneath. When the slope angle is decreased, the berm has to make a shift as well to maintain sufficient width. This means that the entire outer slope has to be rebuild.

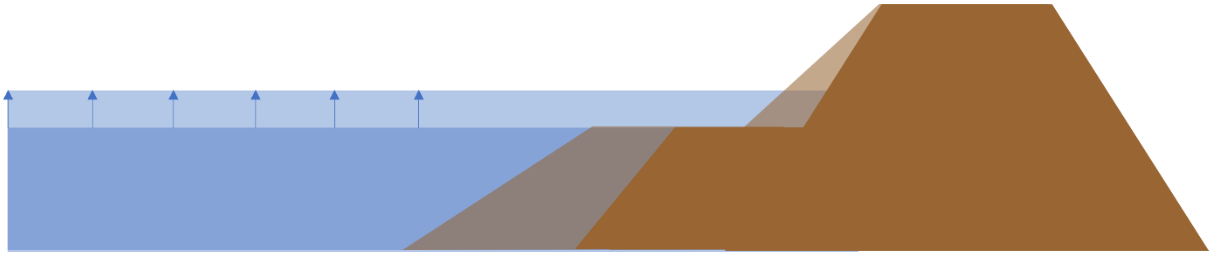


Figure 34 schematic representation of slope angle adaptation

Slope angle adaptation is performed in two varieties:

1. Decreasing the angle from 1:1,5 to 1:3
2. Decreasing the angel from 1:3 to 1:4

The steepness of the outer slope is entirely determined by the applied revetment type:

- Xbloc has a maximum steepness of 1:3; a 1:1.5 Xbloc slope can be changed to a 1:3 slope, however a 1:3 Xbloc slope cannot be changed to a 1:4 slope.

This means that when the slope angle of design variant 2 is altered from 1:3 to 1:4, the outer slope revetment cannot be adapted from asphalt to Xbloc.

The tipping point for this adaptational measure can be found underneath in Table 16.

	Variant 1	**Variant 2**	**Variant 3**
Tipping point [mSLR]	N/A	2.25	3.85

Table 16 Tipping point for inner slope adaptation for the three base design variants

The use of this adaptational measure only has implications for the application of outer slope roughness increase of variant 2. It has no further implications for the use of the other adaptational measures mentioned in this chapter and can therefore be used in a combination.

Implications for the applied Xbloc of variant 3

The slope angle of base design variant 3 is 1:1,5. Since the maximum slope angle for interlocking armour units is 1:3, the slope angle can be increased for this design variant. However, the use of interlocking armour units on slopes milder than 1:1,5 causes necessity for heavier units (Delta Marine Consultants, 2018). For slopes milder than 1:1,5, the weight correction factor is 1.25 and for slopes milder than 1:2 the weight correction factor is 1.5 (Delta Marine Consultants, 2018). The application of this adaptational measure for base design variant 3 has consequences for the applied interlocking armour unit weight, which makes it impossible for the units to be placed back on the slope after application of this adaptational measure.

When outer slope angle adaptation is performed on base design variant 3, the entire outer slope has to be rebuild using 1.5 times heavier Xbloc units.

6.2.6 Foreshore level increase

By increasing the foreshore seawards of the sea defence, the waves will not break on the slopes of the sea defence but break due to depth induced breaking. This means that the waves present at the toe of the sea defence are significantly lower than they would be in the base design concept situations (where the water depth is 14 meters during normal situations but at least 20.52 meters during normative storm situations). The full derivation of the scale of foreshore adaptation can be found in Appendix E: Adaptational measures for the Delta21 sea defence.

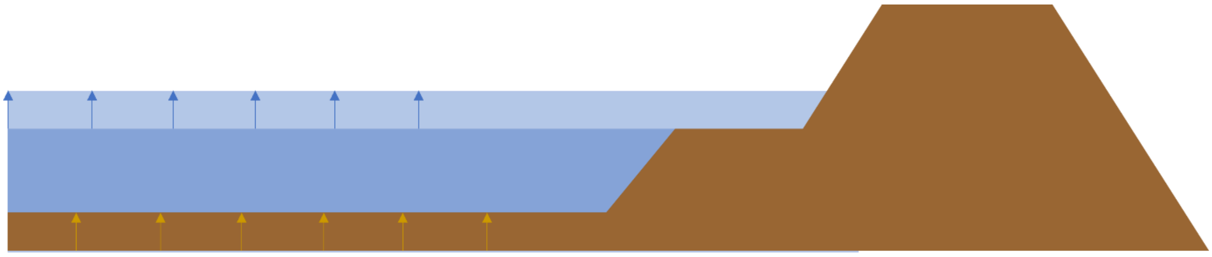


Figure 35 schematic representation of the foreshore level adaptation

Depth induced breaking due to foreshore adaptation causes a change in significant wave height and period. Since the significant wave height and the $T_{m-1,0,t}$ wave period at the toe are fully dependent on the water depth at the toe, an optimum can be found (iteratively) in new water depth after implementing the adaptation. This causes a limitation in the positive effects of a shallow foreshore on overtopping and thereby a limit in the amount of sea level rise that can be countered using this method.

For each of the design variant, two tipping points exist for different amounts of sea level rise and foreshore adaptation. These can be found underneath in Table 17.

Variant 1			**Variant 2**			**Variant 3**		
Foreshore level	Amount of adaptation	Tipping point	Foreshore level	Amount of adaptation	Tipping point	Foreshore level	Amount of adaptation	Tipping point
[NAP+m]	[m]	[mSLR]	[NAP+m]	[m]	[mSLR]	[NAP+m]	[m]	[mSLR]
-1.74	12.26	2	-3.08	10.92	2	-3.08	10.92	2
0.22	14.22	2.5	-0.08	13.92	3	-1.18	12.82	2.5

Table 17 characteristics of foreshore adaptation for the three base design variants

The length of the foreshore is a minimum of 1 deep water wave length $L_{m-1,0}$ (Van der Meer, et al., 2018). However, due to the large difference in incoming and broken waves, a minimum foreshore length of two times the deep water wave length is considered in this adaptation measure. Since the incoming wave period is the same for all three design variants, the length of the foreshore adaptation will be twice the deep water wave length for each design variant.

$$L_{m-1,0} = \frac{gT_{m-1,0}^2}{2\pi} \tag{9}$$

With:

$L_{m-1,0}$ = Deep water wave length [m]

$T_{m-1,0}$ = Deep water wave period [s]

Filling in the parameters corresponding to the Delta21 sea defence gives a foreshore length of:

$$2 * L_{m-1,0} = 2 * \frac{gT_{m-1,0}^2}{2\pi} = \frac{9.81 * 13.85^2}{\pi} = 599\ m$$

The foreshore will have a length of 600 meters, over this length the foreshore will have a slope of 1:100, after which the new water bed will go to the original NAP – 14 m bed level at a 1:12.5 slope.

Due to the changing wave characteristics at the toe of the sea defence (as a consequence of depth induced breaking), this adaptation method will have consequences for the effectiveness of the other adaptational measures as mentioned in this chapter. For example a 1.65 meter increase in crest height for design variant 1 will not necessarily be enough to cope with the consequences of 1 meter of sea level rise after increasing the foreshore level. However, the increase in foreshore level does not pose structural consequences for the use of the other adaptation methods and can therefore be used in combinations.

6.3 Overview of applied design adaptation options and combinations

Not all adaptation options described in Section 6.2 can be applied to every base design variant. Table 18 underneath shows the possible adaptation options and combinations for each of the base design variants. These combinations will be used in Chapter 7 to create the adaptation pathways.

		Variant 1	Variant 2	Variant 3
1	**Crest level increase**	All	All	All
2	**Berm adaptation**	All	All	All
3	**Outer slope roughness increase**		All except slope angle decrease	
4	**Inner slope strength increase**	All		
5	**Slope angle decrease**		All except outer slope roughness	All
6	**Foreshore adaptation**	All	All	All

Table 18 Overview of the applied adaptation measures per base design variant indicated in blue. The text in the table indicates with which other adaptation options the adaptation options can/cannot be combined with.

7. Creating adaptation pathways for the Delta21 sea defence

As described in Section 1.2, the adaptive pathway approach is used to create an overview of the different ways a base design can be altered to adapt to the consequences of climate change. In this chapter the created adaptive pathway schemes, using the adaptation options described in Chapter 6, are elaborated upon per base design concept variant. This chapter describes Step 7 of the design methodology as presented underneath in Figure 36.

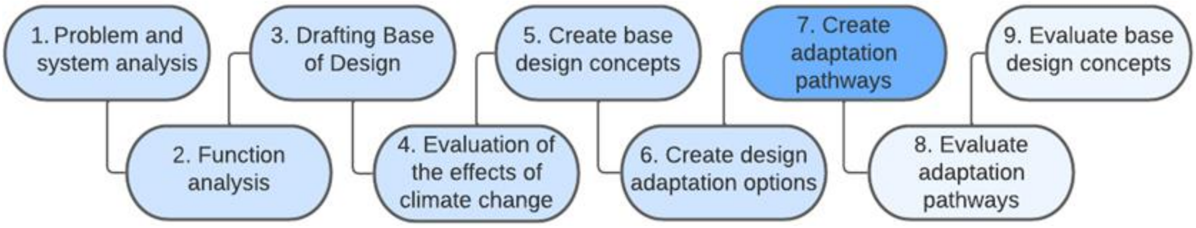


Figure 36 Position of this chapter in the thesis methodology

The creation of an adaptation pathways scheme is a way to gain insight in the different possibilities for an existing structure or situation to be altered in order to adapt to uncertain circumstances in the future.

In Chapter 5, three different variants for the conceptual design of the Delta21 sea defence have been created. Because the inner slope protection, outer slope revetment and overall geometry differ for the three variants, not every adaptation option is viable or effective for all variants. In this section the adaptive pathway schemes, including adaptation option combinations and their effectiveness are described per sea defence variant.

Section 7.1 describes the methodology applied to determine the amount of sea level rise which is mitigated per adaptive pathway. Section 7.2 elaborates and describes the full process of creating the pathway scheme of base design variant 1. In Sections 7.3 and 7.4 the pathway schemes for base design variants 2 and 3 are presented and described. An elaboration on the pathway schemes can be found in Appendix F: Adaptational pathways for the Delta21 sea defence.

7.1 Methodology of determination of sea level rise mitigating effect of pathways

Adaptive pathways are created as combinations of multiple adaptation options in a sequence and the effect of a pathway is expressed in the total amount of mitigated sea level rise after implementing all adaptation steps of the pathway. This section describes the workflow which is used to determine the total amount of mitigated sea level rise per pathway.

The mitigation of the effects of sea level rise is performed via the adaptational measures as described and elaborated in Chapter 6 and Appendix E. Each of the adaptation options mitigate a certain amount of sea level rise for each of the base design concepts. For example, a 1.65 meters crest level increase for design variant 1 mitigates the effects of 1 meter of sea level rise. Therefore the tipping point of the design after implementing this adaptation option is 2 meters of sea level rise.

The calculation of the mitigated amount of sea level rise is performed using overtopping Formula 2 as presented on page 35 in reverse. The calculation is performed per base design variant, using the characteristics of the base design variant as starting point. These design variants are designed for 1 meter of sea level rise, which is therefore the base tipping point.

Adaptation with the use of the adaptation options changes some of the characteristics of the sea defence, per adaptation option this is presented in Table 19 underneath. To determine the tipping point of the adaptation pathway, the characteristics of the sea defence are changed in the overtopping formula.

	Changed variable in overtopping formula							
Adaptation option	$tan\alpha$	$\xi_{m-1,0}$	R_c	H_s	γ_b	γ_f	γ_β	q
1. Crest level adaptation			Increase					
2. Berm adaptation					Decrease	Increase		
3. Slope roughness						Decrease		
4. Slope angle*	Increase	Decrease			Increase	Decrease		
5. Inner slope strength								Increase
6. Foreshore adaptation		Increase		Decrease				

Table 19 Variables of the overtopping formula changed by the adaptation options **The roughness coefficient (γ_f) for slope angle adaptation does not decrease when the outer slope is covered in hydraulic asphalt.*

The mitigated amount of sea level rise is calculated via the following steps as presented in Figure 37.

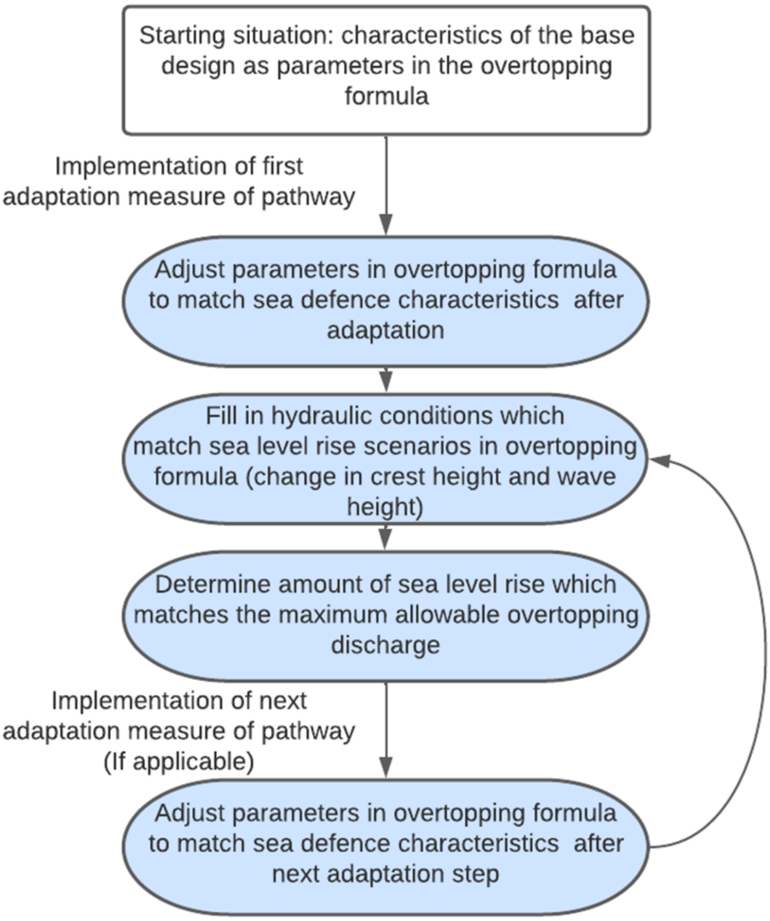


Figure 37 Flowchart presenting the steps taken to calculate the mitigated amount of sea level rise and tipping point per adaptive pathway

By applying the methodology presented in Figure 37 the tipping point for each of the pathways and combination of adaptation options is determined per base design variant. These tipping points are presented per combination of adaptation options in Sections F.2 to F.4 of Appendix F. The tipping points per adaptative pathway are presented in Tables 21, 23 and 25 underneath for design variants 1, 2 and 3 respectively.

7.2 Creation of adaptation pathway scheme for sea defence variant 1

The creation of an adaptation pathway scheme starts with the ‘base situation’: the existing situation which has to be adapted to changing circumstances. For base design variant 1, this variant forms the base of the adaptation pathway scheme.

The first sea defence design variant has an inner slope with a grass over clay top layer and the outer slopes are covered by a single layer of interlocking armour units on a 1:3 slope. The crest height of the base design is NAP + 16 m and the berm width is 24 meters, designed with asphalt concrete.

The characteristics of the base situation have large consequences for the adaptation options which can be applied to alter the sea defence.

Since the roughness of the base design variant is already the maximum roughness the sea defence can achieve (because of the application of Xbloc in the base design), this variable cannot be adapted in order to minimise overtopping discharges in the future. The use of interlocking armour units also rules out the adaptation option of altering the slope angle as the interlocking elements work more efficient on steeper slopes.

Because of the fact that this variant has an inner slope protected by grass on clay, the sea defence can be adapted by protecting the inner slope from erosion by the application of asphalt as reinforcement.

The adaptation options which can be applied for base design variant 1, and the characteristics of the sea defence after application of these options, are shown below in Table 20.

Adaptation type	**Adaptation step**	**Crest level**	**Berm width**	**Berm level**	**Outer slope angle**	**Inner slope type**	**Outer slope type**	**Foreshore level**
[-]	**[-]**	**[NAP+m]**	**[m]**	**[NAP+m]**	**[1:#]**	**[-]**	**[-]**	**[NAP+m]**
Crest level increase	Crest + 1,65 m	16 → 17,65	24	6,52	3	Clay	Xbloc	-14
	Crest + 3,30 m	16 → 19,30	24	6,52	3	Clay	Xbloc	-14
	Crest + 4,95 m	20,95	24	6,52	3	Clay	Xbloc	-14
	Crest + 6,60 m	22,60	24	6,52	3	Clay	Xbloc	-14
Berm adaptation	Berm 50 m (26 m increase)	16	24 → 50	6,52 → 7,52	3	Clay	Xbloc	-14
	Berm 75 m (51 m increase)	16	75	8,52	3	Clay	Xbloc	-14
Inner slope adaptation	Inner slope	16	24	6,52	3	Asphalt	Xbloc	-14
Foreshore adaptation	Foreshore to NAP - 1,74 m	16	24	6,52	3	Clay	Xbloc	-1,74
	Foreshore to NAP + 0,22 m	16	24	6,52	3	Clay	Xbloc	0,22

Table 20 Design adaptation options and characteristics of the sea defence after application of these options

The adaptation options as presented in Table 20 above can all be applied as stand-alone adaptations or in a sequence package with each other.

An example of a sequence of adaptation options and the consequences this has for the sea defence characteristics is shown below in the “Intermezzo 1” window.

Intermezzo 1: an example of an adaptation sequence

Different measures to counter the effect of sea level rise have been designed as is shown in Table 20 above. In the case that the amount of sea level rise is larger than one singular adaptation step mitigates, a combination of multiple of these steps can be applied. In this thesis a combination of steps is called an adaptation pathway. This intermezzo uses the following sequence of adaptation steps as an example:

1. Foreshore level increase through nourishment to NAP - 1,74 m
2. Crest level increase by 4,95 m to NAP + 20,95 m
3. Berm width increase by 26 m to 50 m

Before adaptation, the base situation geometry of design variant 1 can be schematized as follows:

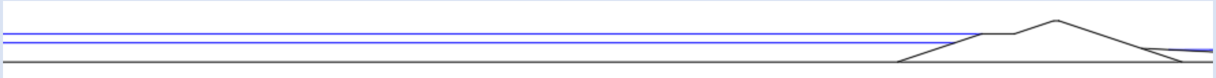


Figure I1.1: Geometry of base design variant 1

In this schematization the blue line indicates the still water level during design conditions.

A foreshore level increase with 12,26 meters to a level of NAP – 1,74 m is enough to counter the effects of a total of 2 meters of sea level rise (which is 1 meter more than the base design situation). In this case the dike geometry will be as shown underneath in Figure I1.2.

Figure I1.2: Geometry of base design variant 1 after application of a foreshore level increase to NAP -1,74 m

In the case that the sea level rise is more than 2 meters, the next step to be performed in this pathway is an increase in crest level with 4,95 m to NAP + 20,95 m. This will adapt the sea defence further, to a maximum amount of 4,2 meters of sea level rise. After implementation of this step, the dike geometry will be as shown underneath in Figure I1.3.

Figure I1.3 Geometry of base design variant 1 after application of a foreshore increase to NAP - 1,74 m and a crest level increase of 4,95 m

For the case that the sea level rises more than 4,2 meters, a berm width increase of 26 meters to a total width of 50 meters is applied. This will adapt the sea defence to 5 meters of sea level rise, which is the maximum amount of sea level rise taken into account in this thesis. The dike geometry will be as shown underneath in Figure I1.4.

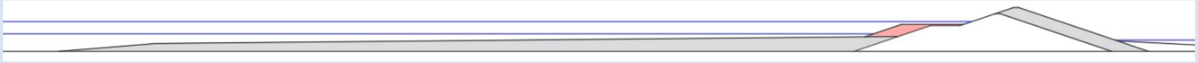


Figure I1.4 Geometry of base design variant 1 after application of a foreshore increase to NAP - 1,74 m, a crest level increase of 4,95 m and a berm width increase to 50 m

The adaptational pathway which is formed by this adaptation sequence is highlighted in the adaptive pathway schem below in Figure I1.5.

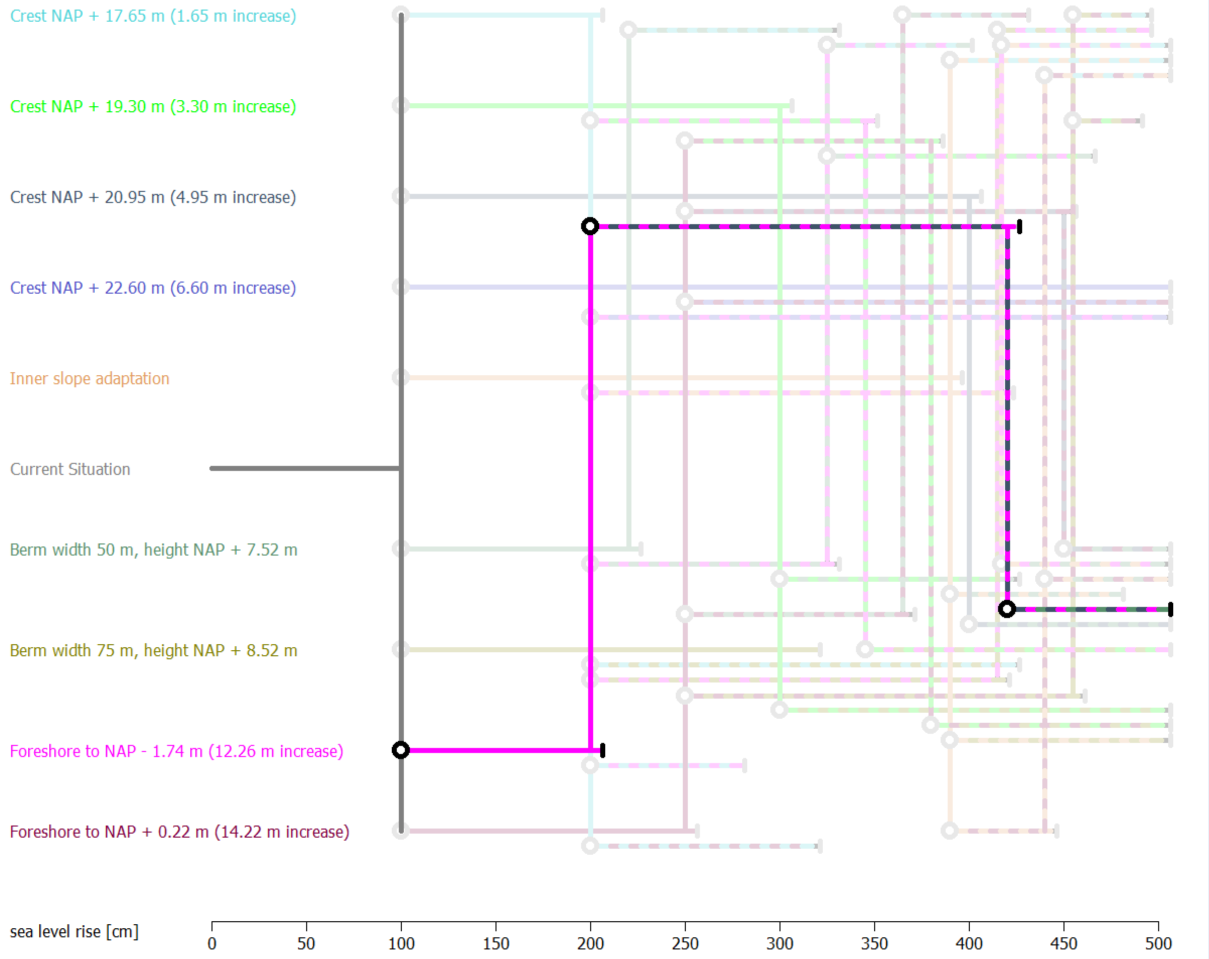


Figure I1.5 The pathway adaptation scheme for the adaptation sequence as described in this intermezzo

All adaptation pathways for base design variant 1 are described in Table 21 below. In this table, pathway 38 was the example pathway in Intermezzo 1 above.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
0	1	0	-	-	-
1	2	1	Crest + 1,65 m		
2	2	1	Foreshore to - 1,74 m		
3	2,2	1	Berm 50 m		
4	2,5	1	Foreshore to + 0,22 m		
5	2,75	2	Foreshore to - 1,74 m	Crest + 1,65 m	
6	3	1	Crest + 3,30 m		
7	3,15	2	Foreshore to + 0,22 m	Crest + 1,65 m	
8	3,15	1	Berm 75 m		
9	3,25	2	Foreshore to - 1,74 m	Berm 50 m	
10	3,25	2	Berm 50 m	Crest + 1,65 m	
11	3,45	2	Foreshore to - 1,74 m	Crest + 3,30 m	
12	3,65	2	Foreshore to + 0,22 m	Berm 50 m	
13	3,8	2	Foreshore to + 0,22 m	Crest + 3,30 m	
14	3,9	1	Inner slope		
15	3,95	3	Foreshore to - 1,74 m	Berm 50 m	Crest + 1,65 m
16	4	1	Crest + 4,95 m		
17	4,15	2	Foreshore to - 1,74 m	Berm 75 m	
18	4,15	2	Foreshore to - 1,74 m	Inner slope	
19	4,2	2	Crest + 3,30 m	Berm 50 m	
20	4,2	2	Crest + 1,65 m	Berm 75 m	
21	4,2	2	Foreshore to - 1,74 m	Crest + 4,95 m	
22	4,25	3	Foreshore to + 0,22 m	Berm 50 m	Crest + 1,65 m
23	4,4	2	Inner slope	Foreshore to + 0,22 m	
24	4,5	2	Foreshore to + 0,22 m	Crest + 4,95 m	
25	4,55	2	Foreshore to + 0,22 m	Berm 75 m	
26	4,6	3	Foreshore to - 1,74 m	Berm 50 m	Crest + 3,30 m
27	4,75	2	Inner slope	Berm 50 m	
28	4,85	3	Foreshore to + 0,22 m	Berm 50 m	Crest + 3,30 m
29	4,9	3	Foreshore to - 1,74 m	Berm 75 m	Crest + 1,65 m
30	4,9	3	Foreshore to + 0,22 m	Berm 75 m	Crest + 1,65 m
31	5	1	Crest + 6,60 m		
32	5	2	Crest + 4,95 m	Berm 50 m	
33	5	2	Crest + 3,30 m	Berm 75 m	
34	5	2	Foreshore to - 1,74 m	Berm + 6,60 m	
35	5	2	Foreshore to + 0,22 m	Berm + 6,60 m	
36	5	2	Inner slope	Crest + 1,65 m	
37	5	2	Inner slope	Berm + 75 m	
38	5	3	Foreshore to - 1,74 m	Crest + 4,95 m	Berm 50 m
39	5	3	Foreshore to - 1,74 m	Crest + 3,30 m	Berm 75 m
40	5	3	Inner slope	Foreshore to - 1,74 m	Crest + 1,65 m
41	5	3	Inner slope	Foreshore to - 1,74 m	Berm 50 m
42	5	3	Foreshore to + 0,22 m	Crest + 4,95 m	Berm 50 m
43	5	3	Foreshore to + 0,22 m	Crest + 3,30 m	Berm 75 m
44	5	3	Inner slope	Foreshore to + 0,22 m	Crest + 1,65 m
45	5	3	Inner slope	Foreshore to + 0,22 m	Berm 50 m

Table 21 Adaptation pathways for static sea defence variant 1

All adaptation pathways as indicated in Table 21 above are presented in an adaptation pathway scheme which is created as described in Intermezzo 1. This scheme is shown underneath in Figure 38 and more elaborate in Appendix F: Adaptational pathways for the Delta21 sea defence.

The pathway numbers which are indicated in Table 21 are stated behind every pathway.

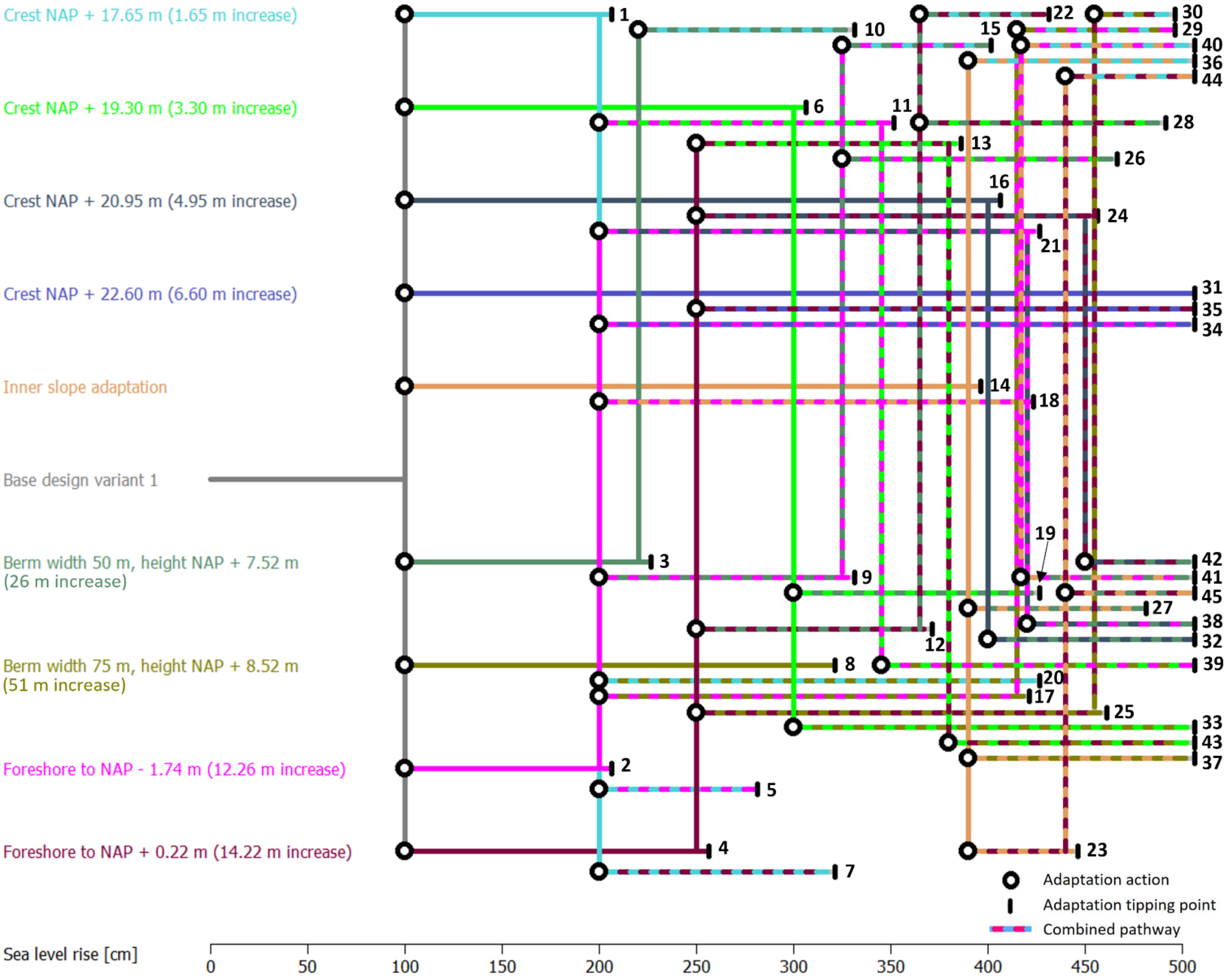


Figure 38 The adaptive pathway scheme showing possible adaptation options and combinations for sea defence variant 1

7.3 The adaptation pathway scheme for sea defence variant 2

The second sea defence design variant has a crest and inner slope protected for erosion by an asphalt layer, topped by a grass top layer. The outer slope is smooth, covered in asphalt concrete and has a roughness of $\gamma_f = 1$. The crest height of the base design is NAP + 16 m and the berm is 22 meters wide.

Because the inner slope of design variant 2 is already reinforced by asphalt, this adaptation option cannot be applied for design variant 2. However since the outer slope is covered in asphalt concrete with a roughness of $\gamma_f = 1$, the roughness can be adapted substituting this asphalt concrete layer on the slopes for Xbloc to lower the overtopping discharge.

The adaptation options which can be applied for base design variant 2, and the characteristics of the sea defence after application of these options, are shown below in Table 22.

Adaptation type	Adaptation step	Crest level	Berm width	Berm level	Outer slope angle	Inner slope type	Outer slope type	Foreshore level
[-]	[-]	[NAP+m]	[m]	[NAP+m]	[1:#]	[-]	[-]	[NAP+m]
Crest level increase	Crest + 1,75 m	17,75	22	6,52	3	Asphalt	Asphalt	-14
	Crest + 3,50 m	19,50	22	6,52	3	Asphalt	Asphalt	-14
	Crest + 5,25 m	21,25	22	6,52	3	Asphalt	Asphalt	-14
	Crest + 7,00 m	23,00	22	6,52	3	Asphalt	Asphalt	-14
Berm width increase	Berm 50 m (28 m increase)	16	50	8,52	3	Asphalt	Asphalt	-14
	Berm 75 m (53 m increase)	16	75	9,52	3	Asphalt	Asphalt	-14
Roughness adaptation	-	16	22	6,52	3	Asphalt	Xbloc	-14
Outer slope angle	-	16	22	6,52	4	Asphalt	Asphalt	-14
Foreshore adaptation	Foreshore to NAP - 3,08 m	16	22	6,52	3	Asphalt	Asphalt	-3,08
	Foreshore to NAP - 0,08 m	16	22	6,52	3	Asphalt	Asphalt	-0,08

Table 22 Design adaptation options and characteristics of the sea defence after application of these options

The adaptation options as shown in Table 22 above can be applied as stand-alone adaptations or in a sequence package with other adaptation options.

The adaptation options altering the outer slope roughness and outer slope angle rule each other out as interlocking armour units are more effective on steep slopes. Therefore, Xbloc placed on a 1:4 slope is not taken into account in this thesis and this combination is not used. An adaptation pathway can only use one of these two adaptation options.

All adaptation pathways for base design variant 2 are described in Table 23 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4
0	1	0	-	-	-	-
1	2	1	Crest + 1,75 m			
2	2	1	Foreshore to -3,08 m			
3	2,25	1	Slope angle			
4	2,8	2	Foreshore to -3,08 m	Crest + 1,75 m		
5	2,8	2	Slope angle	Foreshore to -3,08 m		
6	3	1	Crest + 3,5 m			
7	3	1	Foreshore to -0,08 m			
8	3,2	1	Berm 50 m			
9	3,4	2	Slope angle	Crest + 1,75 m		
10	3,55	2	Foreshore to -3,08 m	Crest + 3,50 m		
11	3,65	2	Slope angle	Foreshore to -0,08		
12	3,7	2	Foreshore to -0,08 m	Crest + 1,75 m		
13	3,7	3	Slope angle	Foreshore to -3,08 m	Crest + 1,75 m	
14	3,85	1	Slope roughness			
15	3,85	2	Foreshore to -3,08 m	Slope roughness		
16	4	1	Crest + 5,25 m			
17	4	2	Slope angle	Berm 50 m		
18	4,05	2	Foreshore to -3,08 m	Berm 50 m		
19	4,3	2	Foreshore to -0,08 m	Slope roughness		
20	4,35	2	Crest + 1,75 m	Berm 50 m		
21	4,35	2	Foreshore to -3,08 m	Crest + 5,25 m		
22	4,35	2	Foreshore to -0,08 m	Crest + 3,50 m		
23	4,5	1	Berm 75 m			
24	4,5	2	Slope angle	Crest + 3,50 m		
25	4,5	3	Slope angle	Foreshore to -3,08 m	Berm 50 m	
26	4,5	3	Slope angle	Foreshore to -0,08	Crest + 1,75 m	
27	4,65	3	Slope angle	Foreshore to -3,08 m	Crest + 3,50 m	
28	4,85	3	Slope roughness	Foreshore to -3,08 m	Crest + 1,75 m	
29	4,9	2	Foreshore to -0,08 m	Berm 50 m		
30	4,9	2	Slope roughness	Berm 50 m		
31	4,9	3	Foreshore to -3,08 m	Crest + 1,75 m	Berm 50 m	
32	5	1	Crest + 7,00 m			
33	5	2	Crest + 1,75 m	Berm 75 m		
34	5	2	Crest + 3,5 m	Berm 50 m		
35	5	2	Foreshore to -3,08 m	Crest + 7,00 m		
36	5	2	Slope angle	Crest + 5,25 m		
37	5	2	Slope angle	Berm 75 m		
38	5	2	Foreshore to -0,08 m	Crest + 5,25 m		
39	5	2	Foreshore to -0,08 m	Berm 75 m		
40	5	2	Slope roughness	Crest + 1,75 m		
41	5	2	Slope roughness	Berm 75 m		
42	5	2	Foreshore to -3,08 m	Berm 75 m		
43	5	3	Foreshore to -3,08 m	Crest + 3,50 m	Berm 50 m	
44	5	3	Slope angle	Crest + 1,75 m	Berm 50 m	
45	5	3	Slope roughness	Foreshore to -3,08 m	Berm 50 m	
46	5	3	Slope roughness	Foreshore to -3,08 m	Crest + 3,50 m	
47	5	3	Slope angle	Foreshore to -3,08 m	Crest + 5,25 m	
48	5	3	Slope angle	Foreshore to -3,08 m	Berm 75 m	
49	5	3	Foreshore to -0,08 m	Crest + 1,75 m	Berm 50 m	
50	5	3	Slope roughness	Foreshore to -0,08 m	Crest + 1,75 m	
51	5	3	Slope roughness	Foreshore to -0,08 m	Berm 50 m	
52	5	3	Slope angle	Foreshore to -0,08 m	Crest + 3,50 m	
53	5	3	Slope angle	Foreshore to -0,08 m	Berm 50 m	
54	5	4	Slope angle	Foreshore to -3,08 m	Crest + 1,75 m	Berm 50 m

Table 23 Adaptation pathways for static sea defence variant 2

The adaptation pathways as indicated in Table 23 above are presented in an adaptation pathway scheme which is created as described in Intermezzo 1. This scheme is shown underneath in Figure 39 and more elaborate in Appendix F: Adaptational pathways for the Delta21 sea defence.

The pathway numbers which are indicated in Table 23 are stated behind every pathway.

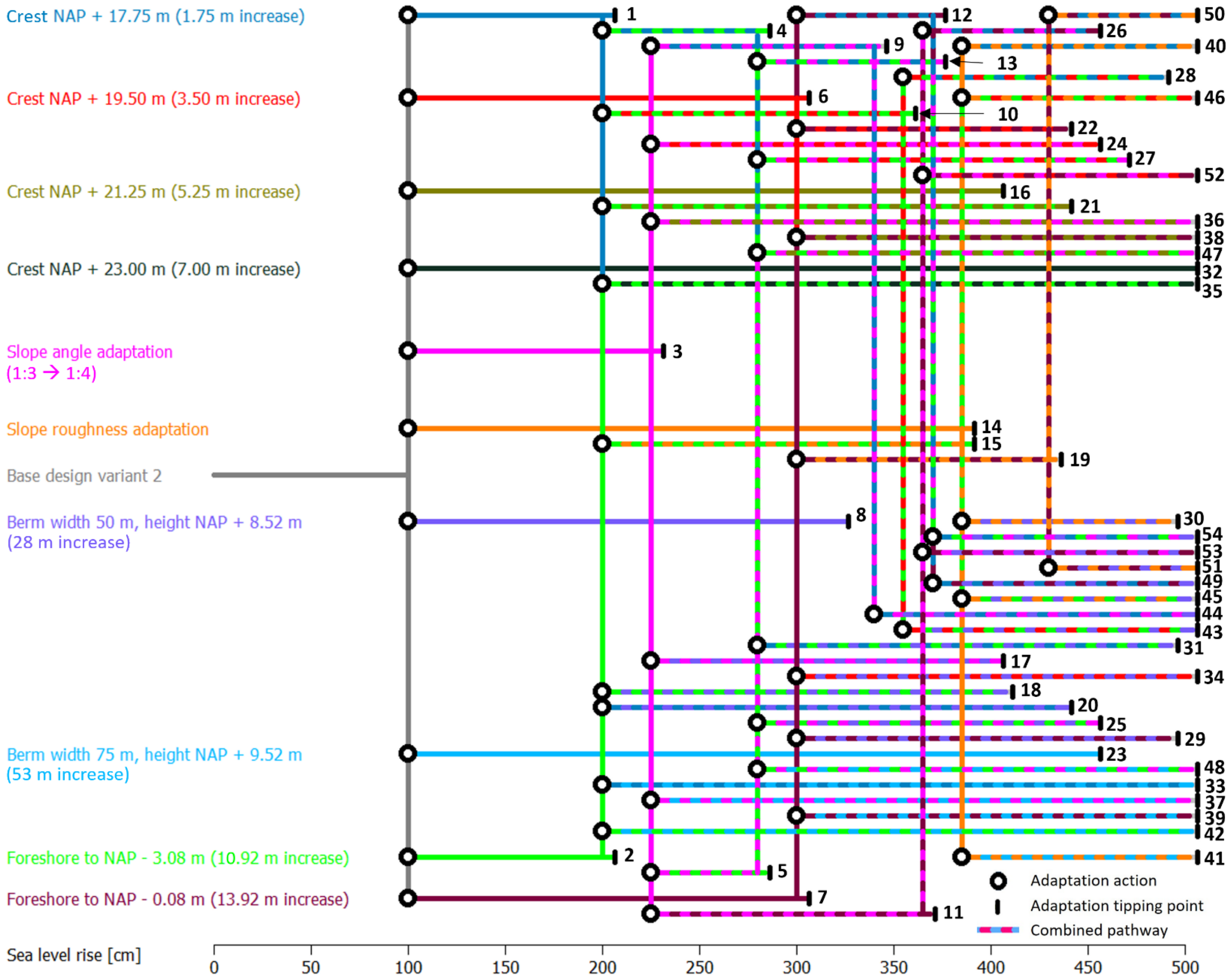


Figure 39 The adaptive pathway scheme showing possible adaptation options and combinations for sea defence variant 2

7.4 The adaptation pathway scheme for sea defence variant 3

The third static sea defence design variant has an inner slope with an asphalt layer topped by a clay and grass top layer. The outer slope is covered by interlocking armour units, the crest height of the base design is NAP+16 m and the berm width is 23 meters wide.

Because the inner slope of base design variant 3 is already reinforced by asphalt and the outer slope is covered in concrete armour units, the adaptation options of inner slope reinforcement and outer slope roughness adaptation cannot be applied for this design variant.

The adaptation options which can be applied for base design variant 3, and the characteristics of the sea defence after application of these options, are shown below in Table 24.

Adaptation type	**Adaptation step**	**Crest level**	**Berm width**	**Berm level**	**Outer slope angle**	**Inner slope type**	**Outer slope type**	**Foreshore level**
[-]	**[-]**	**[NAP+m]**	**[m]**	**[NAP+m]**	**[1:#]**	**[-]**	**[-]**	**[NAP+m]**
Crest level increase	Crest + 1,95 m	17,95	23	6,52	1,5	Asphalt	Xbloc	-14
	Crest + 3,90 m	19,90	23	6,52	1,5	Asphalt	Xbloc	-14
	Crest + 5,85 m	21,85	23	6,52	1,5	Asphalt	Xbloc	-14
	Crest + 7,80 m	23,80	23	6,52	1,5	Asphalt	Xbloc	-14
Berm width increase	Berm 50 m (27 m increase)	16	50	8,52	1,5	Asphalt	Xbloc	-14
	Berm 75 m (52 m increase)	16	75	9,52	1,5	Asphalt	Xbloc	-14
Outer slope angle	-	16	23	6,52	3	Asphalt	Xbloc	-14
Foreshore adaptation	Foreshore to NAP -3,08 m	16	23	6,52	1,5	Asphalt	Xbloc	-3,08
	Foreshore to NAP -1,18 m	16	23	6,52	1,5	Asphalt	Xbloc	-1,18

Table 24 Design adaptation options and characteristics of the sea defence after application of these options

The adaptation options as shown in Table 24 above can all be applied as stand-alone adaptations or in a sequence package with other adaptation options.

All adaptation pathways for base design variant 3 are described in Table 25 below.

Pathway number	**Tipping point [mSLR]**	**Number of adaptation steps**	**Adaptation step 1**	**Adaptation step 2**	**Adaptation step 3**
0	1	0	-	-	-
1	2	1	Crest + 1,95 m		
2	2	1	Foreshore to -3,08 m		
3	2,5	1	Foreshore to -1,18 m		
4	2,75	2	Foreshore to -3,08 m	Crest + 1,95 m	
5	3	1	Crest + 3,90 m		
6	3,15	2	Foreshore to -1,18 m	Crest + 1,95 m	
7	3,2	1	Berm 50 m		
8	3,45	2	Foreshore to -3,08 m	Crest + 3,90 m	
9	3,8	2	Foreshore to -1,18 m	Crest + 3,90 m	
10	3,85	1	Slope angle		
11	3,85	2	Foreshore to -3,08 m	Slope angle	
12	4	1	Crest + 5,85 m		
13	4	2	Foreshore to -3,08 m	Berm 50 m	
14	4,15	2	Foreshore to -3,08 m	Crest + 5,85 m	
15	4,2	2	Foreshore to -1,18 m	Slope angle	
16	4,35	2	Crest + 1,95 m	Berm 50 m	
17	4,4	2	Foreshore to -1,18 m	Crest + 5,85 m	
18	4,45	2	Foreshore to -1,18 m	Berm 50 m	
19	4,55	1	Berm 75 m		
20	4,8	2	Foreshore to -3,08 m	Crest + 7,80 m	
21	4,8	3	Foreshore to -3,08 m	Crest + 1,95 m	Berm 50 m
22	4,9	2	Slope angle	Berm 50 m	
23	5	1	Crest + 7,80 m		
24	5	2	Crest + 3,90 m	Berm 50 m	
25	5	2	Crest + 1,95 m	Berm 75 m	
26	5	2	Foreshore to -3,08 m	Berm 75 m	
27	5	2	Slope angle	Crest + 1,95 m	
28	5	2	Slope angle	Berm 75 m	
29	5	2	Foreshore to -1,18 m	Crest + 7,80 m	
30	5	2	Foreshore to -1,18 m	Berm 75 m	
31	5	3	Foreshore to -3,08 m	Crest + 3,90 m	Berm 50 m
32	5	3	Foreshore to -1,18 m	Crest + 1,95 m	Berm 50 m
33	5	3	Slope angle	Foreshore to -3,08 m	Crest + 1,95 m
34	5	3	Slope angle	Foreshore to -3,08 m	Berm 50 m
35	5	3	Slope angle	Foreshore to -1,18 m	Crest + 1,95 m
36	5	3	Slope angle	Foreshore to -1,18 m	Berm 50 m

Table 25 Adaptation pathways for static sea defence variant 3

The adaptation pathways as indicated in Table 25 above are presented in an adaptation pathway scheme which is created as described in Intermezzo 1. This scheme is shown underneath in Figure 40 and more elaborate in Appendix F: Adaptational pathways for the Delta21 sea defence.

The pathway numbers which are indicated in Table 25 are stated behind every pathway.

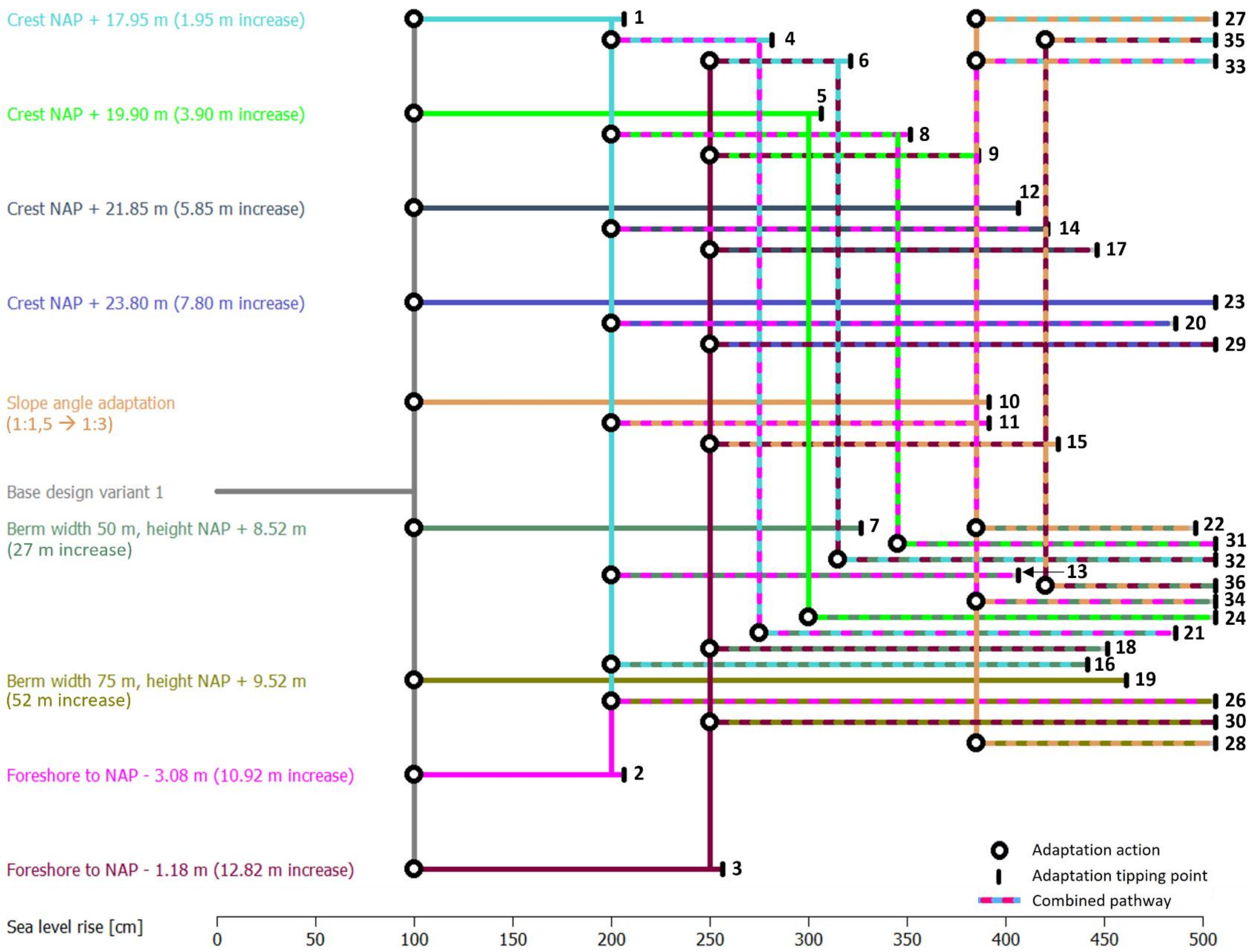


Figure 40 The adaptive pathway scheme showing possible adaptation options and combinations for sea defence variant 3

7.5 Sidenote on the use of foreshore nourishment as an adaptation option

The use of foreshore adaptation has serious downsides: not only does this adaptive measure make use of very large amounts of nourishment (a layer of 10.92 meters of sand have to brought in place, over a distance of at least 600 meters) for the mitigation of relatively small amounts of sea level rise, the use of foreshore adaptation also reduces the effectivity of the other adaptation options which might be implemented in the future.

For example: after implementation of foreshore nourishment, a crest height increase of 1.95 meters for base design variant 3 does not mitigate the effects of 1 meter, but only the effects of 0.75 meters of sea level rise. This can be seen when comparing pathways 1, 3 and 6 in Table 25 above.

On top of that, foreshore adaptation has large consequences for the Natura2000 area which is located in the North Sea right at the outer toe of the new Delta21 sea defence. Because the waves need a lot of distance to break (at least 600 meters, in the case of the Delta21 sea defence), the toe of the sea defence will shift at least 600 meters into the Natura2000 area, covering this area in a large layer of sand. This does not only have consequences for the natural value of the area, building in a Natura2000 area can have large consequences for the required building permits as well.

Because of the negative effect on other adaptation options, the use of foreshore nourishment in a combination with these other adaptation options will not be taken into account in the pathway evaluation process in Chapter 8.

The adaptive pathway schemes which will be taken into account in the pathway evaluation process of Chapter 8 are presented in Appendix G: Adaptive pathway schemes without the use of foreshore adaptation in a combination.

8. Determination of the preferred adaptation pathways

Chapters 5, 6 and 7 handle the base designs for the Delta21 sea defence and different ways in which these designs can be altered to mitigate the effects of sea level rise. As presented in Chapter 7, the various adaptation options can be combined in order to mitigate the effect of future sea level rise up to 5 meters. All considered adaptive pathways are presented in Appendix G.

In this chapter the most viable adaptation options and pathways for each of the three base design variants is determined. Sections 8.1 handles the evaluation methodology, after which the criteria are further explained in Section 8.2. The full evaluation of design variant 1 is presented in Section 8.3, Sections 8.4 and 8.5 present the preferred adaptation pathways for design variants 2 and 3 respectively.

This process is indicated as step 4 of the adaptive pathway approach as mentioned in Section 2.2 of this thesis and handles step 8 of the thesis methodology as presented in Figure 41 underneath.

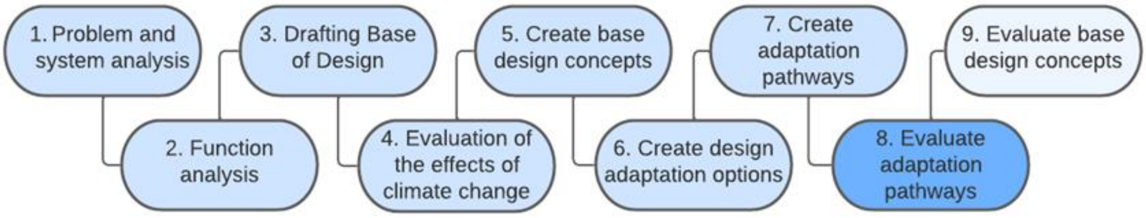


Figure 41 Position of the chapter in the thesis methodology

8.1 Description of the pathway evaluation process

The construction costs of the project are an important evaluation criteria, however in modern infrastructure projects the ecological footprint is very important as well. Therefore not only the direct construction costs are used in the evaluation, but also the environmental cost indicator is considered.

The area in which the Delta21 project will be constructed currently is a Natura2000 area, in the future the area in front of the toe of the sea defence will keep this status. Constructing in the area is a sensitive matter and tied to a lot of legislation. Expanding the sea defence further into Natura2000 area in order to adapt to sea level rise requires new rounds of negotiation. Therefore the amount of space in front of the sea defence required for expansion in the future is a sensitive topic, which makes this the third evaluation criteria.

The uncertainty of climate change translates in an uncertainty in the amount and rate of sea level rise which might occur in the future. Adapting the sea defence can be performed in multiple ways, the flexibility and ability of future adaptation is the last criteria considered in this evaluation.

The evaluation of the adaptive pathways will be performed for four different sea level rise scenarios: 2, 3, 4 and 5 meters of sea level rise.

The procedure for each of these scenarios will be the same for the three base design variants:

- All sea defence adaptation options (or adaptive pathways) which adapt the sea defence to the amount of sea level rise corresponding to the particular scenario are listed.
- Each pathway is evaluated for the four evaluation criteria, the values for these are determined using the methodology as described in Section 8.2 and Appendices I, J and K.
- Using these evaluation criteria values, the preferable adaptive pathway per sea level rise scenario is selected.

To conclude the selection of the preferred adaptative pathway, the evaluations per sea level rise scenario are combined in order to find the overall preferable adaptive pathway for each of the base design variants.

The selection of the preferred adaptive pathway per base design variant is performed with the use of 4 selection criteria: direct construction costs, environmental cost indicator, the change in toe location and the flexibility and ability of further adaptation after implementation of an earlier measure. The way these criteria are determined per pathway is explained in Section 8.2.

In the selection of the preferrable adaptive pathway, all evaluation criteria have the same importance or the same "weight". The preferred adaptive pathway per sea level rise scenario per base design variant is selected via logical reasoning using the above mentioned four evaluation criteria as arguments.

8.2 Description of the pathway evaluation criteria

The way in which the values for the evaluation criteria are determined for the individual adaptive pathways is described in this section.

8.2.1 Environmental cost indicator

Sustainability, circularity and environmental awareness are gaining importance in society and thereby also in large infrastructural projects in the Netherlands. Because of this the outcomes of Life-Cycle-Analysis (LCA) are taken into account for these projects more regularly. For the different types of products and suppliers which come together in a large project, the lifecycle analysis of these products is typically performed using various different methods (Ecochain, 2019). This causes the outcomes of these analysis to differ widely over the market as well. In order to be able to compare the different impacts products and processes have, the more general environmental cost indicator (ECI) or in Dutch "milieu kosten indicator (MKI)" is created.

The environmental cost indicator is a single score unit which bundles various different environmental impacts in a single score, expressed in Euros. The various different impacts are defined as presented in Table 26 underneath.

Impact category	**Unit**	**Weighting factor (€/unit)**
Global warming	kg CO_2-eq	0,05
Ozone depletion	kg CFC-11-eq	30,00
Acidification of soil and water	kg SO_2-eq	4,00
Eutrophication	kg PO_4^3-eq	9,00
Depletion of abiotic resources – elements	kg Sb-eq	0,16
Depletion of abiotic resources – fossil fuels	kg Sb-eq	0,16
Human toxicity	kg 1,4 DB-eq	0,09
Freshwater toxicity	kg 1,4 DB-eq	0,03
Marine water toxicity	kg 1,4 DB-eq	0,0001
Terrestrial toxicity	kg 1,4 DB-eq	0,06
Photochemical oxidant creation (smog)	kg C_2H_4-eq	2,00

Table 26 Environmental impact categories and their weighting factor for the determination of the environmental cost indicator *(Ecochain, 2019)*

The environmental costs indicator is created out of a materials life cycle analysis. For every product the impact of the raw materials and processes that lead to the used material are listed and the impact is reviewed (Ecochain, 2019). By translating the different impacts to an amount of Euros, the different kinds of environmental impacts of materials and processes can be compared. This results in a method to compare the environmental impact of vastly different design variants.

This method is visualized in Figure 42 underneath.

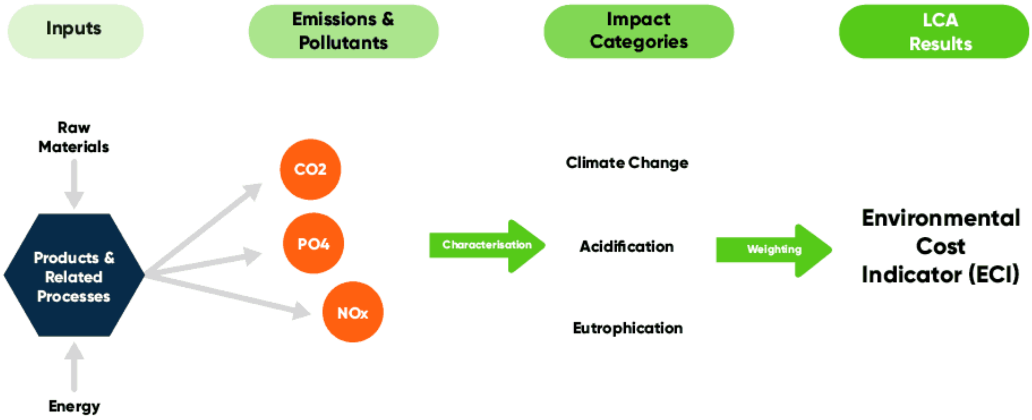


Figure 42 The ECI workflow *(Ecochain, 2019)*

Environmental cost indicator in the Delta21 project

The environmental cost indicator is used to compare different sea defence adaptation strategies. The different measures which can be implemented to adapt the sea defence to future levels of sea level rise all have a different environmental cost indicator, which is used as one of the criteria to pick the preferred adaptation method.

In the determination of the ECI of the different adaptation options, firstly the ECI of the different construction materials is determined. In this thesis the values for the different materials are used as indicated in DuboCalc, which is general software created to determine the ECI value for infrastructural projects.

The ECI values for the different construction materials and processes come from the “Hoog Water Beschermingsprogramma (HWBP)” database as created by Rijkswaterstaat and the national environmental database or “Nationale milieudatabase”. These databases are available in the DuboCalc program and cannot be sourced. The values per unit as used in this thesis are listed in Table 27 underneath.

Material or process	**Unit**	**ECI – value per unit [€]**
Delivering and applying clay	m^3	4,44
Delivering and applying sand for base design	m^3	1,50
Delivering and applying sand for adaptation options	m^3	3,88
Delivering and applying sand for foreshore adaptation	m^3	0,94
Delivering and applying Hydraulic Asphalt	tonnes	46,50
Delivering and applying Open stone Asphalt	tonnes	20,43
Delivering and applying Xbloc	Pcs.	647,15
Removing clay layer	m^3	0,10
Removing Hydraulic Asphalt	tonnes	2,90
Removing Open stone Asphalt	tonnes	1,05
Removing Xbloc	Pcs.	3,23
Replacing clay layer	m^3	0,15
Replacing Xbloc	Pcs.	3,23

Table 27 ECI-values for applied materials and processes

Using these ECI-values, the environmental cost indicators for the design variants and their adaption options can be determined. The estimation of the ECI-values for the separate adaptational pathways is regarded in Appendix I: Determination of environmental cost indicator.

In the evaluation a low ECI-value is preferable, as this indicates low environmental impact.

8.2.2 Direct construction costs

In every infrastructural project the costs are an important factor in the determination of the preferable design variant. In the Netherlands the standard methodology for cost estimation or "Standaardsystematiek Kostenraming" (from now on SSK-methodology) has been developed to standardize the way costs for large construction projects are estimated. This creates the possibility to make a fair comparison between different design variants and, for example, bids on a tender.

In the SSK-methodology the total investment costs are build up using the direct construction costs and various percentage factors to determine the final investment costs. The SSK-methodology determines the investment costs using the following build-up:

1. Foreseen construction costs
    a. Direct construction costs
    b. Indirect construction costs
2. Risk in the construction costs
3. Real estate costs
4. Foreseen direct engineering costs
5. Unforeseen engineering costs
6. Extra costs
    a. Insurances
    b. Fees and charges
    c. Underground infrastructure
    d. Unforeseen extra costs

Of these, only the direct construction costs (1.a) are fully (quantitively) determined. All other expense items are determined as percentages of the direct construction costs.

During this phase of the project, a lot of the costs are still unknown or undefined. During every stage later in the project, more materials and therefore costs will be defined which makes the estimation more accurate.

Determining the direct construction costs for the Delta21 sea defence

Since the total investment costs are a sum of several expense items which are a percentage product of the direct construction costs, only the determination of the direct construction costs is enough to create a comparison between the different design variants and adaptational pathways.

The study does not require a precise estimation of the direct construction costs, it does however require an estimation of the direct construction costs for the parts in which the variants and pathways significantly differ from one another. For example the costs of filter layers, detailed transition constructions between slopes and berms, the use of geotextiles, etc. will apply for each of the variants and adaptation methods and can be defined as a percentage of the construction costs. However the amounts of clay, sand, asphalt concrete and interlocking armour units do differ over the different variants and adaptation methods and are therefore considered in the evaluation.

The most important costs that are determined are presented underneath in Table 28. These costs are key figures determined with the help of the construction management group of Witteveen + Bos and cannot be source referenced.

Material or process	Unit	Direct construction costs per unit [€]
Delivering and applying clay	m^3	25,00
Delivering and applying sand	m^3	7,50
Delivering and applying Hydraulic Asphalt	tonnes	70,00
Delivering and applying Open stone Asphalt	tonnes	75,00
Delivering and applying Xbloc	Pcs.	6700,00
Removing clay layer	m^3	2,50
Removing sand	m^3	2,50
Removing Hydraulic Asphalt	tonnes	10,00
Removing Open stone Asphalt	tonnes	10,00
Removing Xbloc	Pcs.	750,00
Replacing clay layer	m^3	5,00
Replacing Xbloc	Pcs.	750,00

Table 28 Direct construction costs for various materials and processes used in the Delta21 sea defence

Using the processes and material costs as mentioned in the table above, the direct construction costs required for the comparison between the different conceptual design variants and their adaptation pathways can be estimated. The estimation of the direct construction costs for the adaptational pathways is regarded in Appendix J: Determination of direct construction costs.

8.2.3 Change in toe location

The third evaluation criteria used to determine the preferable adaptation method for the Delta21 sea defence is the change in toe location.

With the use of some of the adaptation options (crest height, berm, slope angle and foreshore adaptation) the location of the toes of the sea defence will shift. Changing the crest height will mean a shift of the inner toe into the energy storage lake, while a change in berm width or slope angle results in an outer toe shift into the North Sea. The latter holds for the application of foreshore adaptation as well.

Shifting the toe of the dike into the North Sea also means a shift of the toe into the Natura2000 area located right in front of the sea defence. Since the location of these areas are heavily regulated by European law, getting a permit to build in these areas is difficult and building processes are highly restricted. Therefore an outer toe shift is not preferable and should be kept as small as possible.

When the inner toe is shifted into the energy storage lake, the area of this lake will change which can have consequences for the energy storage capacity. This however is only an issue when the lake is constructed as small as possible, which (in agreement with Huub Lavooij and Leen Berke, initiators of the Delta21 initiative) is not the case. Therefore a relocation of the inner toe of the sea defence does not have negative consequences and is not regarded in the comparison between the pathways.

The shift of the outer toe is determined in meters and regarded in the evaluation for the various sea level rise scenarios and adaptation options. The change in toe location is presented in Appendix K: Evaluation of toe relocation and adaptability.

8.2.4 Flexibility and adaptability

The main driver of the adaptability for the conceptual design of the Delta21 sea defence is the uncertainty in the amount of sea level rise and the rate at which it might occur in the future. Since adapting the sea defence is a costly operation, there is a need to do this as economically and smart as possible. When surpassing the initial 1 meter of sea level rise, it is unknown how much further the sea level will rise until the end of the lifetime. This brings the risk of constructing an expensive adaptation which mitigates a large amount of sea level rise without this being necessary, or on the other hand of applying too small of an adaptation step which requires a short interval between two steps and thereby also increasing the costs and environmental impact.

In short the flexibility and adaptability of the considered pathway are determined by three requirements:

1. The implemented adaptation options should not exclude or impact the use of other adaptation options
2. It is preferred that there are multiple options of adaptation after implementing earlier adaptation options, to ensure flexibility in the future
3. It is preferred that adaptation options can be applied in multiple smaller (less expensive) steps, which reduces the necessity of constructing an expensive adaptation with the risk of being over dimensioned

No matter which adaptation step is chosen to be constructed first, it is important that adaptability is ensured after application of the measure. Therefore an adaptation step which does not have a negative impact on- or exclude the use of other adaptation steps in the future is preferred.

The flexibility of a measure is determined by looking at the amount of possible efficient adaptation pathways which can be created after the implementation of the first measure. All possible efficient pathways have been formed in Chapter 7 and are presented in Appendix G. Naturally, the amount of sequential pathways is lower for adaptation options which have a high tipping point, as less adaptations are necessary to efficiently counter 5 meters of sea level rise after implementing high tipping point measures.

The amount of possible adaptation pathways after implementation of the considered pathway is presented in Appendix K: Evaluation of toe relocation and adaptability.

Flexibility in adaptation is not only measured in the amount of pathways which can be formed after implementation of an adaptation step, but also in the amount of steps a pathway can be constructed in. For example a crest level increase of 6.60 meters can be performed in a maximum of 4 steps of 1.65 meters, which creates the possibility of implementing this measure in small steps. This increases the flexibility after implementing one of these small steps. Berm adaptation can be performed in 2 steps maximum, while roughness, slope angle and inner slope adaptation are all singular steps (which you can perform once).

In the comparison of the pathways the argumentation is build up using the arguments above.

8.3 Determination of the preferred adaptation strategy for design variant 1

The first considered design variant is design variant 1, of which the adaptive pathway scheme is presented in Appendix G. As discussed in Section 8.1 the adaptive pathways are evaluated per meter sea level rise, starting at 2 meters of sea level rise to a maximum of 5 meters of sea level rise. Using this evaluation the preferred adaptation strategy for design variant 1 is determined.

In the evaluation, the pathway numbers as presented in the tables below and the pathways schemes of Chapter 7 are mentioned between brackets behind the individual adaptation options.

8.3.1 Pathway evaluation for 2 meters of sea level rise

In this section all pathways adapting the sea defence to 2 meters of sea level rise are evaluated. In addition to this, also the singular adaptation steps which adapt the sea defence to more than 2 meters of sea level rise are taken into account as these are also options to be applied as a first adaptation step when the base design variant does not meet the water safety requirements anymore. An exception to this is the case in which the first step of an adaptation option (or whole adaptation pathway) is sufficient to adapt the sea defence to 2 meters of sea level rise. An example of this is for example the case in which a berm width increase to 50 meters is sufficient, in this case a berm width increase to 75 meters is not included.

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. Not every pathway in Appendix G is required to mitigate the effects of 4 meters of sea level rise, all considered pathways in this evaluation and their scores are shown underneath in Table 29.

Pathway number	Adaptation step 1	Adaptation step 2	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
1	Crest + 1,65 m		1188	4877	0	16
2	Foreshore to -1,74 m		5434	43508	678	1
3	Berm 50 m		3501	14563	26	13
4	Foreshore to + 0.22 m		6702	53663	706	-
4.2	Foreshore to -1,74 m	Foreshore to + 0.22 m	6702	53663	706	-
14	Inner slope		838	3558	0	4

Table 29 adaptive pathways which adapt sea defence base design variant 1 to 2 meters of sea level rise

Environmental cost indicator

Inner slope adaptation (pathway 14) has the lowest ECI-value. Crest level increase (1) has a lower ECI-value than berm adaptation (3), which is due to the fact that Xblocs do not have to be moved when implementing a crest level increase. Foreshore level increase (2, 4, 4.2) has the highest ECI-value by far, however when performing a large amount of foreshore level increase (4, 4.2) it does not matter if this is performed in one or two adaptation steps.

Direct construction costs

Inner slope adaptation (14) has the lowest direct construction costs. Although being more expensive than inner slope adaptation, crest level increase (1) has a substantially lower building cost than either berm (3) or foreshore adaptation (2, 4, 4.2). The latter being the most expensive due to the (very) large amount of sand being put into place. Berm adaptation mainly is expensive due to the relocation of Xbloc.

Shift in toe location

Both the adaptation of the crest level (1) as well as inner slope adaptation (14) impose no shift in the outer toe of the sea defence. A berm width increase to 50 meters (3) imposes a 26 meter shift in the outer toe location, while an adaptation of the foreshore imposes a 678 to 703 meter outer toe shift.

Flexibility and adaptability

After foreshore adaptation (2, 4, 4.2), inner slope adaptation (14) has the least amount of efficient adaptation options which follow. This is due to the fact that this adaptation method already has a very high tipping point (inner slope adaptation mitigates the effects of 3.9 meters of sea level rise, see Section 7.2 Table 21) which takes away part of the necessity to be highly adaptable. From the other three adaptation methods, crest adaptation (1) provides the largest amount of efficient adaptation methods to follow up the first adaptation step.

Conclusion

Even though inner slope adaptation (14) provides the smallest amount of efficient adaptation pathways after implementation of the primary adaptation option, this is still the preferred method for base design variant 1 for the 2 meters of sea level rise scenario. The low ECI-value and construction costs, as well as the high tipping point and lack of toe relocation cause inner slope adaptation to be the adaptation method of choice for this scenario.

Foreshore adaptation (2, 4, 4.2) is the least efficient adaptation method by far, due to the substantially higher ECI-value and Direct construction costs as well as the (very) large imposed shift in outer toe location. On top of that, foreshore adaptation rules out (efficient) further adaptation of the new sea defence, which makes this the least preferred adaptation option.

8.3.2 Pathway evaluation for 3 meters of sea level rise

The second considered sea level rise scenario is one in which 3 meters of sea level rise occurs, which is 2 meter more than the base design variants are designed for.

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. Not every pathway in Appendix G is required to mitigate the effects of 4 meters of sea level rise, all considered pathways in this evaluation and their scores are shown underneath in Table 30.

Pathway number	Adaptation step 1	Adaptation step 2	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
6	Crest + 3,30 m		2408	9165	0	7
6.2	Crest + 1,65 m	Crest + 3,30 m	2433	9916	0	7
8	Berm 75 m		6930	21167	51	4
8.2	Berm 50 m	Berm 75 m	7225	29879	51	4
10	Berm 50 m	Crest + 1,65 m	4689	19440	26	5
14	Inner slope		838	3558	0	4

Table 30 adaptive pathways which adapt sea defence base design variant 1 to 3 meters of sea level rise

Environmental cost indicator

Inner slope adaptation (14) has the lowest ECI-value and crest level increase (6) has a lower ECI-value than berm adaptation (8), which is due to the fact that Xblocs do not have to be moved when implementing a crest level increase.

In general it can be said that performing adaptations in multiple steps increases the ECI-value of the overall pathway, because of the fact that construction materials (like clay or Xbloc) are relocated multiple times during the construction process. This can be seen when comparing pathways 6 with 6.2 and 8 with 8.2.

Direct construction costs

The direct construction costs of inner slope adaptation (14) are the lowest, which makes that the preferred adaptation method. It can be said that the movement and application of Xblocs (as is the case for berm adaptation) increases the direct construction costs significantly, therefore crest level adaptation (6) is preferred over berm adaptation (8). A combination of berm and crest adaptation (10) is less expensive than a single berm width increase to 75 meters (8). Also when performed in steps it is preferred to combine berm width adaptation with crest level increase (10), over two steps of berm width increase (8.2). This is seen when comparing pathway 8.2 with 10.

Shift in toe location

The only adaptational method which imposes a shift in toe location is berm width increase (8, 8.2 and 10).

Flexibility and adaptability

A crest level increase of 3,30 meters (6) occurs in more pathways used to alter the sea defence to more than 3 meters of sea level rise than inner slope adaption (14) or berm adaptation (8). This gives a lot of freedom for efficient adaptation in the future. The use of inner slope adaptation (14) requires less adaptations in the future due to the high tipping point, this gives less optional efficient adaptive pathways for the future but is however still well adaptable in combination with the other adaptation measures.

Conclusion

For a scenario in which 3 meters of sea level rise occurs and base design variant 1 is the Delta21 sea defence, a change of inner slope protection (14) is the preferred adaptation pathway. This due to the low ECI-value, direct construction costs and lack of outer toe relocation.

8.3.3 Pathway evaluation for 4 meters of sea level rise

The third considered sea level rise scenario is one in which 4 meters of sea level rise occurs, which is 3 meter more than the base design variants are designed for.

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. Not every pathway in Appendix G is required to mitigate the effects of 4 meters of sea level rise, all considered pathways in this evaluation and their scores are shown underneath in Table 31.

Pathway number	Adaptation step 1	Adaptation step 2	Adaptation step 3	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
16	Crest + 4,95 m			3683	13576	0	2
16.2	Crest + 1,65 m	Crest + 4,95 m		3709	14346	0	2
16.3	Crest + 3,30 m	Crest + 4,95 m		3709	14346	0	2
16.4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	3734	15077	0	2
19	Crest + 3,30 m	Berm 50 m		5909	23729	26	2
19.2	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m	5934	24479	26	2
20	Crest + 1,65 m	Berm 75 m		8119	26044	51	1
20.2	Crest + 1,65 m	Berm 50 m	Berm 75 m	8413	34757	51	1
27	Inner slope	Berm 50 m		4275	18121	26	1

Table 31 adaptive pathways which adapt sea defence base design variant 1 to 4 meters of sea level rise

Environmental cost indicator

The ECI-value of an increase in crest level (16) is the lowest of all pathways adapting sea defence variant 1 to 4 meters of sea level rise. It does not matter how many steps are taken (16 to 16.4). After this the combination of inner slope adaptation and an increase in berm width (27) has the lowest ECI-value. The use of berm adaptation in combination with crest level increase (19 and 20) result in higher ECI-values, which go up accordingly to the size of the berm width expansion (comparing pathways 19 and 20). Berm width increase requires the removal and re-appliance of Xbloc units on the outer slopes which increases the ECI-value.

Direct construction costs

The direct construction costs for only crest adaptation (16) are the lowest, after which a combination of inner slope adaptation and berm width increase (27) follows. The use of a combination of berm width adaptation and crest level increase (19 and 20) cause the highest direct construction costs. Berm width increase requires the removal and re-appliance of Xbloc units on the outer slopes which increases the direct construction costs. For crest level increase the amount of steps (16 to 16.4) increase the direct construction costs, although they are always lower than those for the other adaptation options.

Shift in toe location

Only the increase in berm width (19 and 20) shifts the location of the inner toe to the Natura2000 area in in the North Sea. For a berm width increase to 50 meters this is 26 meters and for a berm width increase to 75 meters this is 51 meters.

Flexibility and adaptability

Pathways 16 and 19 lead to slightly more adaptation options than pathways 20 and 27, therefore the first two are preferred. On top of that can pathway 16 (crest level increase) be used in a lot of varieties and step sizes, which makes this the preferrable adaptation pathway regarding adaptability.

Conclusion

When looking at the criteria adapting the sea defence to 4 meters of sea level rise, an increase in crest level with 4,95 meters is the preferrable adaptation method for base design variant 1. It does not matter in how many steps the crest level is increased (pathways 16, 16.2, 16.3 and 16.4).

8.3.4 Pathway evaluation for 5 meters of sea level rise

The last considered sea level rise scenario is one in which 5 meters of sea level rise occurs, which is 4 meter more than the base design variants are designed for and the maximum amount of sea level rise as taken into account in this thesis.

Not every pathway in Appendix G mitigates the effects of 5 meters of sea level rise, all considered pathways in this evaluation are shown underneath in Table 32. In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. As all pathways considered in this evaluation step adapt the sea defence to 5 meters of sea level rise, the amount of possible adaptation pathways after implementation of the considered step is not presented. The scores of the different paths for these criteria are also indicated in Table 32 below.

Pathway number	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]
31	Crest + 6,60 m				5014	18109	0
31.2	Crest + 1,65 m	Crest + 6,60 m			5040	18899	0
31.3	Crest + 3,30 m	Crest + 6,60 m			5040	18899	0
31.4	Crest + 4,95 m	Crest + 6,60 m			5040	18899	0
31.5	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m		5065	19637	0
31.6	Crest + 1,65 m	Crest + 3,30 m	Crest + 6,60 m		5065	19637	0
31.7	Crest + 1,65 m	Crest + 4,95 m	Crest + 6,60 m		5065	19637	0
31.8	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m	5089	20361	0
32	Crest + 4,95 m	Berm 50 m			7184	28139	26
32.2	Crest + 1,65 m	Crest + 4,95 m	Berm 50 m		7210	28910	26
32.3	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m		7210	28910	26
32.4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m	7234	29641	26
33	Crest + 3,30 m	Berm 75 m			9338	30332	51
33.2	Crest + 3,30 m	Berm 50 m	Berm 75 m		9633	39045	51
33.3	Crest + 1,65 m	Crest + 3,30 m	Berm 75 m		9364	31083	51
33.4	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m	Berm 75 m	9658	39795	51
36	Inner slope	Crest + 1,65 m			2860	11998	0

37	Inner slope	Berm 75 m			7704	24725	51
37.2	Inner slope	Berm 50 m	Berm 75 m		7999	33437	51

Table 32 adaptive pathways which adapt sea defence base design variant 1 to 5 meters of sea level rise

As five meters of sea level rise is the maximum amount of sea level rise considered in this thesis, the amount of possible pathways after implementation of the discussed adaptative pathway is not presented in Table 32 above.

Environmental cost indicator

Pathway 36 which makes use of inner slope adaptation and a crest level increase of 1,65 meters has the smallest ECI-value by almost a factor 2. Inner slope adaptation in combination with a large berm width increase (37) has the highest ECI-value.

It can also be concluded that the amount of steps in which the crest level is increased (31 – 31.8) only makes a small difference in comparison to the values of the various adaptation options due to the absence of inner slope reinforcement. Berm width increase requires removal and re-appliance of Xbloc units which imposes a high ECI-value.

Direct construction costs

The same as for the ECI-value, the direct construction costs for pathway 36 are the lowest. Therefore this is the preferred adaptational pathway considering this evaluation criteria.

Shift in toe location

The shift in toe location for base design variant 1 has a maximum of 51 meters, which is the case for all adaptational pathways which include the use of a berm width increase to a total width of 75 meters. All adaptation pathways which do not make use of berm width increase, do not shift the location of the outer toe of the sea defence.

Flexibility and adaptability

Most of the pathways include an increase of crest level, which makes this a first adaptation step which gives the most flexibility as it can be expanded with all available adaptation methods.

Conclusion

The preferred pathway for base design variant 1 under the influence of 5 meters of sea level rise is pathway 36. This pathway, which makes use of an inner slope adaptation and a crest level increase of 1,65 meters, has the lowest ECI-value and direct construction costs and does not move the toe of the sea defence further into the North Sea.

8.3.5 Description of the preferred adaptation strategy for design variant 1

In Sections 8.3.1 to 8.3.4 the preferred adaptation strategy for 2, 3, 4 and 5 meters of sea level rise are determined. The preferred adaptation pathways per sea level rise scenario are presented underneath in Table 33. In this section the preferred adaptation strategy is determined in terms of adaptation options and the sequence in which these options can best be applied in the future.

Sea level rise scenario	Adaptation step 1	Adaptation step 2	Adaptation step 3
2 mSLR	Inner slope adaptation		
3 mSLR	Inner slope adaptation		
4 mSLR	Crest level + 4,95 m		
5 mSLR	Inner slope adaptation	Crest level + 1,65 m	

Table 33 Overview of the preferred adaptation strategies as determined in Sections 8.3.1 to 8.3.4

As inner slope adaptation combined with a crest level increase of 1,65 meters has better evaluation scores than a crest level increase with 4,95 meters (lower direct construction costs and ECI-value), the preferred adaptation method for base design variant 1 is a combination of inner slope adaptation and (later) a crest level increase of 1,65 meters.

Sequence of steps

Inner slope adaptation has a high tipping point at the lowest ECI-value and direct construction costs, this argument also makes this a safe choice for a case in which the sea level does not rise quickly. Inner slope adaptation is the preferred step for 2 and 3 meters of sea level rise. A single step of crest level adaptation is enough to fully adapt the sea defence to 5 meters of sea level rise if necessary. This is indicated as pathway 36 in Figure 43.

Tipping point after adaptation [mSLR]	Preferred adaptation step 1	Preferred adaptation step 2	Preferred adaptation step 3
3,9	Inner slope adaptation		
5	Inner slope adaptation	Crest level + 1,65 m	

Table 34 preferred adaptation pathway per sea level rise scenario for base design variant 1

As inner slope adaptation has lower direct construction costs and a lower ECI-value, this will also be the first adaptation step to be implemented when more than one meter of sea level rise occurs.

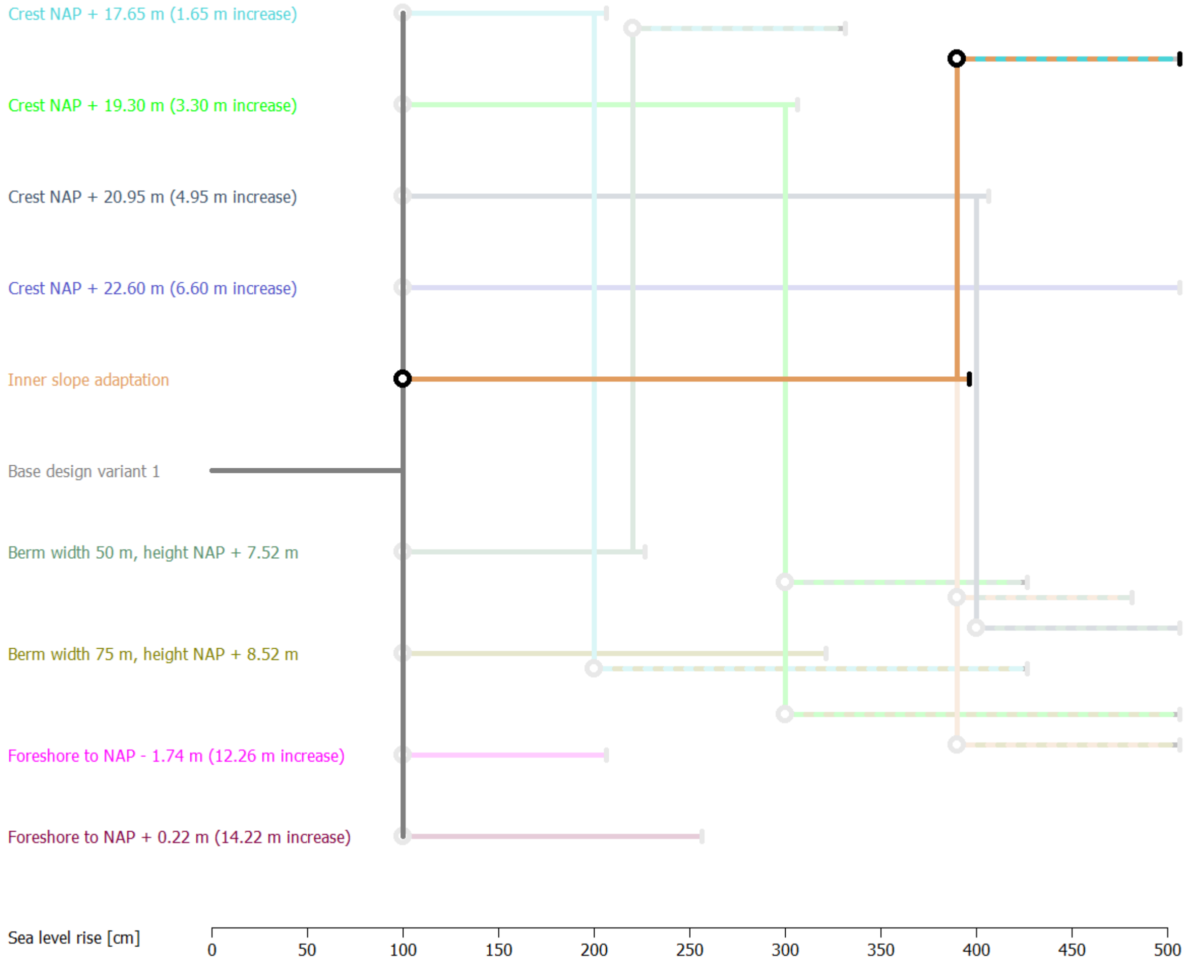


Figure 43 The preferred pathway for design variant 1

8.4 Determination of the preferred adaptation strategy for design variant 2

The full evaluation of the individual adaptive pathways is performed in Appendix L: Pathway evaluation for design variants 2 and 3. In this evaluation the preferred adaptation strategy for 2, 3, 4 and 5 meters of sea level rise are determined. The preferred adaptation pathways per sea level rise scenario are presented underneath in Table 35. In this section the preferred adaptation strategy is determined in terms of adaptation options and the sequence in which these options can best be applied in the future.

Sea level rise scenario	Adaptation step 1	Adaptation step 2	Adaptation step 3
2 mSLR	Crest level + 1,75 m		
3 mSLR	Berm width to 50 m		
4 mSLR	Berm width to 50 m	Crest level + 1,75 m	
5 mSLR	Berm width to 50 m	Crest level + 3,50 m	

Table 35 Overview of the preferred adaptation strategies as determined per sea level rise scenario

A berm width increase to 50 meters and crest level increase with 3.50 meters can be implemented in five different orders:

Sequence number	Adaptation step 1	Adaptation step 2	Adaptation step 3
1	Berm width to 50 m	Crest level + 1,75 m	Crest level + 3,50 m
2	Crest level + 1,75 m	Berm width to 50 m	Crest level + 3,50 m
3	Crest level + 1,75 m	Crest level + 3,50 m	Berm width to 50 m
4	Crest level + 3,50 m	Berm width to 50 m	
5	Berm width to 50 m	Crest level + 3,50 m	

Table 36 The five different orders for pathway 34 of design variant 2

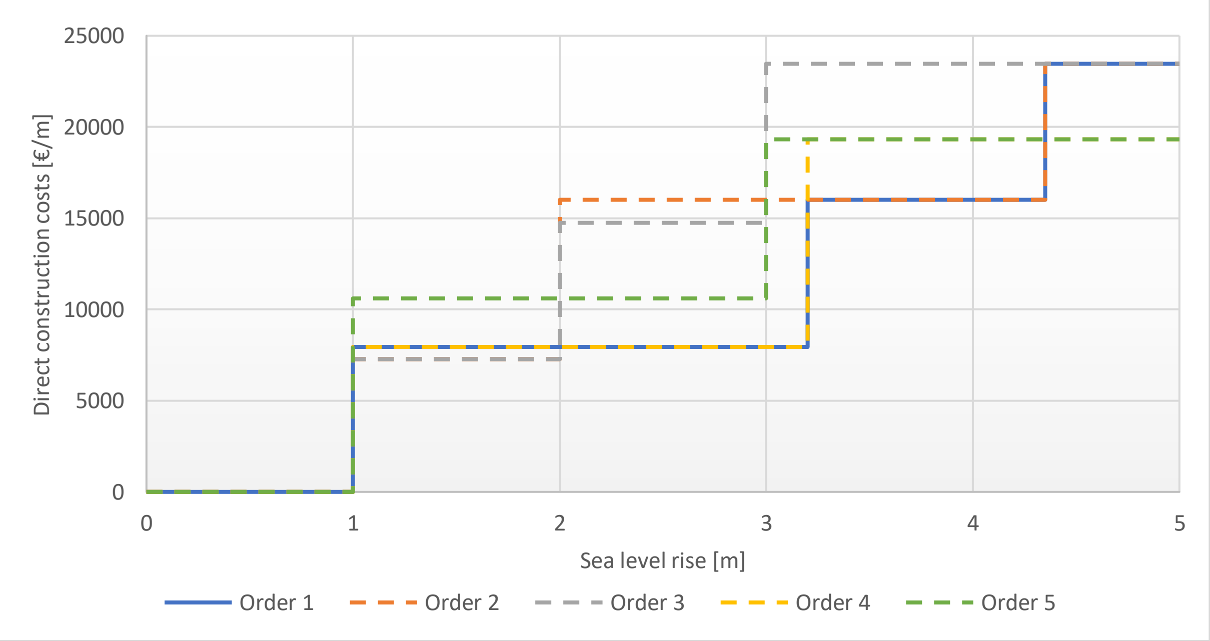


Figure 44 The evolution of the direct construction costs under the influence of sea level rise in the five different adaptation orders as shown in Table 36

Figure 45 The evolution of the environmental cost indicator under the influence of sea level rise in the five different adaptation orders as shown in Table 36

Of the five possible orders of implementing pathway 34 to design variant 2, orders 4 and 5 limit the amount of steps from three to two. This requires two steps with larger impact on the direct construction costs and the environmental costs indicator. Also the flexibility in adaptation is restricted.

When performing the adaptation of design variant 2 in three steps, order 2 has the lowest direct construction costs and environmental cost indicator for scenarios in which the sea level rise stops between 1 and 2 meters. However once more sea level rise occurs, order 1 is the most efficient. Therefore order 1, which starts with a berm width increase of 28 meters and then implements two steps of 1.75 meters of crest level increase, is the preferred order of adaptation for design variant 2.

The preferred pathway is pathway 34 as presented in Figure 46 and the order of adaptation is presented underneath in Table 37.

Tipping point after adaptation [mSLR]	Preferred adaptation step 1	Preferred adaptation step 2	Preferred adaptation step 3
3,2	Berm width + 28 m		
4,35	Berm width + 28 m	Crest level + 1,75 m	
5	Berm width + 28 m	Crest level + 1,75 m	Crest level + 3,50 m

Table 37 preferred adaptation pathway per sea level rise scenario for base design variant 2

This adaptation is also presented in the pathway scheme of design variant 3 underneath in Figure 46.

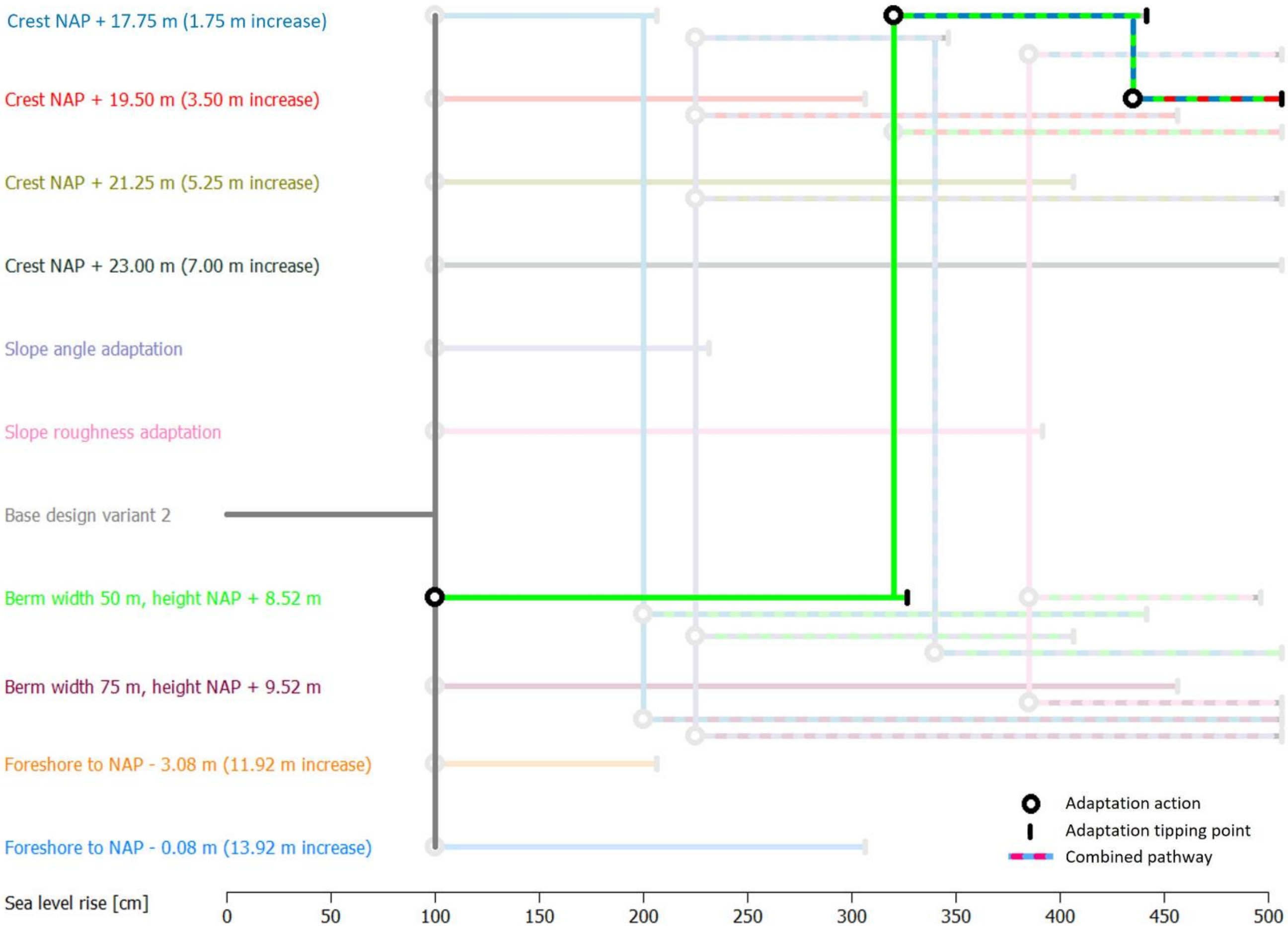


Figure 46 The preferred pathway for design variant 2

8.5 Determination of the preferred adaptation strategy for design variant 3

The full evaluation of the individual adaptive pathways is performed in Appendix L: Pathway evaluation for design variants 2 and 3. In this evaluation the preferred adaptation strategy for 2, 3, 4 and 5 meters of sea level rise are determined. The preferred adaptation pathways per sea level rise scenario are presented underneath in Table 38. In this section the preferred adaptation strategy is determined in terms of the sequence in which these options can best be applied in the future.

Sea level rise scenario	Adaptation step 1	Adaptation step 2	Adaptation step 3
2 mSLR	Crest level + 1,95 m		
3 mSLR	Berm width to 50 m		
4 mSLR	Berm width to 50 m	Crest level + 1,95 m	
5 mSLR	Berm width to 50 m	Crest level + 3,90 m	

Table 38 Overview of the preferred adaptation strategies as determined per sea level rise scenario

A berm width increase to 50 meters and crest level increase with 3.90 meters can be implemented in five different ways:

Sequence number	Adaptation step 1	Adaptation step 2	Adaptation step 3
1	Berm width to 50 m	Crest level + 1,95 m	Crest level + 3,90 m
2	Crest level + 1,95 m	Berm width to 50 m	Crest level + 3,90 m
3	Crest level + 1,95 m	Crest level + 3,90 m	Berm width to 50 m
4	Crest level + 3,90 m	Berm width to 50 m	
5	Berm width to 50 m	Crest level + 3,90 m	

Table 39 The five different orders for pathway 24 of design variant 3

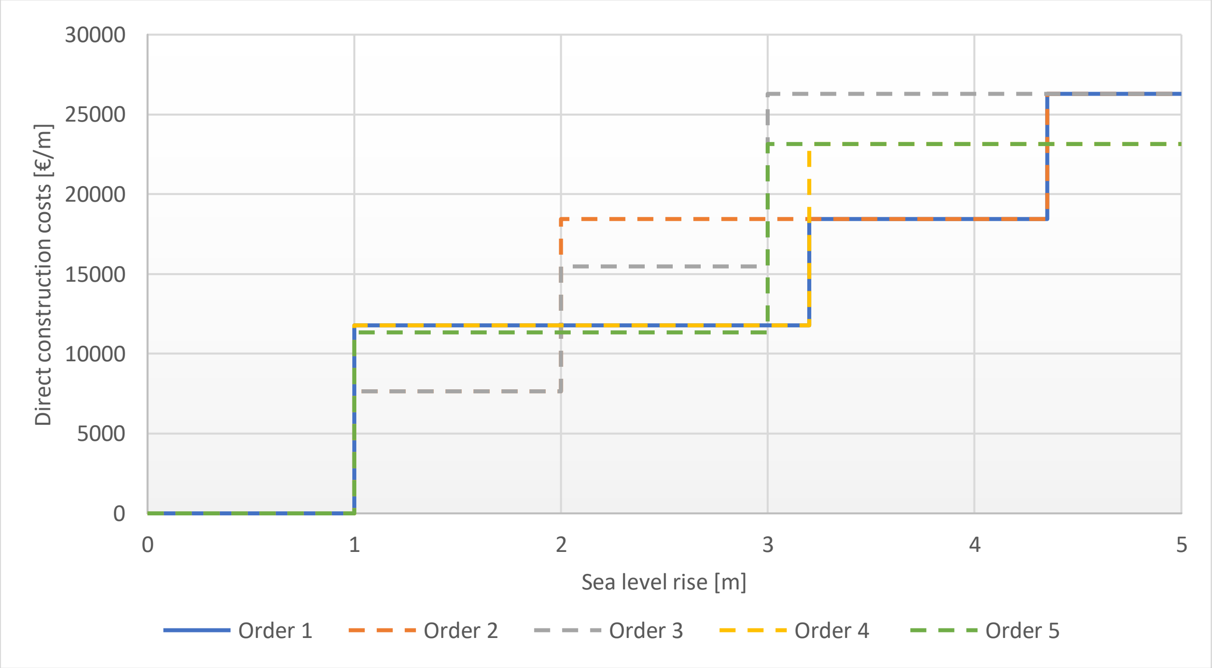


Figure 47 The evolution of the direct construction costs under the influence of sea level rise in the five different adaptation orders as shown in Table 39

Figure 48 The evolution of the environmental cost indicator under the influence of sea level rise in the five different adaptation orders as shown in Table 39

Of the five possible orders of implementing pathway 24 to design variant 3, orders 4 and 5 limit the amount of steps from three to two. This requires two steps with larger impact on the direct construction costs and the environmental costs indicator. Also the flexibility in adaptation is restricted. However when sea level rise stops before 3 meters of sea level rise, order 5 is the most efficient way of adapting sea defence variant 3 by increasing the crest level to NAP + 19.90 meters in a single step of 3.90 meters.

When performing the adaptation of design variant 2 in three steps, order 3 has the lowest direct construction costs and environmental cost indicator for scenarios in which the sea level rise stops between 1 and 2 meters. However once more sea level rise occurs, order 1 is the most efficient while maintaining flexibility in adaptation. Therefore order 1, which starts with a berm width increase of 28 meters and then implements two steps of 1.95 meters of crest level increase, is the preferred order of adaptation for design variant 2.

Assuming that sea level rise does not stop after 3 meters, the preferred pathway is pathway 24 as presented in Figure 49 and the order of adaptation is presented underneath in Table 40.

Tipping point after adaptation [mSLR]	**Preferred adaptation step 1**	**Preferred adaptation step 2**	**Preferred adaptation step 3**
3,2	Berm width + 27 m		
4,35	Berm width + 27 m	Crest level + 1,95 m	
5	Berm width + 27 m	Crest level + 1,95 m	Crest level + 3,90 m

Table 40 preferred adaptation pathway per sea level rise scenario for base design variant 3

This adaptation is also presented in the pathway scheme of design variant 3 underneath in Figure 49.

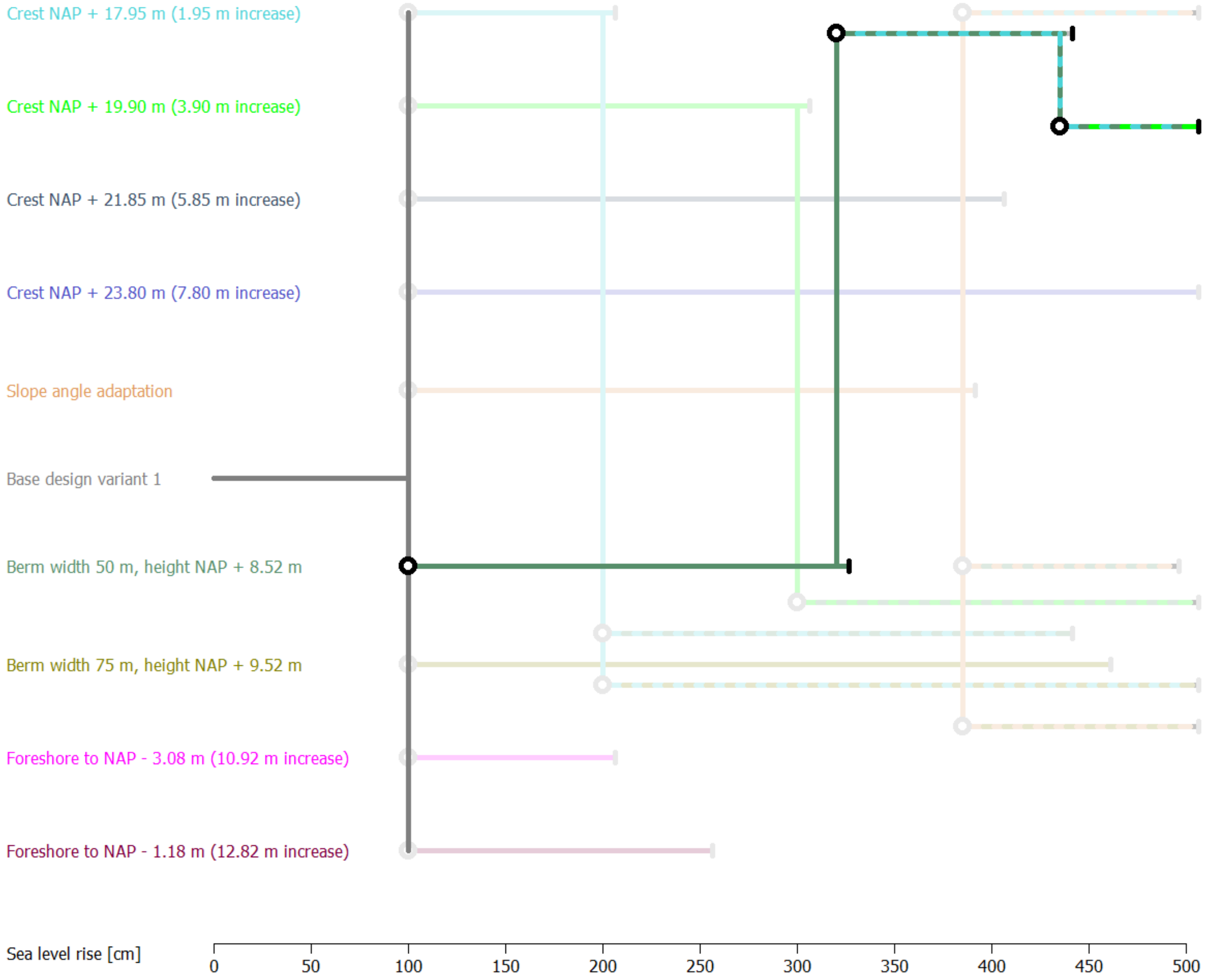


Figure 49 The preferred pathway for design variant 3

8.6 Overview of the sea defence after adaptation to 5 meters of sea level rise

Now the preferred adaptation method is known for every base design variant of the Delta21 sea defence, an overview can be created in which is shown what the fully adapted sea defence would look like for 5 meters of sea level rise. This overview is presented underneath in Table 41.

Design variant:		**Variant 1**		**Variant 2**		**Variant 3**	
		Base	**5 mSLR**	**Base**	**5 mSLR**	**Base**	**5 mSLR**
Crest height	**[m+NAP]**	16	17,65	16	19,50	16	19,90
Crest width	**[m]**	4	4	4	4	4	4
Berm width	**[m]**	24	24	22	50	23	50
Berm height	**[m+NAP]**	6,52	6,52	6,52	8,52	6,52	8,52
Outer slope angle	**[-]**	1:3	1:3	1:3	1:3	1:1,5	1:1,5
Inner slope type	**[-]**	Clay	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt
Outer slope type	**[-]**	Xbloc	Xbloc	Asphalt	Asphalt	Xbloc	Xbloc
Cross-sectional volume	**[m^3/m]**	3312	3624	3271	4627	2617	3847
Outer slope length	**[m]**	119	124	117	156	77	111

Table 41 Characteristics of the Delta21 sea defence design variants as base design and after adaptation to 5 meters of sea level rise

It can be seen that, even though the hydraulic design conditions for the three design variants are the same, the geometry and characteristics of the fully adapted sea defence differ a lot.

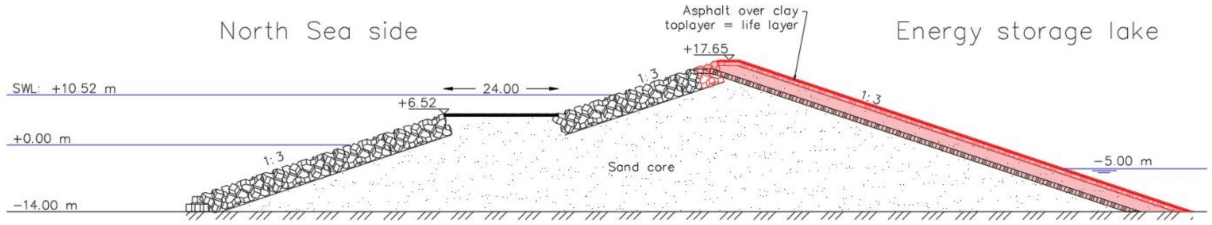


Figure 50 the adapted base design variant 1 with inner slope adaptation and a crest level increase to NAP + 17,65 m (geometry after adaptation indicated in red, base geometry in black)

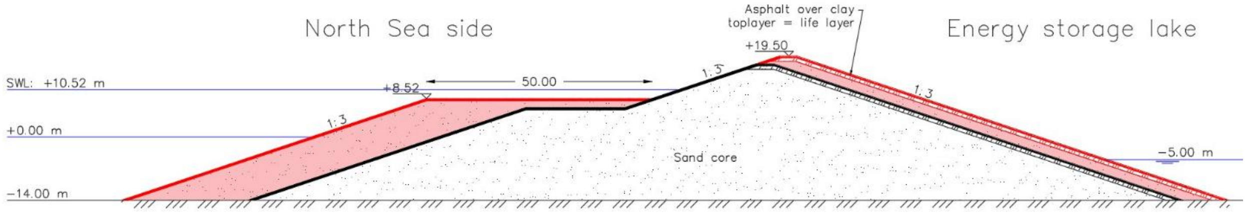


Figure 51 the adapted base design variant 2 with berm width increase with 28 meters to 50 meters and a crest level increase to NAP + 19.50 m (geometry after adaptation indicated in red, base geometry in black)

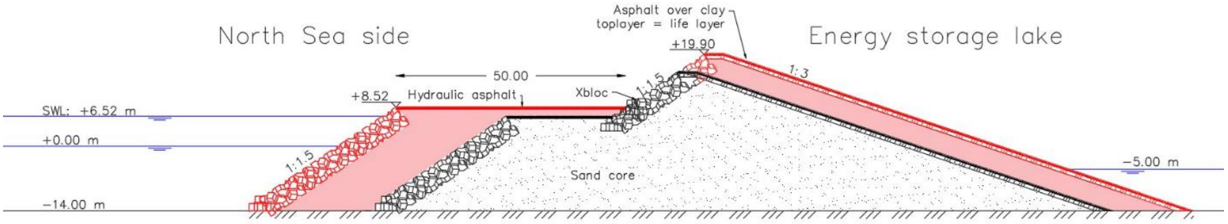


Figure 52 the adapted base design variant 3 with berm width increase with 27 meters to 50 meters and a crest level increase to NAP + 19.90 m (geometry after adaptation indicated in red, base geometry in black)

9. Selection of preferred base design concept

Chapter 8 handles the evaluation of the individual adaptation pathways which were created for each of the three base design variants. These individual base design variants for the Delta21 sea defence were evaluated and this way a preferred design concept is selected. The selection of the preferred base design concept is Step 9 of the thesis methodology as presented in Figure 53.

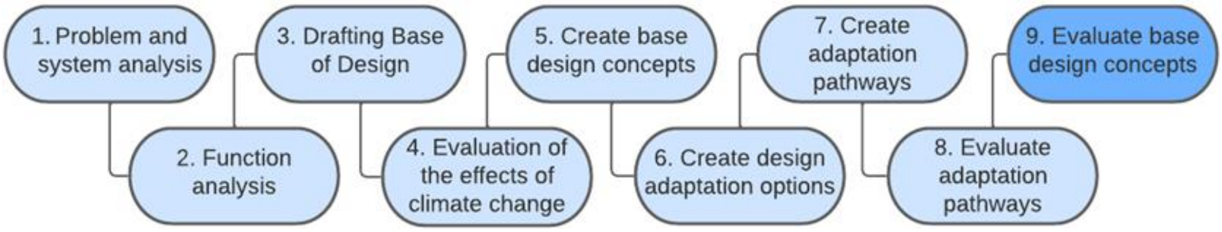


Figure 53 Position of the chapter in the thesis methodology

First the methodology of the selection of the preferred base design is described, after which this methodology is applied to the Delta21 sea defence. The result of the chapter is a recommended design for the Delta21 sea defence.

9.1 Concept evaluation process

The preferred conceptual design for the Delta21 sea defence is selected via the use of three evaluation criteria: the environmental costs indicator, the direct construction costs and the adaptability. These criteria were also used in the determination of the preferred pathway per base design variant.

In order to determine the values for the first two evaluation criteria, first the construction material volumes are to be determined.

The toe of the sea defence is coupled to the location of the shoreline as determined by Esmée van Eeden, therefore the location of this toe is the same for each of the design variants. This means that the location of the toe is not a separate evaluation criteria for the base sea defence design variants, it is however taken into account in the evaluation of the adaptability.

9.1.1 Determination of the construction material volumes

The same materials are taken into account as were used in the evaluation of the individual adaptive pathways for the base design variants as discussed in Chapter 8. These materials are:

- Sand: the core material of the sea defence
- Clay: present on the crest and inner slope of the three design variants
- Open stone asphalt: forms protection against erosion on the inner slope of variants 2 and 3
- Hydraulic asphalt: outer slope protection on the berm of all design variants and on the slope of design variant 2
- Xbloc: a single layer of interlocking armour units on the outer slope of design variants 1 and 3

These materials are determined using the design geometries of design variants 1, 2 and 3 as base.

9.1.2 Calculation of the environmental cost indicator and direct construction costs

Using the construction material volumes, the environmental cost indicator (or ECI) and direct construction costs are determined for each of the base design variants. The methodology for determining the values for these two evaluation criteria is the same as that applied for the individual adaptation pathways per base variant, as is described in Section 8.2.

9.1.3 Evaluation of the adaptability

The evaluation of the adaptability of the three base design variants is based on the pathway schemes which were created in Chapter 7. The preferred pathways for the design variants as determined in Chapter 8 will be compared to each other based on ECI-value and direct construction costs, as well as the consequences of these pathways for the Natura2000 area at the toe of the sea defence. This will allow a proper evaluation of the adaptability of the base situations which will be created by the construction of the three different design variants, and possible measures which should be taken during the early design phase to guarantee sufficient adaptability in the future.

9.1.4 Selection of the preferred base design variant

Using the criteria of environmental cost, direct construction costs and adaptability, the preferred base design variant are be selected via logical reasoning using the above mentioned three evaluation criteria as arguments. This is the same methodology as applied in Chapter 8.

The designs will be evaluated over the entire life time of the defence, so not only are the ECI-value and direct construction costs compared for the base design situations but for the various adaptation steps during the lifetime of the sea defence as well. This way the best image can be created of the impact adaptability has on the base design situations.

When the values of two of the three criteria are close when comparing the three variants, the third criteria is leading. In the case that all evaluation criteria are close, the adaptability is the leading evaluation criteria.

9.2 Determination of the evaluation criteria values for the Delta21 sea defence

Using the methodology as described in Section 9.1, the preferred base design variant for the Delta21 sea defence is determined. First the base design variants are described (very) briefly, after which the evaluation criteria are determined and a preferred base design variant is selected.

9.2.1 Overview of the three base design variants

In total three separate conceptual design variants are created for the Delta21 sea defence, the full description of the three design variants can be found in Chapter 5. The details of each of the variants are shown in Table 42 underneath.

Design variant:		Variant 1	Variant 2	Variant 3
Crest height	**[m+NAP]**	16	16	16
Crest width	**[m]**	4	4	4
Berm width	**[m]**	24	22	23
Berm height	**[m+NAP]**	6,52	6,52	6,52
Slope angle	**[-]**	1:3	1:3	1:1,5
Inner slope type	**[-]**	Clay	Asphalt	Asphalt
Outer slope type	**[-]**	Xbloc	Asphalt	Xbloc
Cross-sectional volume	**[m^3/m]**	3312	3271	2617
Outer slope length	**[m]**	119	117	77

Table 42 Overview of the conceptual design variants

9.2.2 Determination of the Construction material volumes

The geometry as described in Table 42 above is used to create a list of construction materials for each of the base design variants as presented in Table 43 below.

	Design variant:	Variant 1	Variant 2	Variant 3
Sand	**[m^3/m]**	2762	3099	2239
Clay	**[m^3/m]**	95	95	95
Open stone asphalt	**[m^3/m]**	0	19	19
Hydraulic asphalt	**[m^3/m]**	12	58.4	11.5
Xbloc	**[Pcs./m]**	5.2	0	3

Table 43 material volumes per design variant per meter of sea defence

9.2.3 Evaluation of the environmental cost indicator

The environmental cost indicator is determined by creating an overview of the ECI-values for the different construction materials as is described in Section 8.2.1. Coupling this to the construction material volumes as listed in Table 42 above, the environmental cost indicators for the three base design variants are calculated as listed in Table 44 below.

	Design variant:	Variant 1	Variant 2	Variant 3
Sand	**[€/m]**	4154	4662	3367
Clay	**[€/m]**	421	421	421
Open stone asphalt	**[€/m]**	0	814	814
Hydraulic asphalt	**[€/m]**	1339	6521	1283
Xbloc	**[€/m]**	3370	0	1922
TOTAL	**[€/m]**	**9285**	**12418**	**7807**

Table 44 environmental cost indicator per design variant per meter of sea defence

Based on the environmental cost indicator, design variants 2 and 3 do not differ significantly. The ECI-value for base design variant 1 is 37% higher than that of design variant 2 and 39% higher than that of design variant 3, which can be called significant.

The very high environmental cost indicator for design variant 1 is due to the large amount of concrete Xbloc units which is applied in this base design variant.

An asphalt protection on a 1:3 slope (as applied to design variant 2) has a similar environmental cost indicator as an Xbloc protection on a 1:1.5 slope. The steep slope on which Xbloc can be applied makes up for the fact that asphalt is a less expensive option when the slope lengths are equal.

9.2.4 Evaluation of the direct construction costs

The direct construction costs are determined by creating an overview of the values for the different construction materials as is described in Section 8.2.2. Coupling this to the construction material volumes as listed in Table 42 above, the direct construction costs for the three base design variants are calculated as listed in Table 45 below.

	Design variant:	Variant 1	Variant 2	Variant 3
Sand	**[€/m]**	20712	23244	16789
Clay	**[€/m]**	2373	2373	2373
Open stone asphalt	**[€/m]**	0	2988	2988
Hydraulic asphalt	**[€/m]**	2016	9817	1932
Xbloc	**[€/m]**	34895	0	19893
TOTAL	**[€/m]**	**59996**	**38422**	**43975**

Table 45 direct construction costs per design variant per meter of sea defence

Design variant 1 has the highest construction costs, mainly due to the large amount of Xblocs which has to be placed on the 1:3 slope. Variant 3 does also make use of Xbloc units, however in this design variant these are placed on a 1:1.5 slope which reduces the amount of Xblocs to be used. The direct construction costs for design variant 3 are 73% of those of design variant 1.

Design variant 2 does not make use of Xbloc in the base design, in this variant the outer slope is protected in a less expensive hydraulic asphalt layer. The direct construction costs for design variant 2 are 64% of those of design variant 1 and 87% of those of design variant 3.

9.2.5 Evaluation of the adaptability

The three base design variants can all be adapted to (up to) 5 meters of sea level rise by making use of various adaptation methods as described in Chapters 6 and 7. In Chapter 8 the preferred adaptation pathways are selected for each of the three design variants. By comparing the preferred pathways which each other, the base design variant which is adapted the most efficient is determined.

The preferred adaptation pathways

Because of the different characteristics of the three design variants, the ways these can be altered in the future differ as well. In Chapter 8 the most effective ways to adapt the three design variants to sea level rise are determined by the hand of 4 evaluation criteria: environmental cost indicator, direct construction costs, shift in (outer) toe position and adaptability. Each of the three design variants can be adapted to counter 5 meters of sea level rise in various ways. The best adaptation strategy and their values for the evaluation criteria are shown in Table 46 underneath.

	Amount of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	ECI-value [€]	Direct construction costs [€]	Shift in toe position [m]
Variant 1	2	Inner slope	Crest + 1,65 m		2860	11998	0
Variant 2	3	Berm + 28 m	Crest + 1,75 m	Crest + 3,50 m	8973	23466	28
Variant 3	3	Berm + 27 m	Crest + 1,95 m	Crest + 3,90 m	7039	26292	27

Table 46 preferred adaptation option per sea defence design variant

Direct construction costs

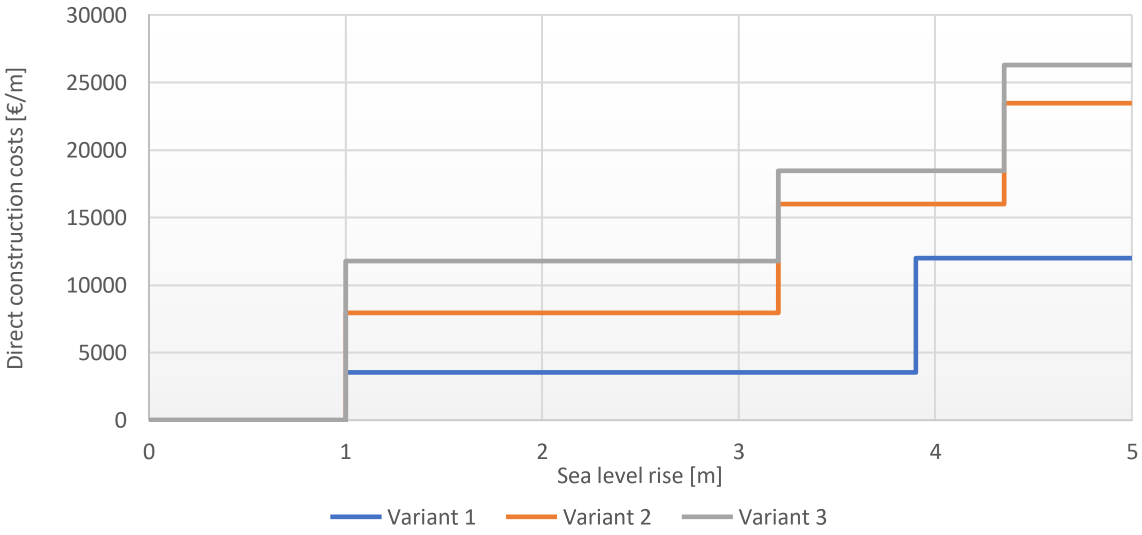


Figure 54 evolution of the direct construction costs through adaptation

The direct construction costs of adaptation for design variant 3 are the highest for each amount of sea level rise which might occur. Design variant 1 has the lowest direct construction costs when adapted. This is due to the fact that inner slope adaptation is relatively inexpensive compared to the other adaptation options, while having a high tipping point.

Environmental costs indicator

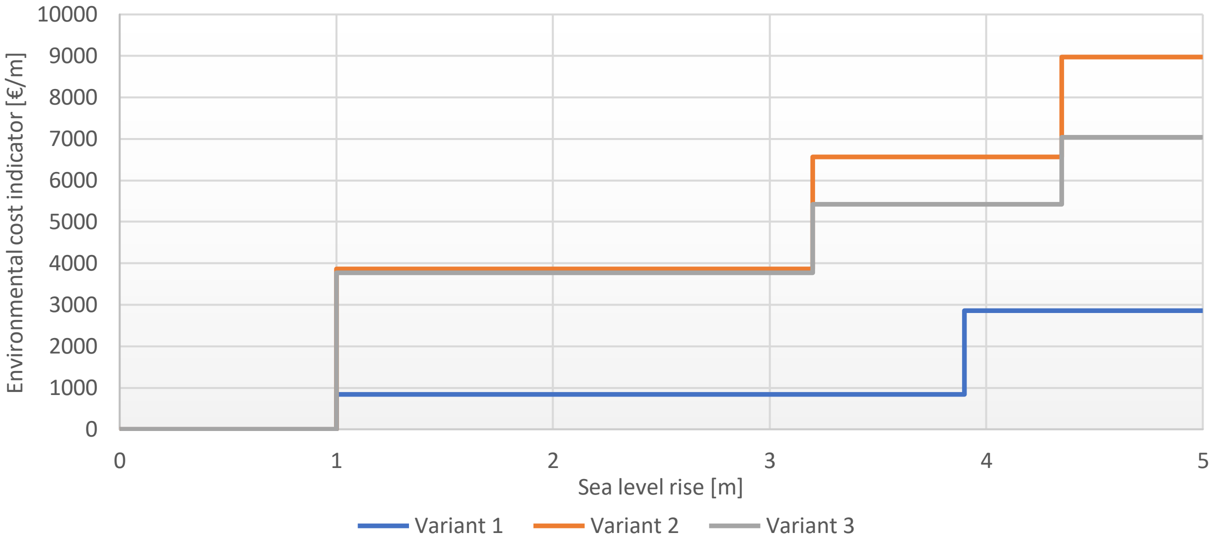


Figure 55 Evolution of the environmental cost indicator through adaptation

The adaptation of design variant 1 imposes the lowest environmental cost indicator for each sea level rise scenario. The ECI-values for the adaptation of design variants 2 and 3 are more or less equal. Even though berm adaptation for design variant 3 requires the removal and re-appliance of Xbloc on the outer slope, the ECI-value for this process is equal to that of variant 2 because of the larger amount of sand and new asphalt necessary for the berm width adaptation of base design variant 2.

Consequences for the Natura2000 area at the toe of the defence

The preferred adaptative pathways for design variants 2 and 3 require a berm width adaptation in order to adapt the sea defence optimally. The consequence of berm width adaptation is a shift in outer toe position by the added berm width of 28 or 27 meters into the Natura2000 area for variants 2 and 3 respectively.

During adaptation all three design variants can make use of various adaptation options which shift the toe of the sea defence into the Natura2000 area in the North Sea. As we want to guarantee full flexibility in adaptability, an area in front of the toe of the new sea defence can be reserved for expansion in the future, this is the case for all three conceptual design variants.

During the alignment of the project boundaries at the start of the Delta21 project, this area in front of the toe should already be reserved for future expansion. This way the use of adaptation options which shift the toe have no further consequences for the Natura2000 area in the future.

Conclusion for the evaluation of the three preferred pathways

As the inner slope of design variant 1 is not reinforced with an asphalt protection layer in the original situation, this design can easily be adapted to sea level rise. The appliance of asphalt does not impose large environmental- or construction costs and also has no consequences for the Natura2000 area in front of the sea defence.

Over-all design variant 1 is the easiest to adapt to sea level rise efficiently as the direct construction costs and ECI-value increase the least because of adaptation and there are no consequences for the Natura2000 area at the toe.

9.3 Evaluation of the Delta21 sea defence base design concepts

All three of the design variants can be adapted to 5 meters of sea level rise in various different ways, therefore the focus of the evaluation of the sea defence concepts is on the consequences the preferred pathways have on the life cycle costs of the Delta21 sea defence.

On top of that, the toe of the sea defence is in a fixed location for all three base design variants. During adaptation all three design variants can make use of various adaptation options which shift the toe of the sea defence into the Natura2000 area in the North Sea. To guarantee adaptability an area in front of the toe of the new sea defence can be reserved for expansion in the future, this is the case for all three conceptual design variants.

By looking at the total lifecycle costs, the preferred adaptive pathway can be taken into account in determining the preferred base design.

Evolution of the direct construction costs

Figure 56 below shows the evolution of the direct construction costs over the lifetime of the Delta21 sea defence. The direct construction costs of the base situation of design variant 1 are significantly higher than those of variant 3 due to the larger geometry which requires larger volumes of sand, clay and Xbloc. The direct construction costs of design variant 3 are higher than those of variant 2 as well, which is entirely due to the use of Xbloc.

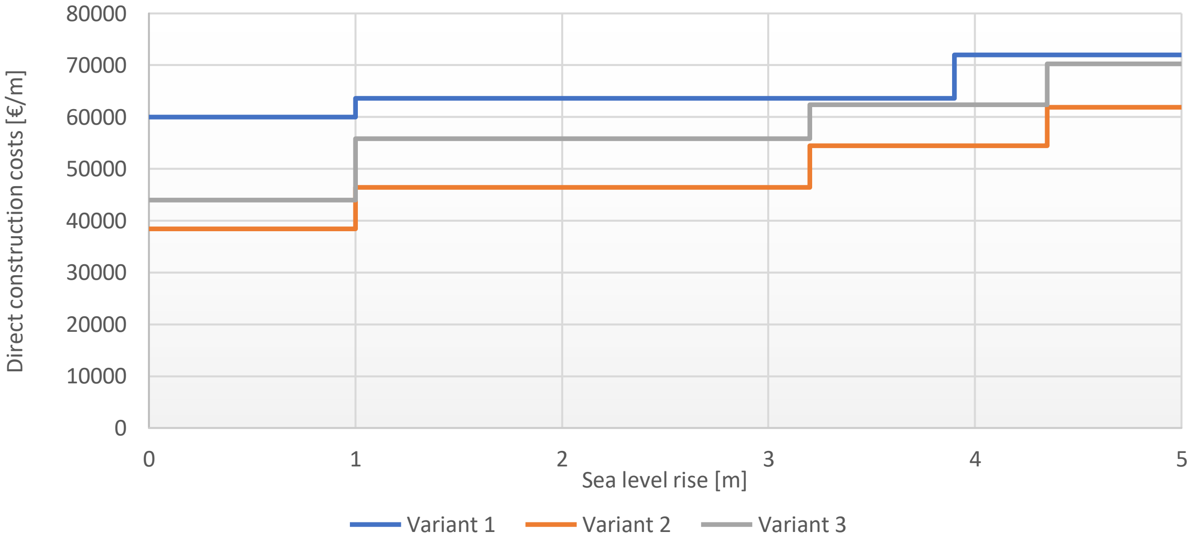


Figure 56 Graph of the total direct construction costs over the lifetime for 1 to 5 meters of sea level rise per sea defence design variant

Due to the adaptation of the sea defences the life cycle construction costs increase. Figure 56 shows that the difference in direct construction costs between design variant 1 and variants 2 and 3 gets smaller when larger amounts of sea level rise occur. Where the difference in direct construction costs between variants 1 and 2 was 36% at the beginning of the lifetime, after 5 meters of sea level rise this difference is decreased to only 15%.

When over 3 meters of sea level rise occurs, the difference in direct construction costs between variants 1 and 3 is generally not significant anymore.

The preferred base design variant based on direct construction costs can only be selected based on the direct construction costs of the base design variants as these differences do not change until a minimum of 3 meters of sea level rise occurs. Based on this design variant 2 is preferred.

Evolution of the environmental cost indicator

During the lifetime of the sea defence, the ECI-value of design variant 2 is larger than that of design variants 1 and 3. Initially design variant 3 has the lowest environmental cost indicator, however during adaptation the preferred adaptation path for design variant 3 increases the total environmental cost indicator more than that of design variant 1. Therefore the ECI-value of design variant 1 is the lowest, once 1 meter of sea level rise has occurred.

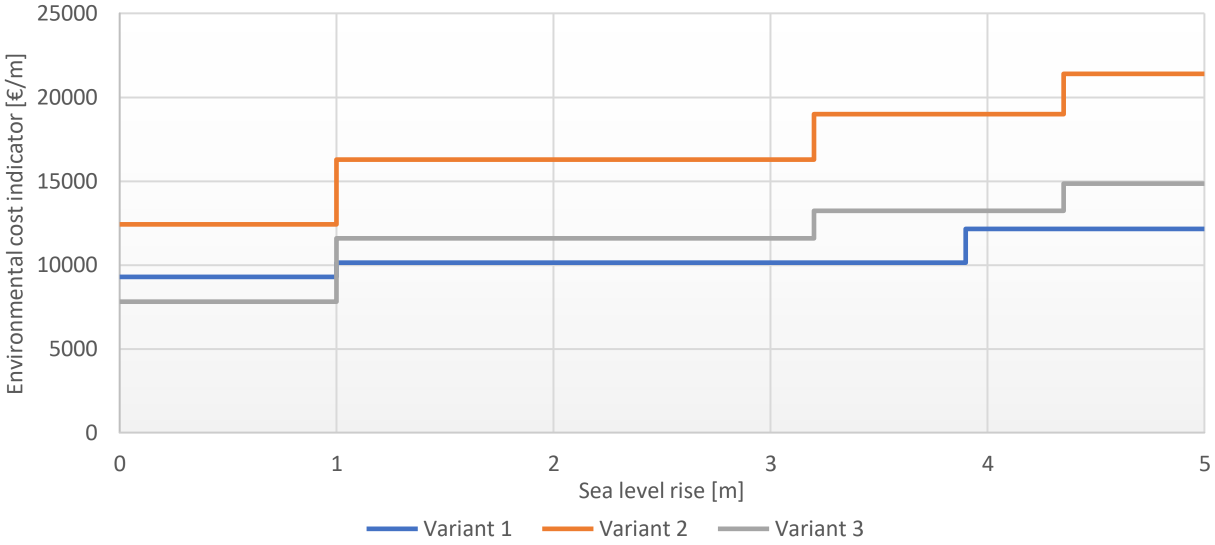


Figure 57 Graph of the total environmental cost indicator over the lifetime for 1 to 5 meters of sea level rise per sea defence design variant

Based on the evolution of the environmental cost indicator over the lifetime of the sea defence, under the influence of sea level rise, design variant 1 is the preferred design variant. Adaptation of this design variant has the lowest environmental impact, due to the mitigation measures which use relatively little resources while having high tipping points.

Impact on the Natura2000 area at the toe of the sea defence

When mitigating the effects of sea level rise with the use of the preferred pathways for design variants 2 and 3, the sea defence is expanded into the Natura2000 area in front of the sea defence. Based on experience with civil engineering projects in the Netherlands, it can be said that getting building permits in these areas is highly restricted and a long and tedious process.

When this is too large of an obstacle, design variants 2 and 3 can only be adapted by the implementation of crest level increase. The preferred pathways for these design variants are not possible in this case. Design variant 1 gives more adaptation options as inner slope adaptation does not move the toe of the sea defence. This means that the preferred pathway can still be implemented.

Conclusions

Purely based on the direct construction costs and environmental cost indicator of the base design variants, design variant 2 is the preferred base design for the Delta21 sea defence. However taking into account the evolution over the lifetime of the sea defence, design variant 1 is the most efficiently adaptable sea defence variant. Therefore base design variant 1 is the preferred design variant when using the adaptive pathway approach in the evaluation of the design variants.

9.4 The recommended design

Based on the evolution of the direct construction costs, environmental cost indicator, influence on the Natura2000 area and adaptability over the lifetime of the sea defence, base design variant 1 is the preferable design for the Delta21 sea defence designed for the failure mechanism of overtopping. The base situation will have the following characteristics:

Design variant:		Design variant 1
Crest level	**[NAP + m]**	16
Toe level	**[NAP + m]**	-14
Crest width	**[m]**	4
Outer slope angle	**[-]**	1:3
Outer slope protection (slopes)	**[-]**	Xbloc armour units
Outer slope protection (berm)	**[-]**	Hydraulic Asphalt Concrete
Berm width	**[m]**	24
Berm level	**[NAP + m]**	6,52
Inner slope angle	**[-]**	1:3
Inner slope protection	**[-]**	A life layer over clay
Maximum allowable overtopping volume	**[l/s/m]**	5

Table 47 Characteristics of the Delta21 sea defence when designed for overtopping

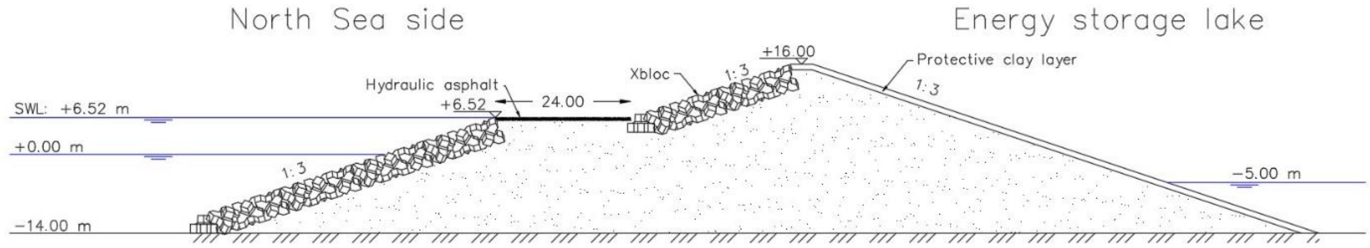


Figure 58 Sketch of static sea defence variant 1

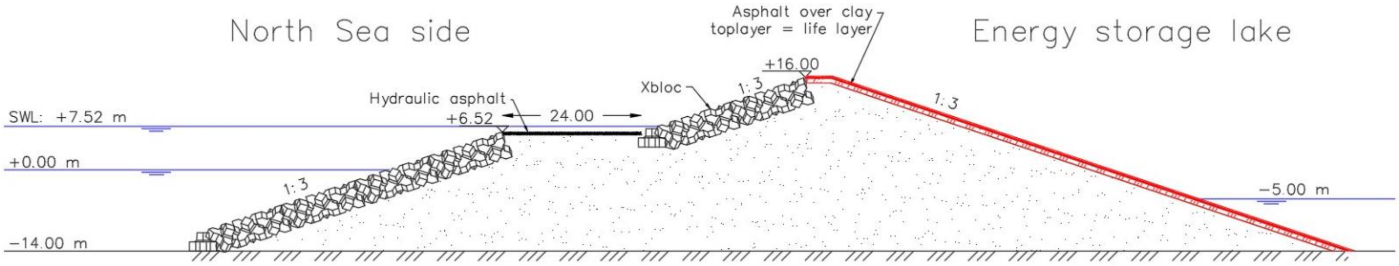


Figure 59 Sketch of static sea defence variant 1 after inner slope adaptation mitigating up to 3.9 meters of sea level rise (indicated in red)

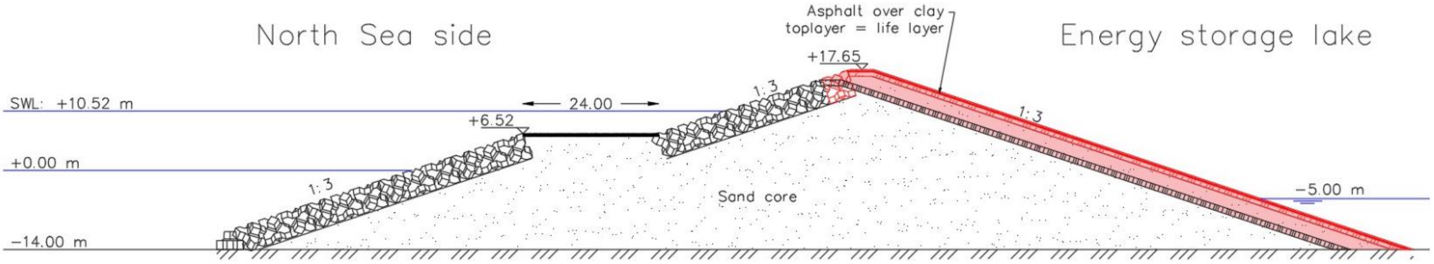


Figure 60 Sketch of static sea defence variant 1 after inner slope adaptation and a crest level increase to NAP + 17.65 m mitigating up to 5 meters of sea level rise (adapted geometry indicated in red, base geometry in black)

10. Discussion

In the design of the Delta21 sea defence and the use of the adaptation pathway approach, multiple assumptions and choices have been made. These assumptions have been presented and described in earlier chapters of this thesis and do not always have a scientific background. This chapter discusses the influence of some of the most relevant topics for the final outcome of the thesis.

10.1 Discussion of the process of creating the conceptual design of the Delta21 sea defence and the adaptation options

Discussion and recommendation on the overall design types

This thesis found the design of the Delta21 sea defence in the form of a sea dike, in this design the possibility of a sea defence in soft (dunes), hybrid or structural form are not taken into account. This narrows down the possible outcomes for the conceptual design of the Delta21 sea defence and therefore does not create the entire picture. The decision to only create a sea defence in the form of a sea dike has mostly been based on the available amount of time to create this thesis. For future research my recommendation is to also create and compare hybrid and structural forms of the Delta21 sea defence.

These different forms of sea defences also come with different types of adaptation methods. When the evaluation criteria for the various designs are the same, the use of the adaptive pathway approach still allows these to be compared in order to select the preferred conceptual design for the Delta21 sea defence.

The flood safety requirement

As a primary sea defence in the Netherlands the Delta21 sea defence has a requirement in safety against flooding. In this case the flooding probability is 1:1000 for the entire project, which is spread over three sections of sea dike, the turbine station and a storm surge barrier. However during the process of determining the failure probability of the separate sections of the sea defence, the section dividing the energy storage lake and the tidal lake (yellow line in Figure 16) is ignored as it is assumed that this section will not fulfil a function in safety against flooding. In reality, in the case that the outer ring fails, the section dividing the energy storage lake and the tidal lake does provide some protection against flooding and should therefore be considered in the failure probability of the entire project.

Considered failure mechanisms

The conceptual design of the Delta21 sea defence has been created for the failure mechanism of overtopping. Using the overtopping formula from the EurOtop overtopping manual (Van der Meer, et al., 2018), the geometry and characteristics of the sea defence have been determined. The consequence of this methodology is that the failure mechanisms of upburst and piping and macro stability have not been considered during the design of the Delta21 sea defence.

Macro stability probably is not a normative failure mechanism in this situation, as a large berm is present on the outer slope of the sea defence. Inward macro stability might play a role, which can also be mitigated by creating a berm on the inner slope of the sea defence. The mitigation measure would be the same for all three base design variants and therefore would not influence the selection of the preferred conceptual design.

Because of the large width of the base of the sea defence, the failure mechanism of up burst and piping is not normative. As the three base design situations have similar base widths, the measures against this failure mechanism will be the same for all three variants when they turn out to be required. Therefore this failure mechanism does not play a role in the selection of the preferred base design variant.

In the determination of the construction material volumes the revetment stability has been taken into account.

Overtopping reduction factors

In the overtopping formula the overtopping discharge is influenced by 3 overtopping reduction factors, being:

- Berm influence factor (γ_b)
- Influence factor for angle wave attack (γ_β)
- Roughness coefficient (γ_f)

Because structural elements are not regarded in this thesis the reduction factor for a wall at the end of a slope (γ_v) is not taken into account.

Because (model) tests of several combinations of these reduction factors over all ranges were not possible in the past, the EurOtop overtopping manual prescribes that the maximum combination of all reduction factors cannot be lower than 0,4. This threshold is given because of an absence of sufficient testing data, and not because reduction factors lower than 0,4 cannot exist. In this thesis this requirement has not been met as this gives more freedom during the design process, therefore future (model) testing will be required when this conceptual design is realized.

Following the same reasoning the minimum berm influence factor of 0,6 is not applied to the conceptual design of the Delta21 sea defence, which again means that future (model) testing will be required to prove whether this assumption is correct when this conceptual design is realized.

In this thesis the calculation of the berm coefficient is conducted via the formula as indicated in the EurOtop overtopping manual (Van der Meer, et al., 2018). However more recently Chen et al. (Chen, Van Gent, Warmink, & Hulscher, 2020) found a more accurate formula which indicated the influence of a berm on overtopping. The use of this formula would result in a slightly lower berm influence factor and therefore less overtopping, which makes the current design method as applied in this thesis slightly more conservative.

Roughness coefficient

The roughness of the outer slope of the sea defence is an important factor in the determination of the overtopping discharge. In two of the three base design variants the outer slope is covered in a single layer of Xbloc units. According to the Xbloc design guidelines (Delta Marine Consultants, 2018) these units have a roughness coefficient of 0.44 which is the roughness coefficient for Xbloc units on permeable slopes.

Model testing in the past for projects like the Afsluitdijk in the Netherlands show lower roughness for the use of these units on impermeable slopes as is the case on the Delta21 sea defence. In the future, model testing will have to prove the real value for the roughness of Xbloc units in this specific situation. When the roughness of these elements turns out to be lower than designed for, this means the occurring overtopping discharge increases and the designed geometries do not suffice.

Size and type of the adaptation options

Some adaptation options are designed to be applied in multiple discrete steps (crest level increase, berm width increase and foreshore adaptation). In reality there are numerous step sizes between these steps, which can cause different optimum pathways for the three base design variants as more combinations can be made. However, in this research the maximum values for the adaptation options have been determined which means that other step sizes will result in pathways which are in between currently presented values. The final outcome of the evaluation will therefore not differ much.

The use of structural elements is not regarded in the study, an adaptation combination which includes these can turn out to be an efficient way to adapt the sea defence to large amounts of sea level rise.

10.2 Discussion of the assumptions in the Boundary conditions

The boundary conditions are used as input for the conceptual design of the Delta21 sea defence. In the determination of these boundary conditions the assumption of correlation between the return periods of extreme wave conditions and high water levels has been made. On top of that assumptions have also been made in the determination of the consequences of climate change on the boundary conditions.

Changing return periods for storm conditions because of climate change

The latest IPCC report (IPCC, 2021) and Klimaatsignaal (KNMI, 2021) state that wind speeds will not increase significantly under the influence of climate change. It is assumed that the deep water wave conditions on the North Sea are fetch induced, which implies that significant wave heights also do not change significantly under the influence of climate change.

IPCC reports do not necessarily state that the return periods for high velocity wind conditions on the North Sea will change under the influence of climate change. In the report the assumption is made that the return periods will not change and also the return periods of the significant waves will not change. However when the return periods for high wind conditions get shorter, the significant wave heights for the Delta21 sea defence will increase.

Hydraulic design conditions

The wave conditions are determined by extreme value analysis from wave data from the Europlatform and the water levels are extracted from Hydra-NL. The assumption has been made that the return periods for extreme water levels and wave heights fully correlate, which is not always the case. For further design a detailed study after the hydraulic boundary conditions is necessary. However, research shows that a big correlation between storm set-up and extreme wave conditions exists and coincide with the assumptions, which would not change a lot after extensive research.

10.3 Discussion of the evaluation of the base design variants and the adaptations

In Chapters 9 and 10 the preferred pathways and base design variant for the Delta21 sea defence have been selected. This selection process makes use of four evaluation criteria, the methodology of determining the values for the criteria per design variant or pathway have large consequences for the outcome of the analysis. Two of the evaluation criteria (direct construction costs and environmental cost indicator) are directly linked to the amount of material required for the construction of the base design variants and various adaptation pathways which causes correlation between the two.

Construction materials

The volumes of the construction materials as determined in Appendix H only regard the materials which are taken up in the direct construction costs as specified by the SSK-methodology. Direct construction costs include clay, sand, (hydraulic and open stone) asphalt and Xbloc units. Indirect construction costs are a percentage factor of the direct construction costs and include all construction costs which are not yet specified in this design phase.

This means that the use of geotextiles, filter layers, connections and other construction details are not taken into account as these are put in the Indirect construction costs as a percentage of the direct construction costs. For future design and proper evaluation between the design variants these costs should be further specified to increase the accuracy of the construction costs.

Determination of environmental cost indicator

The values for the environmental cost indicator are based on the standard values as determined for the national environmental database or "Nationale milieudatabase" in Dutch. This database is created as a guideline for the ECI-values for construction projects in the Netherlands. The use of this database is common practice in early design stages for Dutch civil engineering projects as a lot of factors (where do the materials come from, how are they put in place, etc.) are still unknown or unspecified.

In the environmental cost indicator, not only the environmental impact for the separate construction materials, but also the transportation and construction process are taken into account. For the materials which were used in each of the design variants (clay, sand and open asphalt concrete), the specified values for mentioned processes for this specific project will not have an influence on the outcome of the comparison between the concepts.

However for Xbloc and hydraulic asphalt, which are not used in each of the conceptual design variants, the value changes during further specification do have an influence on this comparison. Therefore in future studies the proper environmental cost indicator for this specific project should be determined, as this decreases the uncertainty in the environmental cost indicator for the different design concepts and a more accurate comparison can be made.

Determination and use of direct construction costs

The direct construction costs are subject of the same uncertainty as the earlier mentioned construction material volumes. As a lot of the materials and associated volumes are not yet specified, the direct construction costs cannot be fully determined. The comparison of the design variants makes use of the above mentioned construction materials and is therefore not complete. However since all the unknowns are put together as a percentage factor in the indirect building costs, it is assumed that this choice does not influence the outcome of the comparison between the variants too much.

When comparing various expenses over a longer period of time, discounting comes into play. Discounting is a method to compare expenditures over a longer period of time, by determining the future value of the expenditure and projecting this on a single moment in the time line. Shortly this means that expenditures made in the future require less of "todays money" due to interest rates. In the comparison between the different design variants, discounting has not been regarded.

For the comparison between the three base design variants this does not play a role, as these would be built at the same moment and discounting then is not in play. It does however play a role in the sequence in which the adaptation options are applied to the preferred base design concepts. When taking discounting into account, it could turn out to be profitable to first apply the cheap adaptation options (for example the two increases in crest height) and later perform the more expensive ones (for example berm width increase).

Discounting will have an influence on the preferred adaptive pathway per design variant. However, because more evaluation criteria than only direct construction costs play a role, it is likely that the implementation of discounting would not influence the choice of the preferred sea defence base variant too much.

The impact on the Natura2000 area

In the selection of the preferred adaptive pathway, it is assumed that an expansion of the sea defence into the Natura2000 area at the toe can be realised when the required extra space for the dike is reserved in advance. However, when this reservation is not possible and future expansion in the Natura2000 area is fully restricted, this has very large consequences for the selection of the preferred adaptive pathways.

A restriction in outer toe relocation would mean that the adaptability of the sea defence can only come from crest level increase (for all design variants), inner slope reinforcement (for design variant 1) and roughness adaptation (for design variant 2). Automatically this would mean that design variants 1 and 2 would score better on adaptability, because of the fact that more than 1 option is available.

Impact of the different evaluation criteria

In the evaluation of the adaptive pathways and base design concepts, four evaluation criteria were used. The current analysis uses these criteria as arguments in the selection of the preferred pathway and base design variant, in this argumentation each of the criteria have the same weight. However the analysis can have a totally different outcome when the criteria do not have the same weight in the argumentation. For example in the case that the direct construction costs are leading: design variant 2 would have been the preferred design variant because of the low costs when compared to the other two design variants.

The same can be said for the case in which expansion into the Natura2000 area is strictly prohibited and construction costs and ECI have the same weight, in that case either design variants 1 or 2 would be preferred over design variant 3 as these provide more flexibility.

For future comparison between different design variants it is key to understand the value of the evaluation criteria in the argumentation. These weights would be the outcome of a discussion between the different stakeholders in the project, the government and the commissioning party. This same discussion could also bring more evaluation criteria or design requirements to the table, which all have an influence in the selection and initial design of the conceptual design variants.

This analysis is out of the scope of this thesis, but has a large influence on the selection of the preferred design variant.

10.4 Discussion of the adaptive pathway approach

This thesis is based on the idea of the use of the adaptive policy pathway approach in the early conceptual design of sea defences in the form of sea dikes. One of the main objectives was to find out if the use of this methodology is useful in the process of creating a conceptual design for a new sea defence.

The adaptive pathway approach can certainly be used in the early conceptual design phase for civil engineering projects as in this case sea defences. During this early phase it can be used as a tool to take adaptability for future changing boundary conditions into account in the evaluation of the first conceptual designs.

The methodology gives new insights in the challenges which might appear in the future. For the Delta21 sea defence the preferred pathways for design variants 2 and 3 make use of a reserved space in front of the new sea defence in an area which otherwise would have been Natura2000 area. Knowing this, reserving this area can already be performed during the first phase of the process, creating more flexibility for adaptation in the future. Via the same logic we also know that adaptation in the future might turn out very difficult when expansion into the Natura2000 area is not possible due to legislation. Then it is advised to select a sea defence which is more adaptable in other ways than expanding into the North Sea.

The use of the adaptive pathway approach will be more effective when more evaluation criteria and possible restrictions are determined for the various adaptive pathways, as this strengthens the comparison between the various design variants and adaptative pathways. When looking at the outcome of the process in Chapter 9, the preferred conceptual design variant is design variant 1. This would probably not have been the case when only looking at the direct construction costs and environmental cost indicator of the base design situation.

When more criteria come forward in the evaluation process of a real-life scenario in which a sea defence should be altered (think about a restriction in crest level increase or berm width increase because of socio-economic reasons), another preferred sea defence variant might come forward completely.

Therefore, in my experience, the adaptive pathway approach is an effective way of taking adaptability into account in the decision making process - even during the early conceptual design phase - for sea defence design. The method however is the most effective when more evaluation criteria are determined, as this strengthens the comparison between the various design variants and adaptative pathways.

10.5 Scenario thinking during the selection of the preferred design variant

In the current thesis methodology, the preferred design variant is determined through a life cycle analysis which assumes that five meters of sea level rise probably will occur during the lifetime of the sea defence. This is not necessarily the case as the various sea level rise scenarios created by the IPCC and KNMI show. The scenarios used in this evaluation have been based on the median value of the graphs in Figure 9 in Section 3.1.2. The occurring sea level rise scenario has a large influence in the selection of the preferred design variant for the Delta21 sea defence.

In Figures 61 and 62 underneath the direct construction costs and environmental cost indicator over the lifetime of the sea defence for three sea level rise scenarios as proposed by the KNMI are presented. In these figures the green lines present the amount of sea level rise over the years which corresponds to the y-axis on the left side of the graph. The blue, grey and orange lines present the direct construction costs and environmental cost indicator for design variants 1, 2 and 3 respectively which correspond to the y-axis on the right side of the graph.

In the graphs presented in Figures 61 and 62, a jump in the direct construction costs and environmental cost indicator is caused by the implementation of an adaptation meaure.

For the lowest scenario (SSP1-2.6) the base design variants fulfil sufficient safety against flooding, as 1 meter of sea level rise is reached in the year 2200. This means that no adaptation is necessary during the lifetime of the sea defence which is indicated as a straight line.

For the second scenario (SSP5-8.5) a single adaptation step is necessary for alle three the base design variants as the tipping point for the first adaptation is not reached before 2200.

The last scenario (SSP5-8.5 H++) reaches 5 meters of sea level rise at the end of the lifetime of the sea defence. For this scenario two adaptation steps are required for design variant 1 and three adaptation steps are required for design variants 2 and 3.

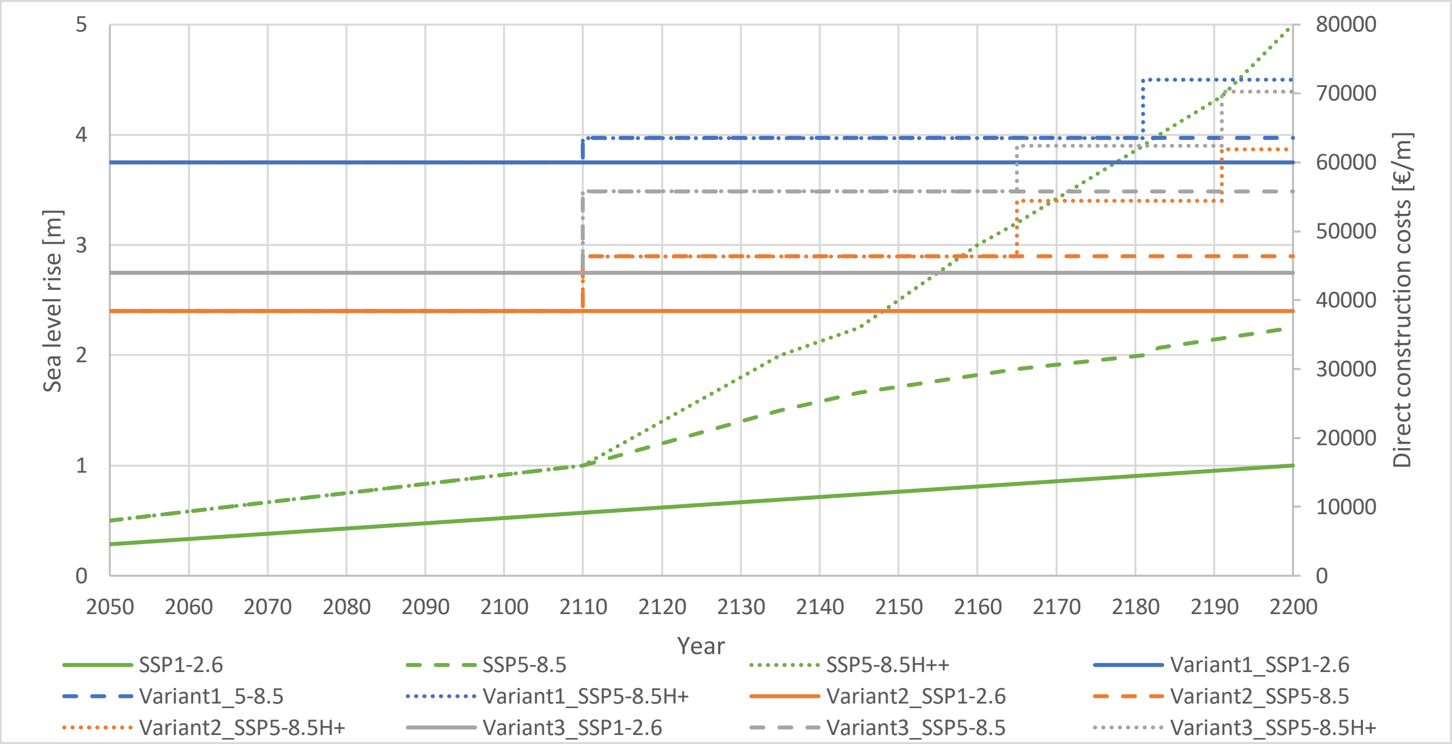


Figure 61 The evolution of the direct construction costs over the lifetime of the Delta21 sea defence for three sea level rise scenarios (SSP1-2.6, SSP5-8.5 and SSP5-8.5 H++ (KNMI, 2021))

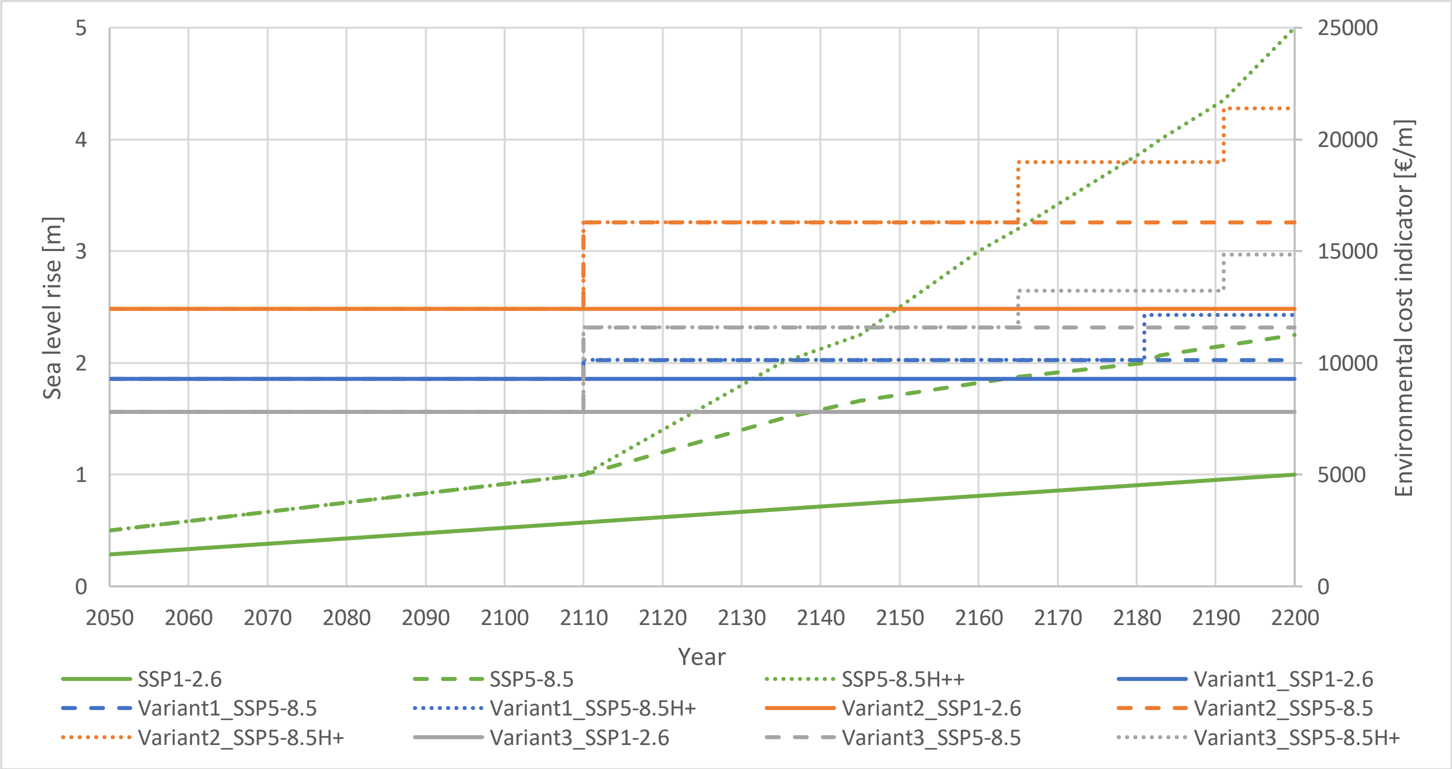


Figure 62 The evolution of the environmental cost indicator over the lifetime of the Delta21 sea defence for three sea level rise scenarios (SSP1-2.6, SSP5-8.5 and SSP5-8.5 H++ (KNMI, 2021))

For the third scenario (SSP5-8.5 H++) the conclusion of Chapter 9 holds. The direct construction costs for design variant 1 do not rise as much as that of the other design variants, because of the inexpensive adaptation options which are applied for this variant. Also the ECI-value for design variant 1 is the smallest once the first adaptation step is applied. Considering the impact on the Natura2000 area at the toe of the sea defence which is not touched during adaptation of design variant 1 makes this the preferred design variant given that sea level rise scenario SSP5-8.5 H++ occurs.

However for the other two considered scenarios (SSP1-2.6 and SSP5-8.5) this conclusion does not necessarily hold. Less sea level rise occurs during the lifetime of the sea defence and therefore less adaptions have to be implemented for the design variants, which changes the evolution of the evaluation criteria over the lifetime of the sea defence significantly.

For the SSP1-2.6 scenario, no adaptation options have to be implemented. Therefore the selection of the preferred design variant is purely based on the characteristics of the base design situation. In this situation, adaptability and impact on the Natura2000 area do not have an impact in the selection process for this timeframe. The preferred design variant cannot easily be determined for this scenario, here more evaluation criteria would play a role in properly determining the preferred design variant.

When scenario SSP5-8.5 occurs, a single adaptation has to be implemented for the three base designs. For this scenario, design variant 2 has the lowest direct building costs but the largest environmental cost indicator. In this scenario (considering the same preferred adaptive pathways from chapter 8), design variant 1 is the only base design variant without an impact on the neighbouring Natura2000 area. In this selection the reasoning from Chapter 9 can still hold, though less convincing as the direct construction costs are still further apart in the final situation. More evaluation criteria would play a role in properly determining the preferred design variant.

It can be said that thinking in scenarios changes the selection process of the preferred design variant and gives insight in the timeframe in which certain adaptations can be expected in the future. The probability of occurrence of these scenarios will play a big role in this as well and once more is known about this topic, this methodology can be used to systematically apply the adaptive pathway approach.

11. Conclusions and recommendations

11.1 Conclusions

This chapter presents the conclusions to the research questions and main objective of the thesis.

The objective of the thesis is to find the characteristics of the conceptual design of the Delta21 sea defence while considering the uncertainties and possible consequences of climate change. These uncertainties will be taken into account by the use of the adaptive pathway approach. The research was conducted using multiple sub-questions that each contribute to answering the main research question:

What will a conceptual design of a static Delta21 sea defence look like bearing in mind the uncertainties and consequences of climate change and can the adaptive pathway approach be used to consider these uncertainties?

This main question is split up in two sub-questions:

Q.1. How can the adaptive pathway approach be implemented in the process of creating a conceptual design for a new sea defence?
Q.2. What design variant for the Delta21 sea defence is preferable, bearing in mind the possible consequences of climate change?

The answers to these are presented in the remainder of this section.

Q.1. How can the adaptive pathway approach be implemented in the process of creating a conceptual design for a new sea defence?

The adaptive pathway approach is not a design methodology, however during the conceptual design phase it can be used to consider the effects of uncertain development of boundary conditions on the design. The use of the adaptive pathway approach helps to gain insight in the process of adapting existing systems to external changes under the influence of sea level rise. This enables the evaluation of design variants with respect to uncertainties in future sea level rise scenarios in a methodological manner. The approach provides a systematic methodology for the selection process of a preferred conceptual design.

In short the conceptual design process using the adaptive pathway approach requires the following steps:

0. Generate base design concepts
1. Identify changes in boundary conditions
2. Identify and design adaptation options
3. Create adaptation pathways
4. Determine preferred adaptation pathway per design concept
5. Determine preferred design concept

Without an initial (existing) situation, the adaptive pathway approach cannot be applied. Therefore, first a base design is developed following the classical design method which acts as this existing situation for the adaptive pathway approach. Because the adaptive pathway approach is used in the selection of the preferred conceptual design variant, multiple base design variants are created parallel. During the design process, the possible future changes in boundary conditions are not yet considered.

The use of the adaptive pathway approach requires knowledge on the changes in hydraulic boundary conditions for different sea level rise scenarios. The identification of the change in boundary conditions is the first step in the conventional use of the adaptive pathway approach.

The changes in boundary conditions require adaptation of the first created base design situations, therefore various adaptation options are designed to modify these designs to the new circumstances. Each of these adaptation options can mitigate the effects of a certain amount of sea level rise, using the adaptive pathway approach this is visualised in an adaptive pathway scheme.

By creating multiple conceptual base situations for the sea defence and also developing multiple pathway schemes side-by-side (one for each of these design variants), a comparison can be made between the concept design variants and the way they are altered in the future.

In this thesis the direct construction costs, environmental cost indicator and consequences of adaptation on the neighbouring Natura2000 area were used as evaluation criteria in the comparison between the adaptive pathways and later the base design variants.

The created adaptive pathways are evaluated per design variant in order to find the preferred method of adaptation for each of the base design variants. This evaluation is performed in four steps of one meter of sea level rise, via which the best adaptation strategy is found for up to 5 meters of sea level rise for every base design variant.

Last, the eventual preferred conceptual design for the sea defence is found through an evaluation and comparison of the base design variants under the influence of sea level rise. Each of the preferred adaptation strategies alter the base design variants in their own way. By evaluating the base design variants and their preferred adaptation strategy, an analysis over the lifetime of the sea defence is created. By making a comparison over the complete life time of the different design variants, the influence of adaptation of these variants is taken into account during the process of selecting the preferred conceptual design. This way, the use of the adaptive pathway approach helps to gain insight in the evolution of the sea defence over the life time and is used in the selection process of preferred conceptual design.

The use of the adaptive pathway approach is useful as a methodological approach for determining the design variant which provides the optimum situation when the necessity of adapting to uncertain conditions arises in the future.

Q.2. What design variant for the Delta21 sea defence is preferable, bearing in mind the possible consequences of climate change?

Based on the evolution of the direct construction costs, environmental cost indicator, influence on the Natura2000 area and adaptability over the lifetime of the sea defence under the influence of sea level rise, the preferable design for the Delta21 sea defence is selected out of three design concepts.

The preferred conceptual design of the Delta21 sea defence has a core created from sand which is dredged from the future energy storage lake and a crest level at NAP + 16 meters. The outer slope is divided by a 24 meter wide berm at NAP + 6,52 meters, the top layer of this berm is made from hydraulic asphalt concrete. The 1:3 outer slope is covered in a single layer of Xbloc concrete armour units.

The inner slope also is 1:3 and covered in a clay layer with a life layer on top, therefore the maximum acceptable overtopping discharge is 5 l/s/m.

The characteristics of the Delta21 sea defence are presented underneath in Table 48 and Figure 63.

Crest level	**[NAP + m]**	16
Toe level	**[NAP + m]**	-14
Crest width	**[m]**	4
Outer slope angle	**[-]**	1:3
Outer slope protection (slopes)	**[-]**	Xbloc armour units
Outer slope protection (berm)	**[-]**	Hydraulic Asphalt Concrete
Berm width	**[m]**	24
Berm level	**[NAP + m]**	6,52
Inner slope angle	**[-]**	1:3
Inner slope protection	**[-]**	A life layer over clay
Maximum allowable overtopping volume	**[l/s/m]**	5

Table 48 characteristics of the preferred conceptual design of the Delta21 sea defence

The base design situation is created for a maximum of 1 meter of sea level rise since 1990. It is however not unthinkable that the sea level will increase more than that single meter during the lifetime of the Delta21 sea defence, therefore the sea defence has to be adaptable to these larger amounts of sea level rise. Using two adaptation steps the sea defence can be adapted to mitigate up to five meters of sea level rise.

The first step is a reinforcement of the inner slope by creating a top layer created out of clay, a layer of asphalt and topped with a life layer. This way the maximum allowable overtopping discharge is increased from 5 to 125 l/s/m and the effects of up to 3,2 meters of sea level rise are mitigated.

When more than 3,9 meters of sea level rise occur, the sea crest level of the sea defence can be increased with 1,65 meters to NAP + 17,65 m. This way the effects of up to 5 meters of sea level rise are mitigated.

In order to guarantee optimum flexibility for adaptability in the future it is advised to reserve space in front of the sea defence, this way all adaptation options can be applied when necessary.

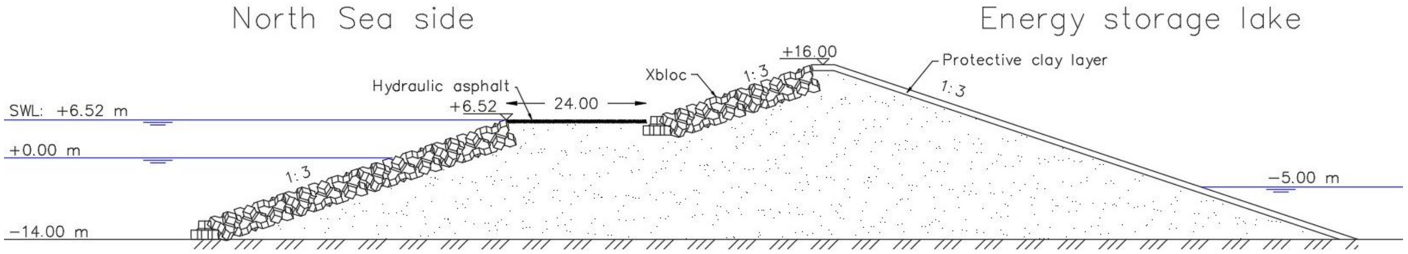


Figure 63 Cross-section of the Delta21 sea defence

Can the adaptive pathway approach be used to consider the uncertainties of climate change in the conceptual design process of sea defences and what will a conceptual design of a static Delta21 sea defence look like bearing these uncertainties in mind?

By first creating various conceptual designs using the classic design methodology and using these designs as input for the adaptive pathway approach, this approach can be used to take the uncertainties of climate change into account during the conceptual design evaluation process. The adaptive pathway approach is a powerful tool to allow easy evaluation of design variants and their future modifications to mitigate the effects of changing boundary conditions. It gives understanding of possible adaptations to be made in the future and can certainly be used in the selection of the preferred conceptual design as part of the design process.

In the case of the Delta21 sea defence, the conceptual design of choice has a crest level at NAP + 16 m with a 1:3 outer slope. A 24 meter wide berm is present at NAP + 6,52 m which is covered in hydraulic asphalt. Concrete Xbloc armour units are used to create the revetment on the outer slopes of the sea defence. The inner slope is covered by a clay layer, which gives the sea defence an allowable overtopping discharge of 5 l/s/m.

This design is created for 1 meter of sea level rise since 1990. When more than 1 meter of sea level rise occurs, first the inner slope can be reinforced with an asphalt layer over the clay layer (on top of this asphalt layer is a life layer) which mitigates the effects of sea level rise up to 3,9 meters. After this the crest level can be increased with 1,65 meters to NAP + 17,65 m to mitigate up to 5 meters of sea level rise.

11.2 Recommendations for further study

Based on the research as performed in this thesis, some recommendations are advised for further research in the future. These recommendations can be used to further develop the design of the Delta21 sea defence and to come to an even more effective use of the adaptive pathway approach.

Failure probability

- In the design of the Delta21 sea defence it is assumed that the flooding probability of the new sea defence will be the same as that of the Haringvliet barrier, namely 1:1000 years. A full risk analysis of the sea defences in the delta might reveal a more suitable and realistic failure probability of the Delta21 sea defence.

- The Delta21 sea defence is assumed to be formed out of the single (outer) line of defence as shown with the yellow line in Figure 16. However when failure of this outer line occurs, the dune row which divides the energy storage lake and the tidal lake will provide safety against flooding as well. It is recommended to assess the new failure probability of the entire Delta21 sea defence, also considering the safety against flooding provided by the stretch of dunes as second line of defence.

Type of sea defence and adaptation options

- This thesis only considers the Delta21 sea defence as a hard sea defence (or sea dike) without structural or dynamic elements. For future studies it might be interesting to also assess the possibility of the use of a dynamic sea defence (in the form of dunes or a hybrid defence) or structural elements.

- In Chapter 5, six options for adapting the sea defence are presented. In this assessment the application of structural elements or the transformation of the hard sea defence to a hybrid sea defence are not considered. By applying other types of adaptation options, the outcome of the pathway evaluation might differ as well. Therefore it is recommended to also consider other types of adaptation options.

Evaluation of the adaptive pathways and base design variants

- During the evaluation of the adaptive pathways and the base design variants the evaluation is performed based on a scenario in which five meters of sea level rise will occur during the lifetime of the sea defence. However as described in the discussion, this is not necessarily the case. Using scenario thinking during the evaluation of the variants might lead to different conclusions in the evaluation. Therefore it is recommended to use scenario thinking during the use of the adaptive pathway approach.

  One of the difficulties in this process is that the chances of occurring for the different climate change scenarios are still unknown. When these chances are determined, a well-informed selection process for the preferred pathways and design variants can be created.

- The direct construction costs are one of the four evaluation criteria used in the evaluation of both the adaptive pathway schemes as well as the three design variants. In the evaluation, discounting is not considered, however this could have large consequences for the selection of the preferred design variant. Therefore the implementation of discounting, coupled to the various sea level rise scenarios could make for an interesting study after the preferred design variants.

- When more evaluation criteria and requirements for the Delta21 sea defence are determined, these can be used to create a new evaluation of the different design variants and adaptive pathways. Therefore a large stakeholder analysis containing the organization of Delta21 as well as other stakeholders (Natura2000, the Dutch government, the Port of Rotterdam, etc.) can create new insights and deliver more criteria in the evaluation. This way a value can be assigned to the various evaluation criteria. This analysis could also cause various adaptation options to be neglected from the start due to restrictions which are not considered in this thesis.

References

CBS. (2022, Maart 7). *More electricity from renewable sources, less from fossil sources*. Retrieved from https://www.cbs.nl/en-gb/news/2022/10/more-electricity-from-renewable-sources-less-from-fossil-sources

Chen, W., Van Gent, M., Warmink, J., & Hulscher, S. (2020). The influence of a berm and roughness on the wave overtopping at dikes. *Coastal Engineering*(Volume 156). doi:https://doi.org/10.1016/j.coastaleng.2019.103613

Delta Marine Consultants. (2018). *Guidelines for XBloc Concept Design.* Gouda.

Delta21. (2018). *Deelrapport natuurherstel.* Retrieved from https://www.delta21.nl/natuurherstel/

Delta21. (2020). *Delta21: Een universeel modulair concept.*

Deltaprogramma. (2022, april 21). *Deltaplan Waterveiligheid*. Retrieved from Nationaal deltaprogramma 2021: https://dp2021.deltaprogramma.nl/

Deltaprogramma. (2022, april 20). *Hoe zit het met de rivierafvoer van 18.000 m3 per seconde?* Retrieved from Website van Deltaprogramma: https://www.deltaprogramma.nl/deltaprogramma/vraag-en-antwoord/hoe-zit-het-met-de-rivierafvoer-van-18.000-m3

Deltares. (2015). *Handreiking Dijkbekledingen, Deel 3: Asfalt.* Lelystad: Rijkswaterstaat WVL en Projectbureau Zeeweringen.

Deltares. (2015). *Handreiking Dijkbekledingen. Deel 2: Steenzettingen.* Delft: Deltares.

Deltares. (2018). *Werkwijzer bepaling Hydraulische Ontwerprandvoorwaarden.*

Doell, P., & Müller Schmied, H. (2012, Maart). How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis. *Environmental Research Letters 7.* doi:10.1088/1748-9326/7/1/014037

Donkers, D. (2021). *Conceptual design of the spillway into the energy storage lake of Delta21.* Delft: Delft University of Technology.

Ecochain. (2019, 06 13). *Environmental Cost Indicator (ECI) – Overview*. Retrieved from Ecochain.com: https://ecochain.com/knowledge/environmental-cost-indicator-eci/

FLOODsite. (2022, augustus 08). *Failure mechanisms of dikes*. Retrieved from FLOODsite: http://www.floodsite.net/juniorfloodsite/html/en/student/thingstoknow/geography/failmechanisms.html

Fowler, H., Lenderink, G., Prein, A., & al., e. (2021). Anthropogenic intensification of short-duration rainfall extremes. *Nat Rev Earth Environ*(2), pp. 107-122. doi:https://doi.org/10.1038/s43017-020-00128-6

Haasnoot, M., Bouwer, L., Diermanse, F., Kwadijk, J., van der Spek, A., Oude Essink, G., . . . Mosselman, E. (2018). *Mogelijke gevolgen van versnelde zeespiegelstijging voor het Deltaprogramma. Een verkenning. Deltares rapport 11202230-005-0002.* Delft: Deltares.

Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E., & van Deursen, W. P. (2012). *Exploring pathways for sustainable water management in river deltas in a changing environment.* Springerlink.com.

Hegnauer, M., Kwadijk, J., & Klijn, F. (2015). *The plausibility of extreme high discharges in the river Rhine.* Delft: Deltares.

Hofland, B., Chen, X., Altomare, C., & Oosterlo, P. (2017). Prediction formula for the spectral wave period Tm-1,0 on mildly sloping shallow foreshores. *Coastal Engineering*, 21-28. doi:http://dx.doi.org/10.1016/j.coastaleng.2017.02.005

Hogeveen, K. (2021). *Climate Adaption of Rubble Mound Breakwaters.* Delft: Delft Technical Universtiy of Technology.

Huijsman, D. (2021). *Adaptation of marine locks against sea level rise.* Delft: Delft University of Technology.

IPCC. (2021). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. Connors, C. Péan, S. Berger, . . . B. Zhou, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Jacquemin, L. (2021). *Delta21: Improved design of the pump-turbine station.* Delft: Delft University of Technology.

KNMI. (2021). *KNMI 2021: KNMI Klimaatsignaal’21: hoe het klimaat in Nederland snel verandert.* De Bilt: KNMI.

Lavooij, H., & Berke, L. (2019). *Update Delta21 2019: Actualisering Delta21.* Delta21.

Loman, G., Hofland, B., Van de Biezen, S., & Poot, J. (2012). *INTEGRAL DESIGN OF HARD SEA DEFENSE OF MAASVLAKTE 2.*

Onwuachu, P. (2021). *The New Haringvliet Barrier.* Delft: Delft University of Technology.

Reeze, B., de la Haye, M., Arts, F., Boudewijn, T., van der Jagt, H., Van Kessel, N., . . . Wegman, C. (2020). *Nulrapportage ecologische toestand Haringvliet en Voordelta 'Lerend implementeren Kierbesluit'. Bureau Waardenburg Rapportnr. 20-340.* Culemborg: Bureau Waardenburg.

Reuber, J., Schielen, R., & Barneveld, H. (2005). *Preparing a river for the future-The River Meuse in the year 2050.*

Rijksoverheid. (2007, november 23). *Compendium voor de leefomgeving*. Retrieved from Natura 2000 - Vogel- en Habitatrichtlijn gebieden en de EHS: https://www.clo.nl/indicatoren/nl142501-begrenzing-van-het-natuurnetwerk-en-natura-2000-gebieden

Rijksoverheid. (2022). *Waterwet*. Retrieved from Wettenbank.nl: https://wetten.overheid.nl/BWBR0025458/2021-07-01

Rijkswaterstaat. (2012). *Basic Documentation Maeslant Barrier.* Ministry of Infrastructure and Environment.

Rijkswaterstaat. (2016). *Basisrapport WBI2017.* Rijkswaterstaat, Water verkeer en leefomgeving.

Rijkswaterstaat. (2019). *Water management in the Netherlands.* Rijkswaterstaat and the Association of Dutch Water Authorities.

Rijkswaterstaat. (2022, April 25). *Haringvliet: Haringvlietsluizen op een kier*. Retrieved from Website van Rijkswaterstaat: https://www.rijkswaterstaat.nl/water/projectenoverzicht/haringvliet-haringvlietsluizen-op-een-kier

Rijkswaterstaat Water, Verkeer en Leefomgeving. (2017). *Handreiking ontwerpen met overstromingskansen.* Utrecht: Rijkswaterstaat Water, Verkeer en Leefomgeving.

Rogers, S., & Nash, D. (2019). *Return of the Dunes: The Science of Post-Florence Recovery*. Retrieved from Sea Grant North Carolina Coastwatch: https://ncseagrant.ncsu.edu/coastwatch/previous-issues/2019-2/spring-2019/return-of-the-dunes-the-science-of-post-florence-recovery/

Rowbottom, L. (2021). *Reliability based adaptation of port infrastructure against climate change.* Delft: Delft University of Technology.

Schiereck, G. J. (2019). *Introduction to Bed, bank and shore protection.* Delft: Delft Academic Press/VSSD.

van Adrichem, S. (2021). *Influence of rapid drawdown on dike stability.*

van Dam, J. (2020). *Ontwerp duinenrij energie-opslagmeer.* Den Haag: De Haagse Hogeschool.

van der Meer, J. (2002). *Technical Report Wave Run-up and Wave Overtopping at Dikes.* Delft: Technical Advisory Committee on Flood Defence.

Van der Meer, J., Allsop, N., Bruce, T., De Rouck, J., Kortenhous, A., Pullen, T., . . . Zanuttigh, B. (2018). *Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application.* EurOtop. Retrieved from www.overtopping-manual.com

van Eeden, E. (2021). *A new dynamic landscape for the Haringvliet.* Technische Universtieit Delft, Master Landscape Architecture, Delft.

van Gent, M. (2019). Climate adaptation of coastal structures. *SCACR2019 - International Short Course/Conference on Applied Coastal Research.* Bari.

van Vliet, M., & Zwolsman, J. (2008, May 20). Impact of summer droughts on the water quality of the Meuse river. *Journal of Hydrology*(Volume 353, Issues 1-2), 1-17. doi:https://doi.org/10.1016/j.jhydrol.2008.01.001

Voorendt, M. (2015). *The development of the Dutch Flood Safety Strategy.* Amsterdam: Bee's Books.

Vrinds, T. (2021). *Adaptive design of flood defence systems.* Delft: Delft University of Technology.

Waterveiligheidsportaal. (2022, Juni). Retrieved from https://waterveiligheidsportaal.nl/#!/nss/nss/norm

Appendices

Appendix A: Flooding and failure probability determination

Flood protection is the number one priority in the design of the sea defence of the Delta21 project, in this subsection the safety requirement for the section of the sea defence is discussed. First the global protection strategy for the Netherlands is described, followed by possible failure mechanisms for sea defences and a description of the way flood defence reliability is determined. Using the safety strategy, location of the flood defence and coupling these to possible failure mechanisms, the failure probability per failure mechanism for the new sea defence will be determined.

The failure probability per failure mechanism is expressed as a return period of failure. From this return period the hydraulic boundary conditions as used in the design of the sea defence are determined.

A.1 Flood safety in the Netherlands

In the Dutch water law the flooding probability is describes as “the chance of loss of water retaining capacity of a dike section, causing the area protected by the dike section to be flooded, resulting in fatalities or substantial economic damage”.

Since the first of January 2017, the Dutch protection standard for all Dutch flood protection infrastructure is determined in the “*Wettelijk Beoordelings Instrumentarium 2017 (WBI2017)*” (Rijkswaterstaat, 2016). In this method it is determined that fatalities due to flooding should have a 10^{-5} chance of occurring per individual per year.

To accomplish this, the Dutch primary flood protection system is divided in different sections which are all assigned an individual flooding probability, the sections in the region of the Delta21 project including flooding probabilities are shown in figure A.1.

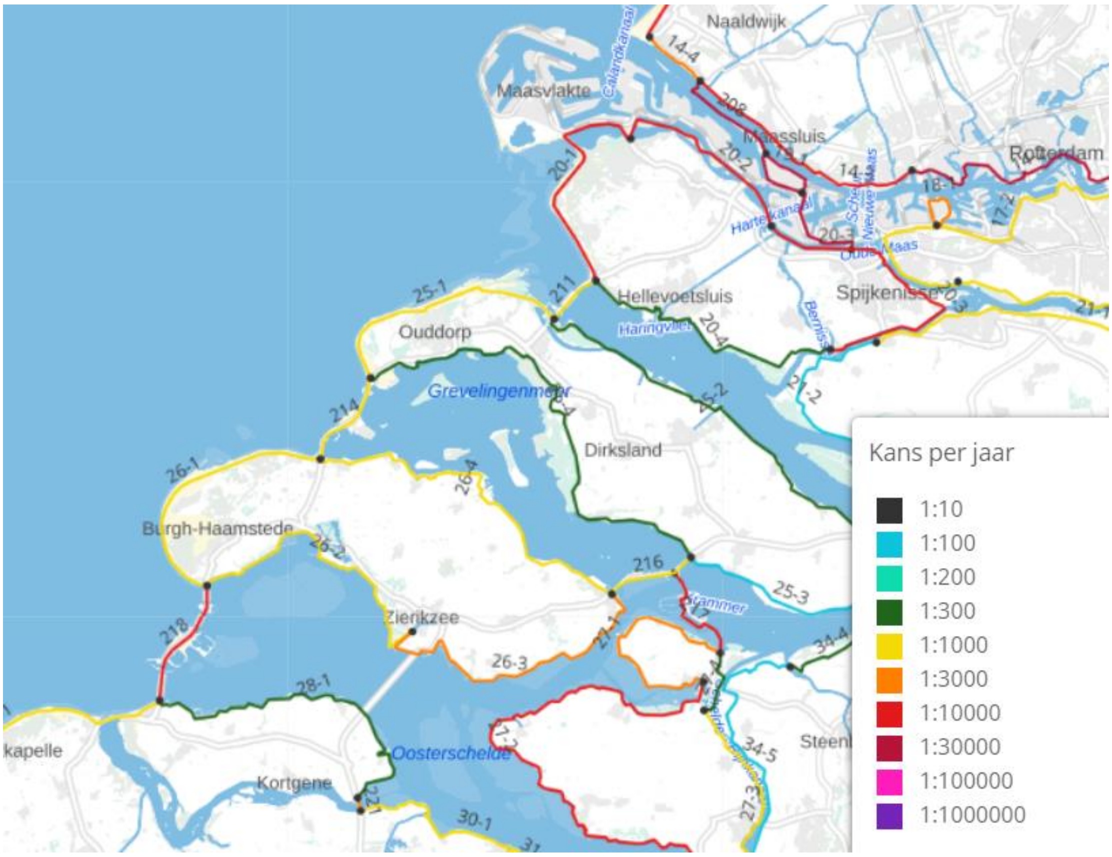


Figure A.1 Flooding probability of the various flood defence segments in the Dutch Southwest Delta (taken from waterveiligheidsportaal.nl) (Waterveiligheidsportaal, 2022)

Because of the lengthy nature of the larger dike sections (as shown in figure A.1), the character of these sections can be different on various locations along the section. Think about the presence of structures in a section or different soil profiles and hinterlands. Therefore the indicated dike sections are divided in smaller sections of which the flooding probabilities are assessed individually. These smaller sections can be regarded as a series of which the flooding probabilities together convert to the overall flooding probability of the main dike section.

This means that the flooding probability of a dike section is not dependent on the reliability of a single element but depends on the reliability of all elements combined. Some sections however do consist of one single element, like the Haringvliet barrier as indicated with section number 211 in figure A.1 which has a flooding probability of 1:1000.

A.2 Failure mechanisms

The flooding probabilities of the individual section elements are to be determined by the use of different failure mechanisms related to the dike section. In this thesis a design is made for a hard sea defence, therefore the failure mechanisms for structures and soft sea defences are not discussed here

Failure mechanisms for hard sea defences

The following failure mechanisms can be distinguished:

- Overflow or overtopping
- Upburst and piping
- Macro instability (both inwards and outwards)
- Damaged revetment and erosion

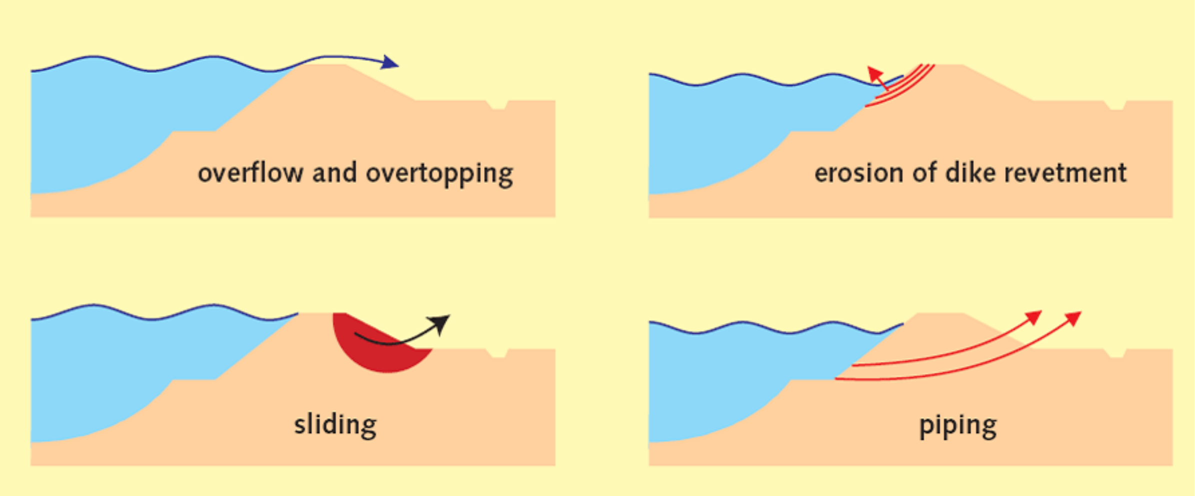


Figure A.2 failure mechanisms for dikes

Failure budget distribution in WBI2017

Above mentioned failure mechanisms play a role in the design and review of different dike sections. However not every failure mechanism is valued the same in the process. In the WBI2017 procedure the distribution of importance of failure mechanisms in the determination of the flooding probability is given, these values are shown in Table A.1 below.

Type of sea defence	**Failure mechanism**	**Type of section**	
		Sandy coast	**Other (dikes)**
Dike	Overtopping	0%	24%
	Upburst and piping	0%	24%
	Inward macro instability	0%	4%
	Damaged revetment and erosion	0%	10%
Structure	Failure of closure	0%	4%
	Piping	0%	2%
	Constructive failure	0%	2%
Dune	Dune erosion	70%	10%
Other		30%	20%
Total		**100%**	**100%**

Table A.1 Failure mechanisms and accompanying contribution to the over-all flooding probability of the dike section (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017)

The values given in Table A.1 above will be used to determine the maximum failure probability per failure mechanism for the sea defence section. In this thesis only the values for dikes (or other) are used, as sandy coasts are not considered.

A.3 The Delta21 sea defence

The new sea defence formed by the Delta21 project will form a new line of protection against both high water on the Rhine and Meuse as well as high water at the North Sea. The Delta21 project will be a replacement for the water retaining function of the Haringvliet Barrier, which will therefore no longer be considered a primary sea defence.

The total length of the sea defence of the Delta21 project is 28.5 km. This stretch of sea defence consists of 2 structures and 3 stretches of sandy coast or dike as indicated in figure A.3.

Figure A.3 overview of the new sea defence sections

It can be seen that only the outer edge of the Delta21 project is considered to be a primary sea defence. In this sea defence the following sections can be determined:

- Section 1:	13.5 kilometres
- Turbine station:	3 kilometres
- Section 2:	7 kilometres
- Storm surge barrier:	1 kilometre
- Section 3:	4 kilometres

Determination of the Delta21 sea defence flooding probability per failure mechanism

Using the “Handreiking ontwerpen met overstromingskansen” (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017), the flooding probability for the new sea defence is determined.

The failure probability per failure mechanism per cross-section of the sea defence will be determined using the following formula:

$$P_{dem,cs} = \frac{P_{max} * \omega}{N} \qquad \text{(formula A.1)}$$

In which:

$P_{dem,cs}$ = The failure probability per failure mechanism per cross-section of the sea defence

P_{max} = The maximum flooding probability for the dike segment per year

ω = maximum contribution of the failure mechanism in the failure probability (as given in table A.1)

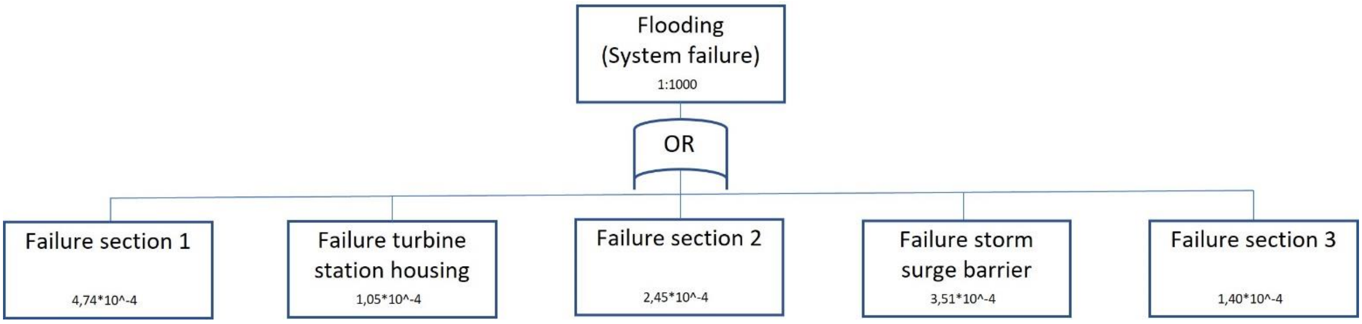
N = The length-effect factor [-]

In order to come to a maximum failure probability per failure mechanism per cross-section of the sea defence first he maximum allowable flooding probability for the dike segment per year should be determined.

A.4 Maximum flooding probability of the Delta21 sea defence sections

The Delta21 sea defence will be a new segment of primary sea defence which will take over this role from the Haringvliet barrier. In the current Dutch waterlaw or “Waterwet” in Dutch (Rijksoverheid, 2022) this barrier currently has a maximum yearly flooding probability of 1:1000. This maximum flooding probability will also be used in the design of the new Delta21 sea defence.

The distribution of failure over the different water retaining components is shown underneath. This distribution is determined by the lengthwise distribution of the components in the total sea defence.



A.5 Failure probability per failure mechanism per cross-section

Now the maximum flooding probabilities for the individual sections of the sea defence are known the failure probability per failure mechanism for the cross-section of the sections can be determined.

In this thesis the failure probability of the structures will not be regarded, therefore only sections 1, 2 and 3 will be discussed in the next section. Since the conceptual design handles both the possibilities for a sandy coast as well as a sea dike, failure probabilities for the failure mechanisms for both scenarios will be worked out.

For the scenario is which sea dikes are implemented, the failure probabilities for the following failure mechanisms will be discussed:

- Overtopping
- Upburst and piping
- Inward macro instability
- Damaged revetment and erosion

For the scenario is which a soft sea defence (or sandy coast) is implemented, only the failure mechanism "dune erosion" will be elaborated on.

Hard sea defence: Overtopping

In order to determine the crest height for a hard sea defence, overtopping is the leading failure mechanism. Therefore this failure mechanism is one of the most important factors during the conceptual design phase of the sea defence.

The failure probability caused by overtopping can be calculated using formula A.1 as mentioned in this appendix above. For overtopping the contribution of the failure mechanism in the overall failure probability of the segment (ω) is 0,24. The length factor is pre-determined in the "Handreiking ontwerpen met overstromingskansen" to be N = 2, this is the same length factor as used for the Haringvliet Barrier. Using formula A.1 the maximum failure probabilities for the different segments is calculated, the results of these calculations are shown underneath in table A.1 for dike segments 1, 2 and 3.

Segment	ω	N	Max. flooding probability	Max. failure probability due to overtopping
1	0.24	2	4.47E-04	5,36E-05
2	0.24	2	2.45E-04	2,94E-05
3	0.24	2	1.40E-04	1,68E-05

Table A.2 maximum failure probability due to overtopping

Hard sea defence: Inward macro stability

The failure probability caused by inward macro stability can also be calculated using formula A.1 as mentioned in this appendix. The contribution (ω) of the failure mechanism inward macro stability is 0.04.

The length factor can be determined using the following formula:

$$N = 1 + \frac{a * L_{traject}[m]}{b} \qquad \text{(formula A.2)}$$

With a = 0.033 and b = 50 for the inward macro stability failure mechanism (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017).

Using formula A.1 and A.2, the following failure probabilities due to inward macro stability can be found for segments 1 to 3.

Segment	ω	N	Max. flooding probability	Max. failure probability due to inward macro stability
1	0.04	9.91	4.47E-04	1.80E-6
2	0.04	5.62	2.45E-04	1.74E-6
3	0.04	3.64	1.40E-04	1.54E-6

Table A.3 maximum failure probability due to inward macro stability

Hard sea defence: Piping and heave

The failure probability caused by piping and heave can also be calculated using formula A.1 as mentioned in this appendix. The contribution (ω) of the failure mechanisms piping and heave is 0.24.

The length factor can again be determined using formula A.2 using a = 0.4 and b = 300 for piping and heave (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017).

Using formula A.1 and A.2, the following failure probabilities due to inward macro stability can be found for segments 1 to 3.

Segment	ω	N	Max. flooding probability	Max. failure probability due to piping and heave
1	0.24	19	4.47E-04	5.65E-6
2	0.24	10.33	2.45E-04	5.69E-6
3	0.24	6.33	1.40E-04	5.31E-6

Table A.4 maximum failure probability due to piping and heave

Hard sea defence: Damaged revetment

The failure probability caused by a damaged revetment can also be calculated using formula A.1 as mentioned in this appendix.

The length factor and contribution factor ω, appointed to this failure mechanism, are dependent on the type of revetment present on the sea defence. Since this thesis discusses a conceptual design, the type of revetment is not yet determined. Therefore the length effects and failure probabilities for the different revetment types is elaborated.

In total there are three types of top layers discussed in the "Handreiking ontwerpen met overstromingskansen": stone revetment, asphalt and grass top layer.

Stone revetment

For a stone revetment the contribution factor is determined to be 0.03 and the length factor is 4 (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017).

Using formula A.1, the following failure probabilities due to a damaged stone revetment can be found for segments 1 to 3.

Segment	ω	N	Max. flooding probability	Max. failure probability due to a damaged stone revetment
1	0.03	4	4.47E-04	3.35E-6
2	0.03	4	2.45E-04	1.84E-6
3	0.03	4	1.40E-04	1.05E-6

Table A.5 maximum failure probability due to a damaged stone revetment

Asphalt top layer

For an asphalt top layer the contribution factor is determined to be 0.10 and the length factor is again to be determined with the use of formula A.2 (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017).

The length factor can again be determined using formula A.2 using b = 1000 and a is the fraction of the length over which the asphalt top layer is present (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017). In table A.5 it is assumed that asphalt will be present on the entire stretch of sea defence.

Using formula A.1 and A.2, the following failure probabilities due to a damaged asphalt top layer can be found for segments 1 to 3.

Segment	ω	N	Max. flooding probability	Max. failure probability due to a damaged asphalt top layer
1	0.10	14.5	4.47E-04	3.07E-6
2	0.10	8	2.45E-04	3.06E-6
3	0.10	4	1.40E-04	3.5E-6

Table A.6 maximum failure probability due to a damaged asphalt top layer

Grass top layer

For grass top layers the maximum failure probability is to be determined using formula A.3 underneath (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017).

$$P_{dem,dsn} = \frac{P_{max} * \omega_B * \lambda_1 * \lambda_2}{N} \qquad \text{(formula A.3)}$$

In which:

$P_{dem,dsn}$ = The failure probability for a grass top layer

P_{max} = The maximum flooding probability for the dike segment per year

ω_B = contribution for revetment failure (as given in table A.1)

λ_1 = Part of failure distribution destined for failure of grass cover (0.5)

λ_2 = Part of failure distribution destined for failure because of grass erosion (0.9)

N = The length-effect factor for overtopping [-]

Using formula A.3 the maximum failure probabilities for the different segments is calculated, the results of these calculations are shown underneath in table A.6 for dike segments 1, 2 and 3.

Segment	ω	N	Max. flooding probability	Max. failure probability due to failure of the grass top layer
1	0.10	2	4.47E-04	1.01E-5
2	0.10	2	2.45E-04	5.51E-6
3	0.10	2	1.40E-04	3.15E-6

Table A.7 maximum failure probability of the transition between a hard and grassy top layer

Appendix B: Design wave height - extreme value analysis

In this appendix the wave height necessary for the design of the sea defence of the Delta21 project is determined using extreme value analysis of the wave data available at the Europlatform. The underlying dataset is downloaded through the website of Rijkswaterstaat Waterinfo (https://waterinfo.rws.nl).

The dataset includes the significant wave height H_s, the mean wave direction in degrees North and mean absolute wave period T_{m02} between 1990 and 2020 at the Europlatform in front of the new coastline, of which the location is shown in figure B.1.

Figure B.1 Location of the Europlatform with distance to the new coastline

B.1 Why the Europlatform dataset?

All data used in the analysis is extracted from the Europlatform dataset, since this is the closest deep water datapoint from the new Delta21 coastline with data available in the evaluated timeframe. The Europlatform has been collecting wave data since the year 1982, which makes it the oldest datapoint in the vicinity of the Delta21 project location.

On top of being the oldest available datapoint, the Europlatform lies directly in line with the direction of the dominant wave direction to the coast of the Delta21 project. All other available datapoints lay further to the south. The only available deep water datapoint to the north of the Europlatform with a dataset between 1990 and 2020 is at the IJmuiden munition deposit location in the North Sea, which is approximately 80 kilometres from the Europlatform and therefore not deemed representative for the wave conditions at the Delta21 project location.

After the analysis the received data has been checked by looking at other datapoints to see if the wave directions and amount of stormy days have similar characteristics. This is the case and therefore the analysed dataset is deemed sufficient for the goal of this thesis.

B.2 Dataset analysis

The first step of the determination of the design wave height is the analysis of the dataset. First the mean wave period Tm02 and mean wave direction are aligned against the significant wave height Hs. This way figures B.2 and B.3 are obtained.

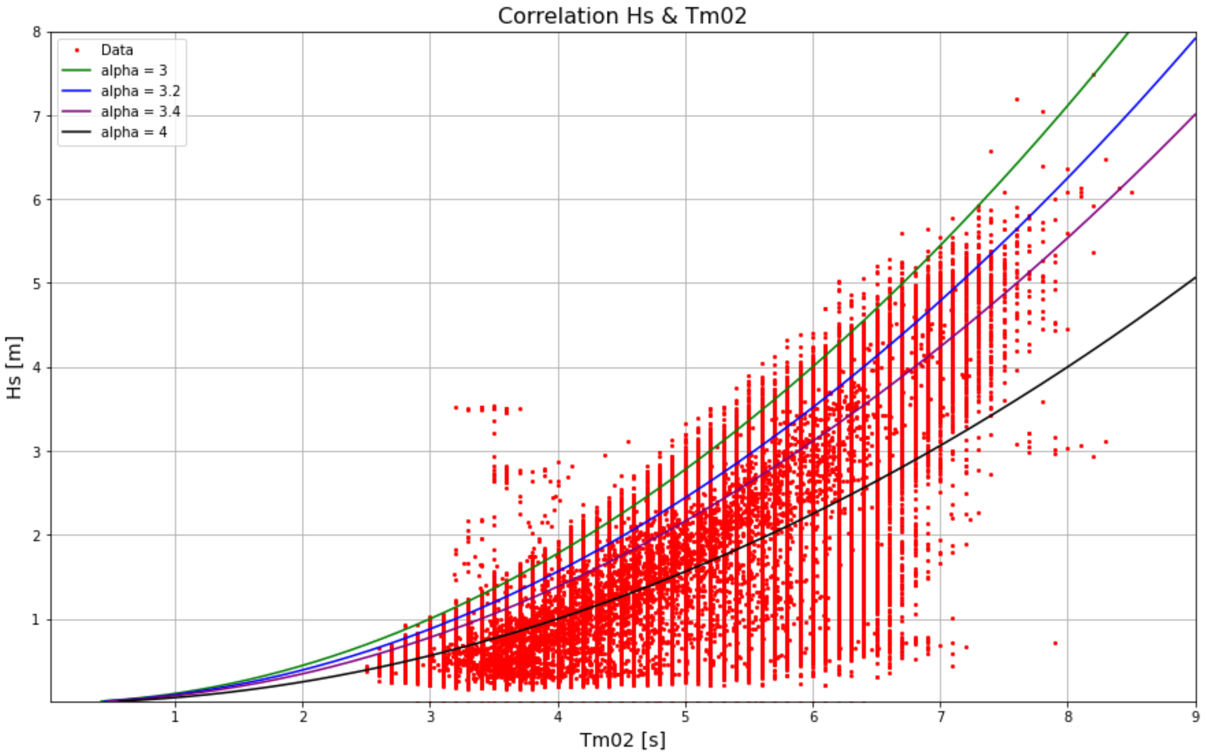


Figure B.2 Correlation between the mean wave period and significant wave height

Firstly the correlation between the significant wave height and the mean wave period is determined using an H,T-plot. The relation between the wave height and period can generally be described in the following form:

$$T_{m02} = \alpha\sqrt{H_s}$$

The curves belonging to α-values of 3, 3.2, 3.4 and 4 are shown in figure B.2, of these curves the α-value of 3.2 provides the best fit for the available dataset especially when looking at the higher values in the spectrum. Using this value, the wave period can be determined for the wave height with the required return period, acquired by the later executed extreme value analysis. Since the T_{m02} period only gives the mean wave period, and not the peak wave period as requested in the SwanOne program, this value has to be transformed further to T_p using the simple relationship (Bosboom & Stive, 2021):

$$T_p = \frac{T_{m02}}{0.7} \rightarrow T_p = \frac{\alpha\sqrt{H_s}}{0.7} = \frac{3.2\sqrt{H_s}}{0.7} = 4.57\sqrt{H_s}$$

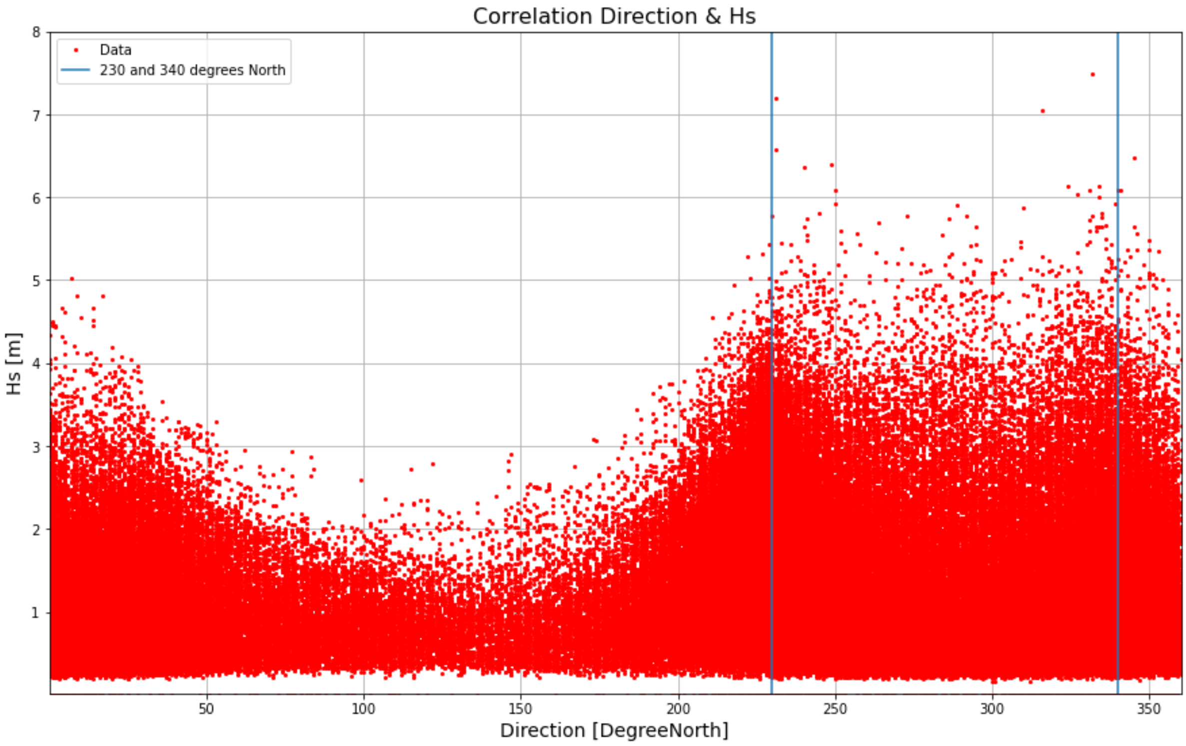


Figure B.3 Correlation between the wave direction and significant wave height

While evaluating the wave direction in combination with the significant wave height it can be seen that the majority of large waves occur between 230 and 340 degrees north with the largest wave density around the 330 or 340 degrees mark.

Since the new coastline orientation is approximately 330 degrees North normal to the coast, this will also provide the largest wave attack on the sea defence of the Delta21 project. It is assumed that the design waves will occur normally incident to the shore.

B.3 Extreme value analysis

After the evaluation of the dataset, it is further analysed to see what the behaviour in storm conditions looks like. First the dataset was filtered for storm conditions with a maximum occurring wave height, this was done using the peak-over-threshold analysis. During this process a storm is defined as a period of time in which all the waves exceed a defined threshold wave height. During this period only the highest wave is taken into account and by counting these waves the number of storms in the dataset can be determined.

Some storms will have wave heights occurring around the threshold level. When the wave heights get lower for a short period of time and then above the threshold again, this storm will be counted as multiple storms by the analysis software. In order to weed out the largest part of this error, it is defined that only one storm can occur per day.

The peak-over-threshold analysis was performed for thresholds of 4, 4.50 and 5 meters. The results of this analysis are shown in table B.4.

Threshold wave height	Number of stormy days per year
Hs > 4.00 m	9.53
Hs > 4.50 m	4.23
Hs > 5.00 m	1.73

Table B.1 number of storms per year for different thresholds

An example for the results of the peak-over-threshold analysis with a storm threshold of 4.50 meters is shown in figure B.4.

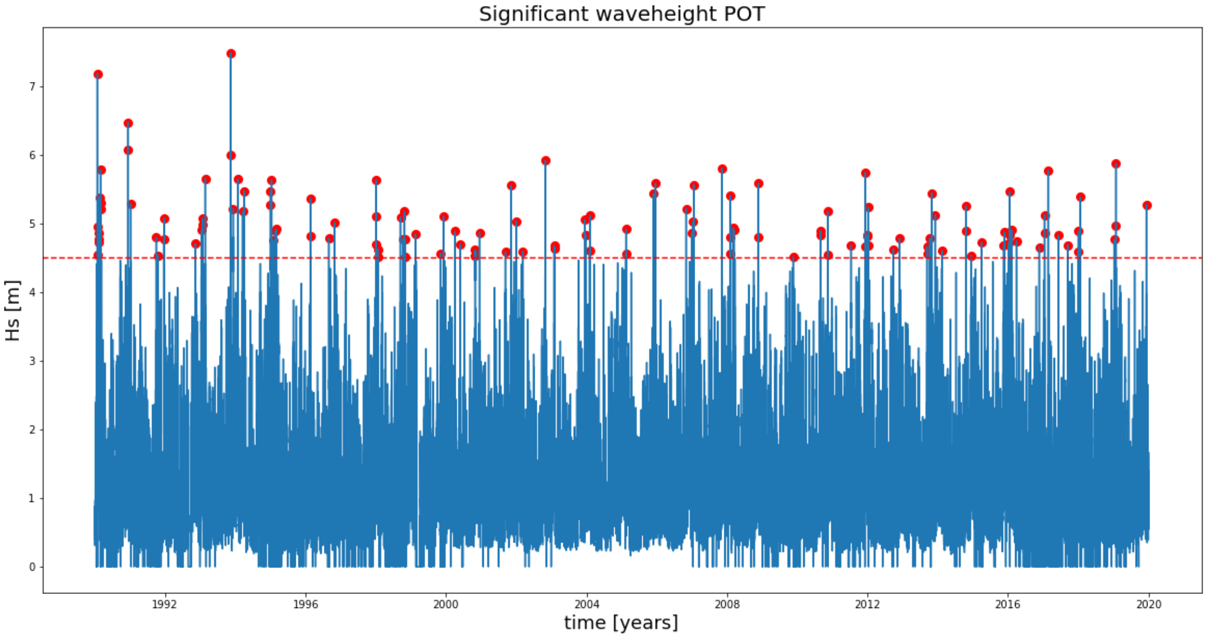


Figure B.4 Peak-over-threshold results for waves over 4.50 meters

B.4 Result of the extreme wave analysis

The results from the peak-over-threshold analysis are further analysed using extreme wave analysis via the method of moments. This way the distribution of the extremely high waves over time was determined. In this analysis a threshold value of 4.50 meters is used to represent stormy conditions at the Europlatform.

After the dataset consisting of storms with wave heights larger than 4.50 meters was created, the data was fit using the Exponential, Generalize Pareto, Weibull and Gumbel distributions. The results of this analysis are shown in table B.2 and figure B.5 underneath.

Distribution	Gamma	Beta	Alpha
Exponential	4.52	0.532	-
Generalized Pareto	4.5199	0.560	-0.0568
Weibull	4.5191	0.544	-0.0568
Gumbel	4.8512	0.313	-

Table B.2 Parameter outcomes for distribution fitting to the wave data

Of the fitted distributions, the Generalized Pareto distribution had the best fit with the data (determined using the Root Mean Square Error). Therefore the wave heights with large return periods will be determined using the following formula:

$$H_s = \gamma + \beta \left(\frac{Q^{-\alpha} - 1}{\alpha} \right)$$

With:

$Q = return\ period\ [years]$ $\beta = 0.560$

$\gamma = 4.5199$ $\alpha = -0.0568$

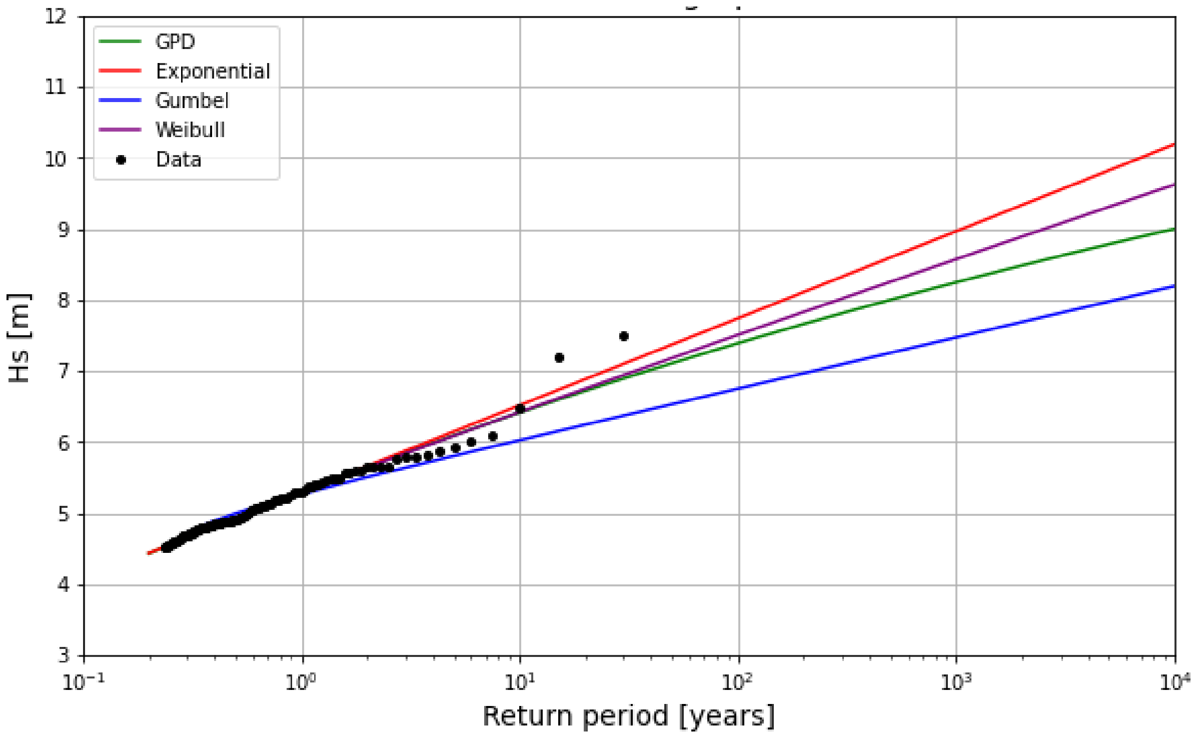


Figure B.5 Distribution fittings to extreme wave data

B.5 Deep water to shallow water propagation

The extreme value analysis gives the distribution of storm waves with the required return periods at the location of the Europlatform. This location however is approximately 44 kilometers from the project site of Delta21. In order to determine the design wave height at the toe of the Delta21 sea defence, SwanOne is used. Input for this model are the following:

- Bathymetry between the Europlatform and the toe of the Delta21 sea defence
- Direction of normal to the coast
- Water depth at the coast
- Wave height H_s for the required return period
- Corresponding wave period
- Mean wave direction
- Wind velocity
- Wind direction

In the determination of the design wave height at the toe, different design wave heights for the various return periods are calculated. In these calculations the bathymetry and direction of normal to the coast did not change, since these are independent of the return period of the waves. However the other variables will change with the various return periods. These variables are explained in chapter 4 of the main report.

The bathymetry between the Europlatform and the position of the new coastline is shown in figure B.5.

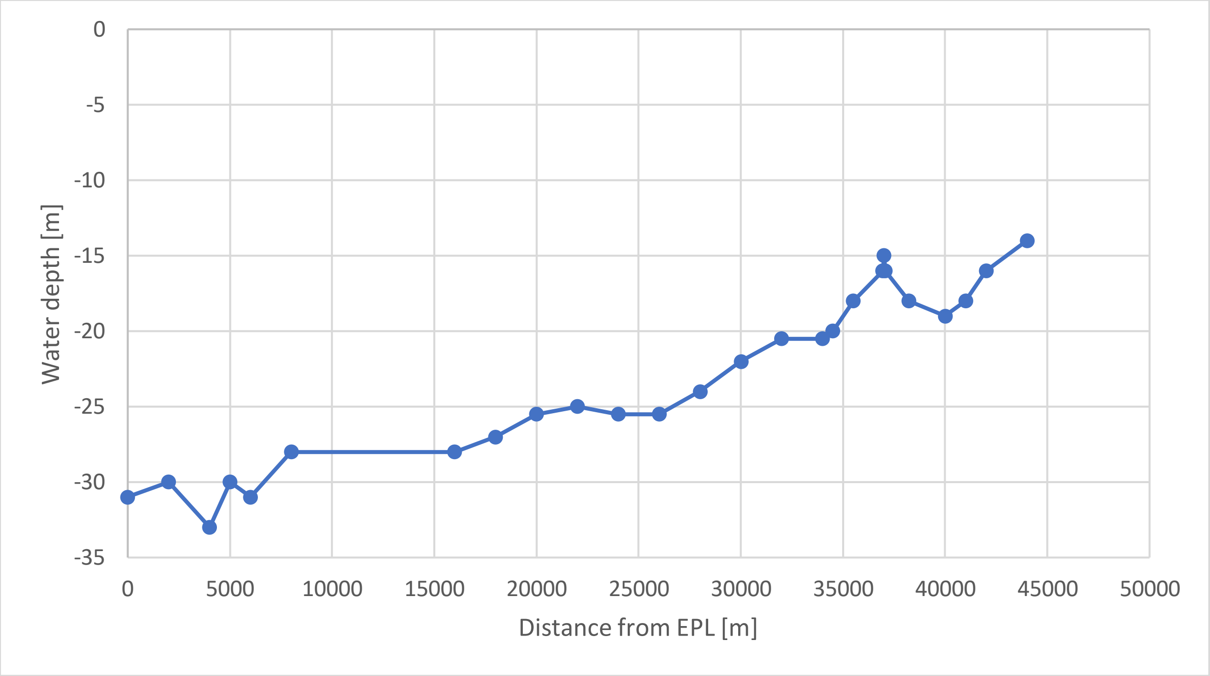


Figure B.6 Bathymetry between EPL and the position of the new coastline

In the table underneath the design wave heights at the toe of the sea defence are shown for different return periods.

Return period	**Depth at toe**	**H_s at EPL***	**T_p at EPL***	**Wave direction**	**Wind velocity**	**Wind direction**	**H_s at toe**
[years]	[m]	[m]	[s]	[° North]	[m/s]	[° North]	[m]
100	18.86	7.39	12.42	330	26.2	300	6.68
300	19.18	7.81	12.77	330	28.3	300	6.95
1000	19.55	8.24	13.12	330	30.5	300	7.21
2237	19.81	8.52	13.34	330	33.2	300	7.41
3000	19.90	8.62	13.41	330	34.9	300	7.51
10000	20.31	9.00	13.71	330	37	300	7.75
18656	20.52	9.18	13.85	330	38	300	7.87
22371	20.58	9.24	13.89	330	38.7	300	7.92
30000	20.69	9.32	13.95	330	39.2	300	7.97
33898	20.73	9.36	13.98	330	39.4	300	8.00
59523	20.93	9.52	14.10	330	40.3	300	8.09
100000	21.11	9.66	14.20	330	41.9	300	8.19

*Table B.3 Wave characteristics at the toe of the new sea defence for various return periods (*EPL = Europlatform)*

In the SwanOne calculation the standard values gamma = 3.3 and cos^m = 2 are used to define the JONSWAP spectrum.

These design wave heights are used in the conceptual design of the Delta21 sea defence.

B.6 Deep water to shallow water propagation after climate change

The rise of sea level is the most important consequence of climate change regarding the Delta21 sea defence. An elevated water level does not only result in a greater water depth, it also has an influence of the wave size at the toe of the new sea defence.

It is assumed that the return periods and wave heights for deep water waves at the location of the Europlatform does not change due to climate change. This assumption is supported by the fact that wind velocities will not get significantly larger due to the changing climate (KNMI, 2021), causing fetch induced waves to be equal in both situations. On top of that the assumption is made that the return periods for high water on the North Sea will also stay the same due to the same reasoning.

In table B.3 the hydraulic boundary conditions are determined while having a standard 1 meter of sea level rise in mind. However during the lifetime of the sea defence the amount of sea level rise can be up to 5 meters with large uncertainty. Therefore in tables B.4 to B.7 the wave height at the toe of the new sea defence is determined bearing in mind 2 to 5 meters of sea level rise.

Return period	**Depth at toe**	**H_s at EPL***	**T_p at EPL***	**Wave direction**	**Wind velocity**	**Wind direction**	**H_s at toe**
[years]	[m]	[m]	[s]	[° North]	[m/s]	[° North]	[m]
100	19.86	7.39	12.42	330	26.2	300	6.89
300	20.18	7.81	12.77	330	28.3	300	7.16
1000	20.55	8.24	13.12	330	30.5	300	7.46
2237	20.81	8.52	13.34	330	33.2	300	7.69
3000	20.90	8.62	13.41	330	34.9	300	7.79
10000	21.31	9.00	13.71	330	37	300	8.05
18656	21.52	9.18	13.85	330	38	300	8.17
22371	21.58	9.24	13.89	330	38.7	300	8.22
30000	21.69	9.32	13.95	330	39.2	300	8.28
33898	21.73	9.36	13.98	330	39.4	300	8.30
59523	21.93	9.52	14.10	330	40.3	300	8.40
100000	22.11	9.66	14.20	330	41.9	300	8.51

Table B.4 Wave characteristics at the toe of the new sea defence for various return periods with 2 meters of SLR

Return period	**Depth at toe**	**H_s at EPL***	**T_p at EPL***	**Wave direction**	**Wind velocity**	**Wind direction**	**H_s at toe**
[years]	[m]	[m]	[s]	[° North]	[m/s]	[° North]	[m]
100	20.86	7.39	12.42	330	26.2	300	7.01
300	21.18	7.81	12.77	330	28.3	300	7.42
1000	21.55	8.24	13.12	330	30.5	300	7.73
2237	21.81	8.52	13.34	330	33.2	300	7.96
3000	21.90	8.62	13.41	330	34.9	300	8.06
10000	22.31	9.00	13.71	330	37	300	8.34
18656	22.52	9.18	13.85	330	38	300	8.47
22371	22.58	9.24	13.89	330	38.7	300	8.51
30000	22.69	9.32	13.95	330	39.2	300	8.57
33898	22.73	9.36	13.98	330	39.4	300	8.60
59523	22.93	9.52	14.10	330	40.3	300	8.71
100000	23.11	9.66	14.20	330	41.9	300	8.81

Table B.5 Wave characteristics at the toe of the new sea defence for various return periods with 3 meters of SLR

Return period	**Depth at toe**	**H_s at EPL***	**T_p at EPL***	**Wave direction**	**Wind velocity**	**Wind direction**	**H_s at toe**
[years]	[m]	[m]	[s]	[° North]	[m/s]	[° North]	[m]
100	21.86	7.39	12.42	330	26.2	300	7.24
300	22.18	7.81	12.77	330	28.3	300	7.64
1000	22.55	8.24	13.12	330	30.5	300	7.96
2237	22.81	8.52	13.34	330	33.2	300	8.21
3000	22.90	8.62	13.41	330	34.9	300	8.31
10000	23.31	9.00	13.71	330	37	300	8.59
18656	23.52	9.18	13.85	330	38	300	8.73
22371	23.58	9.24	13.89	330	38.7	300	8.78
30000	23.69	9.32	13.95	330	39.2	300	8.84
33898	23.73	9.36	13.98	330	39.4	300	8.87
59523	23.93	9.52	14.10	330	40.3	300	8.98
100000	24.11	9.66	14.20	330	41.9	300	9.10

Table B.6 Wave characteristics at the toe of the new sea defence for various return periods with 4 meters of SLR

Return period	**Depth at toe**	**H_s at EPL***	**T_p at EPL***	**Wave direction**	**Wind velocity**	**Wind direction**	**H_s at toe**
[years]	[m]	[m]	[s]	[° North]	[m/s]	[° North]	[m]
100	22.86	7.39	12.42	330	26.2	300	7.35
300	23.18	7.81	12.77	330	28.3	300	7.81
1000	23.55	8.24	13.12	330	30.5	300	8.19
2237	23.81	8.52	13.34	330	33.2	300	8.46
3000	23.90	8.62	13.41	330	34.9	300	8.57
10000	24.31	9.00	13.71	330	37	300	8.83
18656	24.52	9.18	13.85	330	38	300	8.97
22371	24.58	9.24	13.89	330	38.7	300	9.03
30000	24.69	9.32	13.95	330	39.2	300	9.09
33898	24.73	9.36	13.98	330	39.4	300	9.13
59523	24.93	9.52	14.10	330	40.3	300	9.24
100000	25.11	9.66	14.20	330	41.9	300	9.37

Table B.7 Wave characteristics at the toe of the new sea defence for various return periods with 5 meters of SLR

In the graph in figure B.7 the development of the wave heights under the influence of sea level rise is shown graphically.

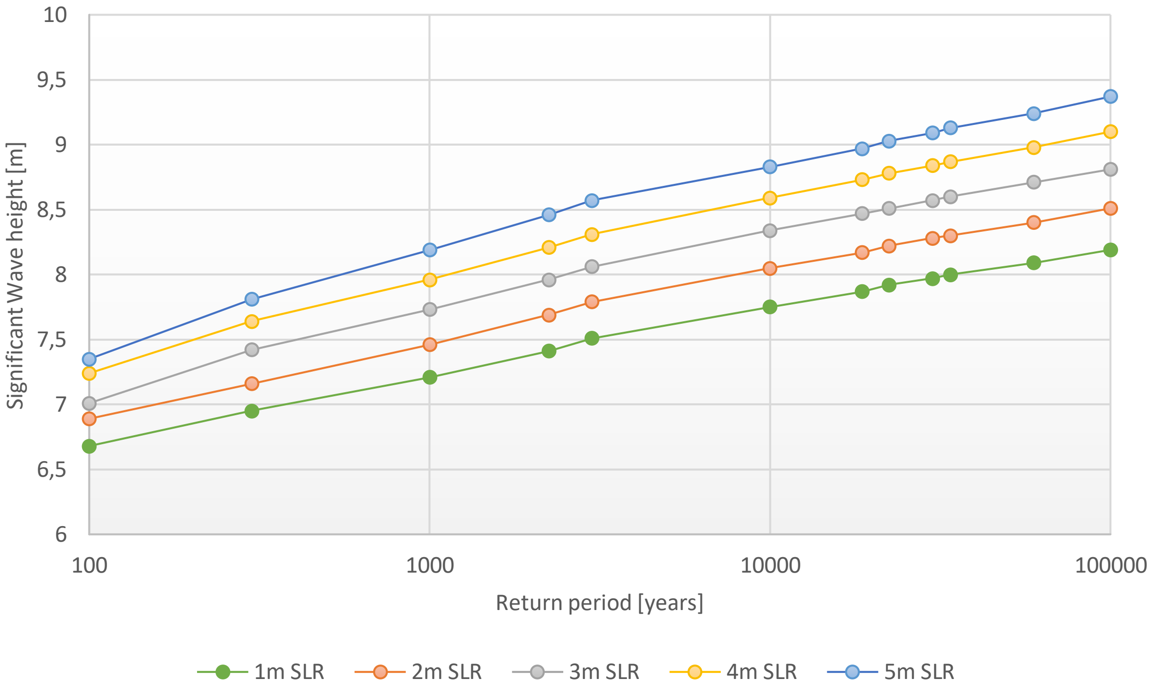


Figure B.7 The influence of sea level rise on the wave height at the toe of the sea defence

Appendix C: Static sea defence design

In this appendix the deterministic design of the Delta21 flood defence in the form of a static sea defence will be created. This will be done using the boundary conditions as determined in Chapter 4 of the main report and the design methodology as described in the WBI2017 methodology (Rijkswaterstaat, 2017).

During this conceptual design phase, the design will be made regarding the failure mechanism of overtopping. This methodology is chosen since this failure mechanism determines the overall design of the outer part of the dike; overtopping is a product of the crest height and the roughness, slope and presence of a berm at the outer section. On top of that overtopping has the largest contribution to the failure probability of the cross-section of the sea defence as determined in Section 3.3.4.

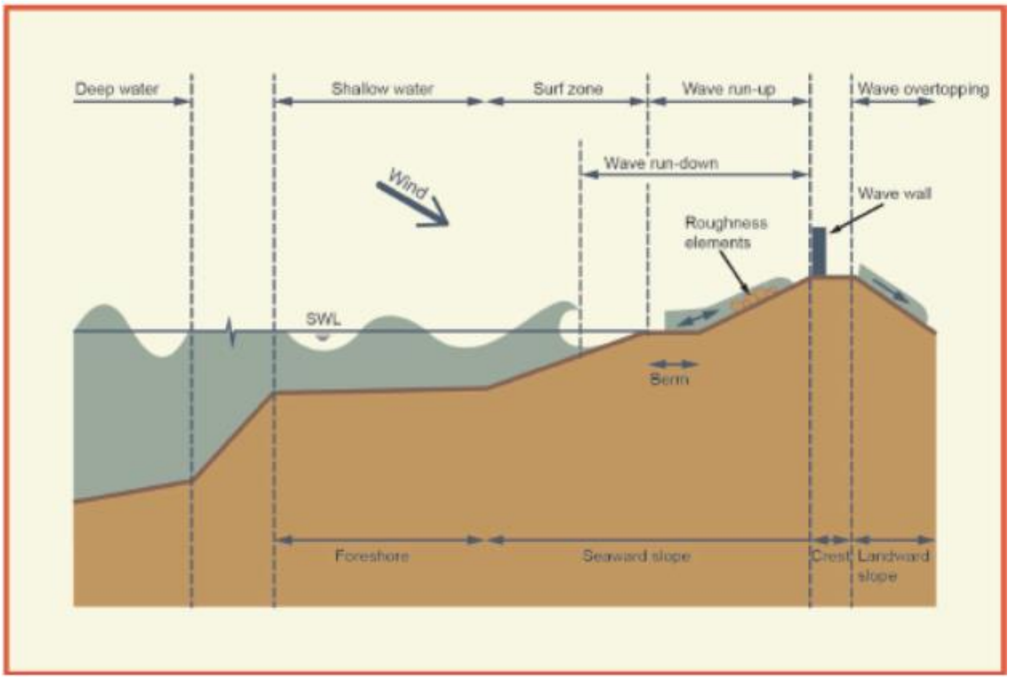


Figure C. 1 wave run-up and overtopping for coastal dikes: definition sketch (taken from the EurOtop overtopping manual) (Van der Meer, et al., 2018)

C.1 Overtopping formula and parameters

The overtopping of the Delta21 sea defence will be calculated using the deterministic overtopping formulas as given by Van der Meer in the Technical Report Wave Run-up and Wave Overtopping at Dikes (van der Meer, 2002).

$$\frac{q}{\sqrt{gH_s^3}} = \frac{0.067}{\sqrt{tan\alpha}} * \gamma_b * \xi_{m-1,0} * \exp\left(-4.3 * \frac{R_c}{H_s} * \frac{1}{\xi_{m-1,0}\gamma_b\gamma_f\gamma_\beta}\right) \tag{1}$$

With a maximum overtopping of:

$$\frac{q}{\sqrt{gH_s^3}} = 0.2 * \exp\left(-2.3 * \frac{R_c}{H_s} * \frac{1}{\gamma_f\gamma_\beta}\right) \tag{2}$$

In which:

$q = Average\ overtopping\ volume\ [l/s/m]$
$H_s = Significant\ wave\ height\ [m]$
$R_c = Crest\ height\ of\ the\ dam\ with\ respect\ to\ the\ still\ water\ line\ [m]$
$\alpha = Outer\ slope\ angle$
$\xi_{m-1.0} = Breaker\ parameter\ based\ on\ T_{m-1.0}$
$\gamma_b = Berm\ influence\ factor$
$\gamma_f = Roughness\ of\ elements\ on\ the\ slope$
$\gamma_\beta = Influence\ factor\ of\ angled\ wave\ attack$

This formula is used as probabilistic calculations are not in the scope of the thesis. In the deterministic formula the constant values (0,067 and 4,3 in C.1 and 0,2 and 2,3 in C.2) are altered one standard deviation from the mean value in order to be more conservative.

Static sea defence design parameters

As described in formulas 1 and 2, multiple parameters determine the amount of overtopping in of the design. The addition of a berm on the front slope of the design results in a berm influence factor γ_b, which not only takes into account the width of the berm but also the height with respect to the still water level. The top layer of the front slope influences the overtopping volume by the roughness, therefore these roughness is represented by the roughness coefficient γ_f. The angle of the outer slope is also represented in formulas 1 and 2.

In cases where the wave attack is not normal to the coast, the influence factor for angled wave attack γ_β also plays a role.

Berm influence factor

For the first conceptual design of the Delta21 sea defence it is assumed that the berm is situated at the height of the still water line as this is most effective as a counter measure against overtopping. Using the guidelines handed by EurOtop the berm influence factor can be calculated using: $\gamma_b = 1 - r_b(1 - r_{dh})$ (Van der Meer, et al., 2018).

In this calculation $r_b = \frac{B}{L_{berm}}$ with B the length of the berm and L_{berm} the length of the slope (over two significant wave heights) including the berm length.

The height of the berm with respect to the still water line is represented by the factor r_{dh}. For this factor three situations are determined:

$$r_{dh} = 0.5 - 0.5\cos\left(\pi\frac{d_b}{R_{u2\%}}\right) \qquad (5) \qquad \text{for a berm above still water line}$$

$$r_{dh} = 0.5 - 0.5\cos\left(\pi\frac{d_b}{2*H_{m0}}\right) \qquad (6) \qquad \text{for a berm below still water line}$$

Otherwise, $r_{dh} = 1$ for berms outside the area of influence.

Because of the fact that the berm is situated at the still water line in the first conceptual designs, $r_{dh} = 0$.

In this thesis, firstly, it is assumed that the berm is located at SWL. However due to the effects of climate change the sea level will increase and therefore the berm will be located below SWL during some situations.

Roughness of elements on the slope and berm

In this case the outer slope of the closure dam is build up out of two slopes, the upper and lower slope. Both slopes can be build up out of different elements which do not have the same roughness. On top of that the top layer of the berm can have a different roughness as well. The roughness of the various different parts of the slope does not have an equal effect on the run-up and overtopping, in fact the roughness of the upper section has the most effect while the roughness of the lower slope has least effect (Chen, Van Gent, Warmink, & Hulscher, 2020).

The roughness coefficient for a slope with different elements can be calculated using the following formula (Van der Meer, et al., 2018):

$$\gamma_f = \frac{\alpha_1 * \gamma_{f1} * L_1 + \alpha_2 * \gamma_{f2} * L_2 + \alpha_2 * \gamma_{f3} * L_3}{\alpha_1 * L_1 + \alpha_2 * L_2 + \alpha_3 * L_3} \qquad (7)$$

In which:

L_1 = length of slope until -0.25$z_{2\%}$ under the water line ($\sqrt{(1.5H_s * 0.25)^2 + (tan\alpha * 1.5H_s * 0.25)^2}$)
L_2 = length of the berm
L_1 = length of slope until +0.5$z_{2\%}$ above the water line ($\sqrt{(1.5H_s * 0.5)^2 + (tan\alpha * 1.5H_s * 0.5)^2}$)

And the three different α_n factors are the influence factors of the position of the roughness elements on the overall outer slope ($\alpha_1 = 0.13$, $\alpha_2 = 0.22$ and $\alpha_3 = 0.65$). The roughness elements on the upper part of the outer slope have more influence on overtopping than the roughness elements on the lower slope and berm (Chen, Van Gent, Warmink, & Hulscher, 2020).

Using formula 7 the roughness of the outer slope can be determined, however the use of material for the outer slope will have large consequences in this determination. For example the use of an asphalt top layer will result of a roughness coefficient of $\gamma_f = 1$, but the use of Xbloc elements can result in an optimal roughness of $\gamma_f = 0.44$ for the slope on which the elements are placed.

In this thesis, two types of outer slope are considered, all of these consider a berm with an asphalt top layer. However the top layer (and therefore roughness) of the upper and lower slope differs:

1. An outer slope with both the upper and lower slope build up from interlocking armour units. In this thesis Xbloc are considered which have a roughness coefficient of $\gamma_f = 0.44$ (Delta Marine Consultants, 2018).

2. An outer slope fully covered in an asphalt top layer, the overall roughness for the entire outer slope will then be $\gamma_f = 1$ (Deltares, 2015).

Since the roughness of the entire outer slope is a function of roughness and the length of the separate sections of the front slope, the overall roughness depends on the width of the berm, top layer of the slopes and slope angles. Therefore the roughness coefficient differs for every considered design variant.

The use of a placed block revetment

Using a density of 2500 kg/m^3 for the placed block revetment, a first indication of the required height of the placed block revetment can be calculated using formula 8:

$$\frac{H_s}{\Delta D} = 5 \qquad (8) \qquad \text{(Deltares, 2015)}$$

In which:

H_s	=	Significant wave height	[m]
Δ	=	Relative density of the top layer elements	[-]
D	=	Thickness of top layer (height of top layer elements)	[m]

This would require a placed stone revetment with a top layer thickness of $D = \frac{H_s}{5\Delta} = \frac{7.87}{5*1{,}43} = 1.09$ m.

The use of placed block revetments is not included in this study as these would need to be unreasonably large due to the large significant wave height.

Influence factor of angled wave attack

In the case that the wave attack obliquely incident to the sea defence, the wave run-up and therefore overtopping are reduced compared to a situation in which the waves are normally incident. However, in the case of the Delta21 sea defence the normative angle of wave attack is normally incident to the sea defence, therefore $\gamma_\beta = 1$.

Slope angle

The last parameter which has an influence on the overtopping of the Delt21 sea defence is the slope angle of the outer slope. In this case multiple slope angles have been implemented, namely 1:1.5, 1:2, 1:3 and 1:4.

Crest walls and other structures

In the design of the Delta21 sea defence the use of structural elements is not regarded, therefore the crest wall reduction factor γ_v is not taken into account in Formula 1.

C.2 Most important boundary conditions for the Delta21 sea defence

The Delta21 sea defence is part of the primary sea defence of the Netherlands and is located in the Dutch Southwest delta. From the Maasvlakte 2 it stretches into the North Sea in an area where the current water depth is approximately 14 meters.

The flooding probability of the total Delta21 project is set to be 1:1000, from there follows that the return period corresponding to failure probability for the failure mechanism overflow is 18656 years. Therefore the sea defence will be designed for an H_s of 7,87 meters and a SWL of NAP + 6,52 m.

One of the requirements for the Delta21 sea defence as stated in the program of requirements is that the sea defence should fit into the landscape. Since at the moment the project location is purely open sea, this is a tough requirement to meet. The Delta21 sea defence will reach into the North Sea from the Maasvlakte 2, here sea a sea defence is present with maximum crest heights between NAP + 13 m and NAP + 16 m. Since no restrictions in crest height are given and the lack of room for the defence is not an issue, it seems logical to have crest heights in line with those present at Maasvlakte 2. Therefore crest heights until NAP + 16 m are considered.

C.3 Allowable overtopping

The acceptable amount of overtopping is determined by various parameters on - and in the surroundings of - the sea defence. The first parameter is the material which is used to create the inner slope of the defence, however the presence and position of vehicles, people and material on and behind the dike can also influence the tolerable amount of overtopping.

In the case of the Delta21 sea defence it is assumed that there are no vehicles or people present on the sea defence during storm conditions. Therefore the tolerable amount of overtopping is solely determined by the material used to create the inner slope op the sea defence. In this thesis two distinct variants are created:

1. the use of only a clay top layer with grass coverage
2. the use of asphalt topped by a soil and grass layer

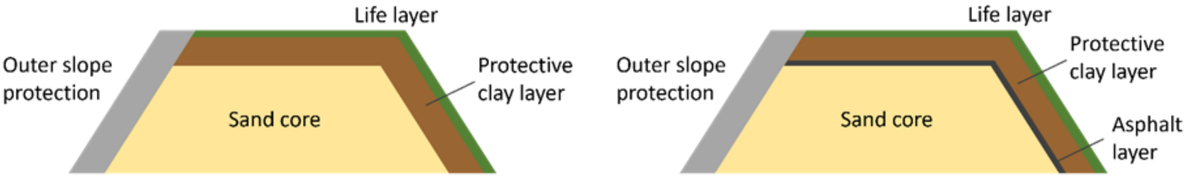


Figure C.1 Schematic representation of crest types 1 and 2

The use of only a clay top layer with grass coverage

In this situation the inner slope of the sea defence is build up out of a clay layer which is covered in grass. Since the erodibility of the grass top layer is the only factor determining the allowable overtopping discharge, the allowable overtopping discharges according to the EuroTop Overtopping Manual is used. This document states that the maximum allowable overtopping discharge for well-kept, closed grass covers is 5 l/s/m (Van der Meer, et al., 2018). It is assumed that the grass-cover of the inner side of the Delta21 sea defence is closed and well-kept since this is a primary sea defence for the Netherlands.

The use of asphalt topped by a soil and grass layer.

When making use of an asphalt layer underneath a thin layer of soil and grass, only the asphalt underneath the toplayer has a function in water safety. While the top soil layer can erode quite easily during normative storm conditions, the asphalt bottom layer has very high resistance against erosion. At slope angles of 1:6 and less steep, overtopping discharges up to 1000 l/s/m can be handled. However for dikes with a slope of 1:3 and steeper, only overtopping discharges until 125 l/s/m are tested (Deltares, 2015). At these discharges the asphalt top layer did not erode, therefore a maximum overtopping discharge of 125 l/s/m is assumed for the Delta21 sea defence.

Since 125 l/s/m of overtopping is a significant amount, it is necessary to check if the volume of water coming in to the energy storage lake is not larger than the pump capacity of the turbine station. When assuming water coming in over sections 1, 2 and the turbine station, a total length of 23,5 kilometres will be overtopped. For an overtopping discharge of 125 l/s/m this means that 2937,5 m^3 of water enters the energy storage lake every second. Since the turbine station capacity is 10.000 m^3/s this amount of overtopping can be stored in the energy storage lake.

C.4 Parametric design of the static Delta21 sea defence

In the previous section of this appendix, the parameters determining the amount of overtopping for sea dikes are elaborated on. In this section multiple designs of the Delta21 sea defence are created; using different slope angles, berm widths, crest heights, roughness elements and an inner slope lined with grass or asphalt.

At the end of this assessment the different variants are selected on the amount of material in the cross-section of the sea defence, the length of the outer slope of the sea defence and the roughness of the elements on the front slope of the sea defence.

In Appendix D: Sea defence design concepts for overtopping, all considered possible variants for the conceptual design of the Delta21 sea defence for the failure mechanism overtopping are listed.

Design variant verification

As mentioned above multiple possible design variants are considered regarding the conceptual design of the Delta21 sea defence. In order to come to the preferable conceptual design variant multiple selection criteria have been established, being:

- Maximum crest height
- Preferred slope angle per revetment type
- Outer slope length
- Cross-sectional volume per meter of sea defence

Maximum crest height

The maximum crest height for the Delta21 sea defence primary design concept is NAP + 16 m. This is the maximum occurring crest height of the sea defence on Maasvlakte 2 and therefore already present in the direct vicinity of the new sea defence.

Preferred slope angle per revetment type

In this conceptual design phase only two types of revetments are regarded: asphalt and interlocking armour units.

For asphalt slopes the maximum slope angle is 1:3 for asphalt concrete in the water overpressure zone (Deltares, 2015). Therefore asphalt slopes steeper than 1:3 are disregarded from this design phase.

The use of concrete armour units requires steep slopes in order to get maximum stability for units with low weight. For Xbloc the slope preferably is 2:3 (or 1:1.5) or steeper for maximum stability, however stability can also be guaranteed by applying heavier units for less steep slopes (Delta Marine Consultants, 2018). Because of the increase in costs per armour units for less steep slopes, steeper slopes are preferred in this study.

Outer slope length

Generally speaking, the costs for the sea defence can be reduced by reducing the necessity of revetments. In the case of the Delta21 sea defence the outer slope will be fully covered in revetment (either asphalt or concrete armour units). Therefore in this case the length of the outer slope is preferred to be small.

Cross-sectional volume per meter of sea defence

In the case of the Delta21 sea defence a large part of the dike will be created with sand. Since in every building project a part of the costs are in the amount of building materials, this should amount should preferably be as small as possible. However due to the dredging activities for the creation of the energy storage lake, sand is a highly available building material available for the creation of the sea defence. Therefore the cross-sectional volume per meter of sea defence is less important than the length of the outer slope revetment or the steepness of the slope.

A sea defence with a grass top layer

In the design of a sea defence with a grass top layer only, it is assumed that this grass top layer is in good conditions and well kept. This is because of the fact that the Delta21 sea defence is a primary sea defence in the Netherlands. Under these conditions the tolerable amount of overtopping is 5 l/s/m (van der Meer, 2002).

As mentioned, multiple variables have been considered in order to come to the first conceptual design of the Delta21 sea defence. During the design process an analysis has been conducted to review the impact of the different variables on overtopping.

In table C.1 an overview is created in which all possible variants of a sea defence with a grass covered inner slope and a maximum crest height of NAP + 16 m are shown.

Design nr.	Slope angle	Berm width	Crest height	Overtopping discharge	Cross-sectional volume	Outer slope length
[-]	[-]	[m]	[NAP+m]	[l/sm]	[m^2/m]	[m]
28	1:3	24	16	4.89	3312,48	118,87

Table C.1 Overtopping discharges for a sea defence with a grassy inner slope and an outer slope with interlocking armour units (γf=0.44)

Sea defence variant 1

Using the criteria of outer slope length and steepness of the concrete armour unit slope, design number 28 as shown in table C.1 above has been selected to be the preferable conceptual design for the Delta21 sea defence with an inner slope with solely a grass top layer.

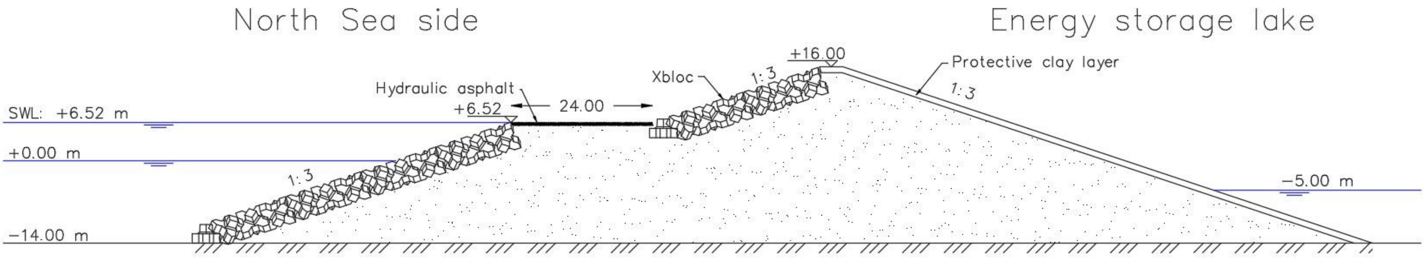


Figure C. 2 Cross-sectional profile of design variant 1

A sea defence with an aspalt layer, topped by grass

The tolerable overtopping discharge for a sea defence with an asphalt layer is higher than that for a sea defence with only a grass top layer. Since the grass top layer can erode quite easily, in this design the choice is made for an inner side build up out of different layers. Above the core there first is an asphalt layer, which is topped by a soil layer on which grass grows. The grass top layer has no function for water safety, this function is fulfilled by the asphalt layer underneath.

Tests have been conducted for asphalt layers to withstand 125 l/s/m of overtopping (Deltares, 2015) and it is assumed that the water retaining function of the energy storage lake is large enough. Therefore 125 l/m/s is considered to be the tolerable amount of overtopping for the Delta21 sea defence with an asphalt inner slope.

In tables C.2 and C.3 an overview is created in which all possible variants of a sea defence with an asphalt covered inner slope and a maximum crest height of NAP + 16 m are shown.

Sea defence design variant 2

The outer slope of the sea defence is fully covered in asphalt and therefore the maximum steepness of this outer slope is 1:3.

Design nr.	Slope angle	Berm width	Crest height	Overtopping discharge	Cross-sectional volume	Outer slope length
[-]	[-]	[m]	[NAP+m]	[l/sm]	[m^2/m]	[m]
19	1:3	31.5	14.5	124.83	3196,72	121,62
20	1:3	28	15	122.45	3213,56	119,71
21	1:3	22	16	117.71	3271,44	116,87
28	1:4	33	13	123.39	3336,66	144,32
29	1:4	23	14	119.57	3327,96	138,45
30	1:4	18	14.5	124.37	3326,24	135,51
31	1:4	15	15	116.80	3367,30	134,57
32	1:4	8	16	118.74	3434,16	131,69

Table C.2 Overtopping discharges for a sea defence with an asphalted inner and outer slope

Since the length of the outer slope is more important than the maximum cross-sectional volume per meter of sea defence, the preferred design variant is design number 21 as shown in table C.2 above.

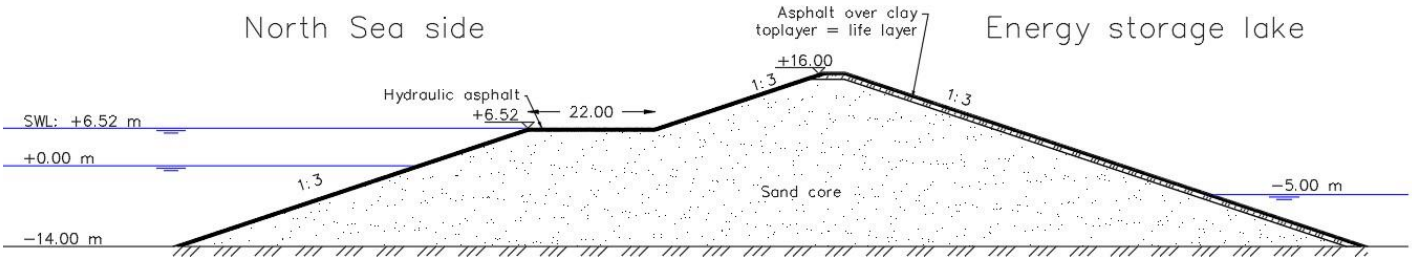


Figure C. 3 Cross-sectional profile of design variant 2

Sea defence design variant 3

In design variant 3, the outer slope of the sea defence is covered in interlocking armour units and therefore the steepness of the slopes is preferred to be at least 2:3 (or 1:1.5). Design number 37 as shown in table C.3 below is the preferred design variant in this case, since this variant has the shortest outer slope length of the variants making use of a 2:3 (or 1:1.5) slope.

Design nr.	Slope angle	Berm width	Crest height	Overtopping discharge	Cross-sectional volume	Outer slope length
[-]	[-]	[m]	[NAP+m]	[l/sm]	[m^2/m]	[m]
35	1:1,5	33	14.5	118.70	2618,72	84,38
36	1:1,5	29	15	120.80	2603,33	81,28
37	1:1,5	23	16	115.94	2616,96	77,08
43	1:2	25	14	119.72	2585,00	87,61
44	1:2	20	14.5	122.13	2555,03	83,73
45	1:2	16	15	119.54	2546,82	80,85
46	1:2	8	16	118.54	2534,16	75,08
48	1:3	23	12	122.68	2603,96	105,22
49	1:3	3	13	122.89	2356,56	88,38
50	1:3	0	14	64.77	2464,00	88,54

Table C.3 Overtopping discharges for a sea defence with an asphalted inner slope and an outer slope with interlocking armour units (γf=0.44)

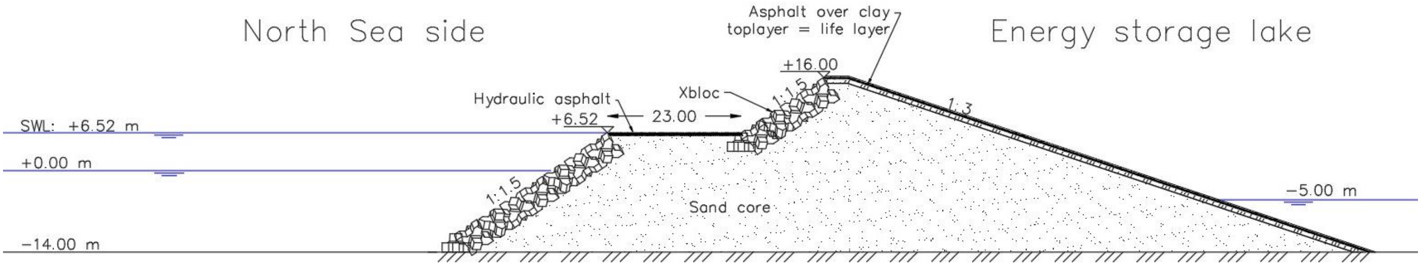


Figure C. 4 Cross-sectional profile of design variant 3

Delta21 sea defence conceptual design variants

In total three separate conceptual design variants are created for the Delta21 sea defence. The details of each of the variants are shown in table C.4 underneath.

Design variant:		**Variant 1**	**Variant 2**	**Variant 3**
Crest height:	[m+NAP]	16	16	16
Crest width:	[m]	4	4	4
Berm width:	[m]	24	22	23
Berm height:	[m+NAP]	6,52	6,52	6,52
Slope angle:	[-]	1:3	1:3	1:1,5
Inner slope type:	[-]	Clay	Clay over Asphalt	Clay over Asphalt
Outer slope type:	[-]	I.A.U.*	Asphalt	I.A.U.*
Cross-sectional volume:	[m^3/m]	3312,48	3271,44	2616,96
Outer slope length:	[m]	118,87	116,87	77,08

Table C.4 Overview of the conceptual design variants **Interlocking Armour Units*

Appendix D: Sea defence design concepts for overtopping

This appendix is an addition to the main report of the thesis and Appendix C: Static sea defence design. In that appendix the design of the Delta21 sea defence is regarded, including the methodology. This appendix presents the possible sea defence variants which all meet the set overtopping discharge requirements.

The first section presents the static sea defence variant with a clay and grass inner slope. The second section regards the sea defence variant with an inner slope covered in asphalt topped by a clay and grass layer.

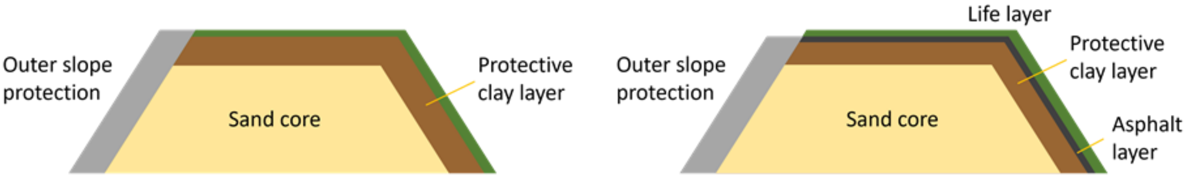


Figure D. 1 Schematic representation of crest types 1 and 2

A sea defence with a grass-over-clay top layer on the inner slope

Tables D.1 and D.2 underneath both present the geometries of sea defence variants with a grass over clay inner slope.

Table D.1 regards sea defence variants with an outer slope fully covered in asphalt, which gives this variant a roughness of γf=1. Table D.2 presents sea defence variants with an outer slope of which the berm is covered in asphalt, but the slopes are covered in interlocking armour units. These interlocking armour units have a roughness of γf=0.44.

Design nr.	Slope angle	Berm width	Crest height	Crest width	Overtopping discharge	Cross-sectional volume	Outer slope length
[-]	[-]	[m]	[NAP+m]	[m]	[l/sm]	[m^2/m]	[m]
1	1:2	33	24	4	4.43	4439,16	117,97
2	1:2	30	25	4	4.37	4574,10	117,21
3	1:3	35	20	4	4.82	4322,20	142,52
4	1:3	30	21	4	4.81	4430,60	140,68
5	1:3	26	22	4	4.58	4565,52	139,84
6	1:3	22	23	4	4.61	4706,44	139,00
7	1:3	18	24	4	4.92	4853,36	138,17
8	1:3	15	25	4	4.83	5026,80	138,33
9	1:4	33	18	4	4.99	4389,16	164,94
10	1:4	27	19	4	4.62	4497,54	163,06
11	1:4	21	20	4	4.66	4612,92	161,19
12	1:4	16	21	4	4.59	4755,82	160,31
13	1:4	11	22	4	4.85	4905,72	159,43
14	1:4	7	23	4	4.85	5083,14	159,55
15	1:4	4	24	4	4.51	5288,08	160,68
16	1:4	1	25	4	4.37	5500,02	161,80

Table D. 1 Overtopping discharges for a sea defence with a grassy inner slope and outer slope with no roughness (γf=1)

Design nr.	Slope angle	Berm width	Crest height	Crest width	Overtopping discharge	Cross-sectional volume	Outer slope length
[-]	[-]	[m]	[NAP+m]	[m]	[l/sm]	[m^2/m]	[m]
17	1:1,5	31	21	4	4.68	3532,37	94,10
18	1:1,5	26	22	4	4.93	3593,52	90,90
19	1:1,5	22	23	4	4.88	3679,69	88,70
20	1:1,5	19	24	4	4.46	3790,88	87,51
21	1:1,5	15	25	4	4.78	3886,05	85,31
22	1:2	28	19	4	4.94	3429,06	101,79
23	1:2	22	20	4	4.75	3477,44	98,03
24	1:2	16	21	4	4.79	3530,82	94,26
25	1:2	10	22	4	4.95	3589,20	90,50
26	1:2	4	23	4	4.98	3652,58	86,73
27	1:2	0	24	4	3.97	3762,00	84,97
28	1:3	24	16	4	4.89	3312,48	118,87
29	1:3	11	17	4	4.82	3232,72	109,03
30	1:3	0	18	4	3.67	3200,00	101,19
31	1:4	21	14	4	4.83	3266,40	136,45
32	1:4	7	14.5	4	4.96	3100,52	124,51
33	1:4	0	15	4	3.60	3059,50	119,57

Table D. 2 Overtopping discharges for a sea defence with a grassy inner slope and outer slope with interlocking armour units (γf=0.44 for the slopes, γf=1 for the berm)

A sea defence with an aspalt layer, topped by grass on the inner slope

Tables D.3 and D.4 underneath both present the geometries of sea defence variants with an inner slope covered in asphalt with a grass over clay top layer..

Table D.3 regards sea defence variants with an outer slope fully covered in asphalt, which gives this variant a roughness of γf=1. Table D.4 presents sea defence variants with an outer slope of which the berm is covered in asphalt, but the slopes are covered in interlocking armour units. These interlocking armour units have a roughness of γf=0.44.

Design nr.	Slope angle	Berm width	Crest height	Crest width	Overtopping discharge	Cross-sectional volume	Outer slope length
[-]	[-]	[m]	[NAP+m]	[m]	[l/sm]	[m^2/m]	[m]
1	1:1,5	31.5	18	4	122.37	3077,97	89,19
2	1:1,5	28	19	4	121.05	3156,81	87,49
3	1:1,5	25	20	4	119.27	3250,00	86,29
4	1:1,5	22	21	4	122.80	3347,69	85,10
5	1:1,5	20	22	4	116.45	3470,40	84,90
6	1:1,5	18	23	4	113.65	3597,61	84,70
7	1:1,5	16	24	4	114.20	3729,32	84,51
8	1:1,5	14	25	4	118.16	3865,53	84,31
9	1:2	35	16	4	119.05	3088,20	102,08
10	1:2	30	17	4	117.17	3142,10	99,32
11	1:2	25	18	4	124.11	3201,00	96,55
12	1:2	22	19	4	115.40	3305,94	95,79
13	1:2	19	20	4	112.05	3415,88	95,03
14	1:2	16	21	4	113.65	3530,82	94,26
15	1:2	13	22	4	120.48	3650,76	93,50
16	1:2	11	23	4	116.80	3796,22	93,73

17	1:2	9	24	4	116.56	3946,68	93,97
18	1:2	7	25	4	119.76	4102,14	94,21
19	1:3	31.5	14.5	4	124.83	3196,72	121,62
20	1:3	28	15	4	122.45	3213,56	119,71
21	1:3	22	16	4	117.71	3271,44	116,87
22	1:3	16	17	4	123.53	3335,32	114,03
23	1:3	12	18	4	117.47	3446,24	113,19
24	1:3	8	19	4	118.38	3563,16	112,36
25	1:3	5	20	4	113.40	3706,60	112,52
26	1:3	2	21	4	113.46	3856,04	112,68
27	1:3	0	22	4	104.67	4032,00	113,84
28	1:4	33	13	4	123.39	3336,66	144,32
29	1:4	23	14	4	119.57	3327,96	138,45
30	1:4	18	14.5	4	124.37	3326,24	135,51
31	1:4	15	15	4	116.80	3367,30	134,57
32	1:4	8	16	4	118.74	3434,16	131,69
33	1:4	2	17	4	122.89	3528,54	129,82
34	1:4	0	18	4	95.74	3712,00	131,94

Table D. 3 Overtopping discharges for a sea defence with an asphalted inner slope and outer slope with no roughness (γf=1)

Design nr.	Slope angle	Berm width	Crest height	Crest width	Overtopping discharge	Cross-sectional volume	Outer slope length
[-]	[-]	[m]	[NAP+m]	[m]	[l/sm]	[m^2/m]	[m]
35	1:1,5	33	14.5	4	118.70	2618,72	84,38
36	1:1,5	29	15	4	120.80	2603,33	81,28
37	1:1,5	23	16	4	115.94	2616,96	77,08
38	1:1,5	17	17	4	119.85	2635,09	72,89
39	1:1,5	12	18	4	120.97	2678,24	69,69
40	1:1,5	8	19	4	116.17	2746,41	67,49
41	1:1,5	3	20	4	123.59	2798,56	64,29
42	1:1,5	0	21	4	108.81	2896,25	63,10
43	1:2	25	14	4	119.72	2585,00	87,61
44	1:2	20	14.5	4	122.13	2555,03	83,73
45	1:2	16	15	4	119.54	2546,82	80,85
46	1:2	8	16	4	118.54	2534,16	75,08
47	1:2	0	17	4	113.02	2526,50	69,32
48	1:3	23	12	4	122.68	2603,96	105,22
49	1:3	3	13	4	122.89	2356,56	88,38
50	1:3	0	14	4	64.77	2464,00	88,54
51	1:4	13	11	4	124.34	2554,26	116,08
52	1:4	0	12	4	63.52	2470,00	107,20

Table D. 4 Overtopping discharges for a sea defence with an asphalted inner slope and outer slope with interlocking armour units (γf=0.44 for the slopes, γf=1 for the berm)

Appendix E: Adaptational measures for the Delta21 sea defence

The first concepts for the Delta21 sea defence are primarily designed bearing in mind 1 meter sea level rise during the 100 year lifetime of the defence. However, during the lifetime of the structure, more sea level rise might occur. In order to coop with more sea level rise than originally designed for, the sea defence should be altered, which can be done using multiple types of adaptational measures.

These measures can be used both as singular adaptation, as well as a series of adaptation steps to further develop the Delta21 sea defence and adapt the structure to the changing environment.

In this appendix the effects of the adaptational measures for the Delta21 sea defence are described and evaluated. Also the effect of the use of different combinations of adaptational measures is reviewed.

E.1 Adaptational measures for static sea defences

For sea dikes multiple adaptational measures are possible. All these measures counter overtopping in their own way and have a different effect on the sea defence. This section determines the characteristics which are necessary to mitigate the effects of sea level rise for the following adaptational measures:

- Crest height adaptation
- Berm adaptation
- Slope roughness adaptation
- Inner slope strength increase
- Outer slope angle adaptation
- Foreshore adaptation

All these adaptational measures can also be performed in various combinations. This means that when one adaptational measure does not have the desired effect, the combination of measures might still create a fully functioning and adaptive sea defence.

In this study, structural elements will not be regarded. This means that the application of crest walls and other structures will not be taken into account.

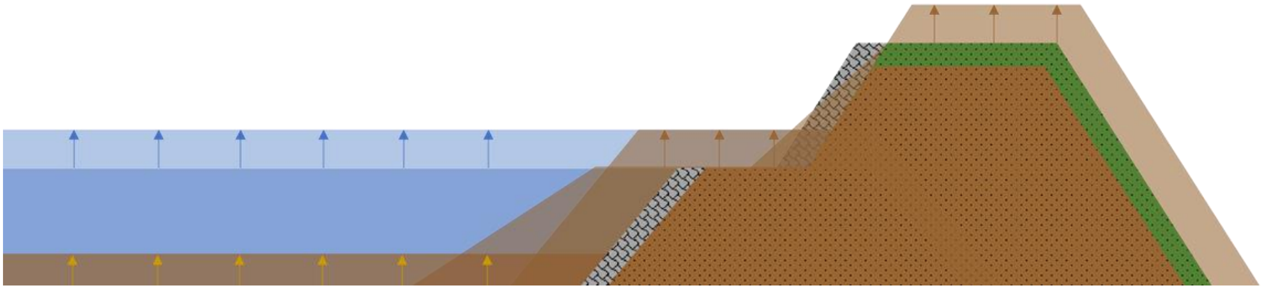


Figure E. 1 All adaptation options for static sea defences schematized in one figure

E.2 Methodology for determining the adaptational measures

Using Function 2 from the main thesis report, the characteristics of the sea defence adaptation options are determined. The input for this formula comes from the various design variants and the information given in the evaluation of the consequences of climate change for the boundary conditions.

E.3 Crest height adaptation

A traditional method in dike reinforcement is increasing the crest height, this is also an option in the case of the Delta21 sea defence. This method is effective for all three base variants for the Delta21 sea defence.

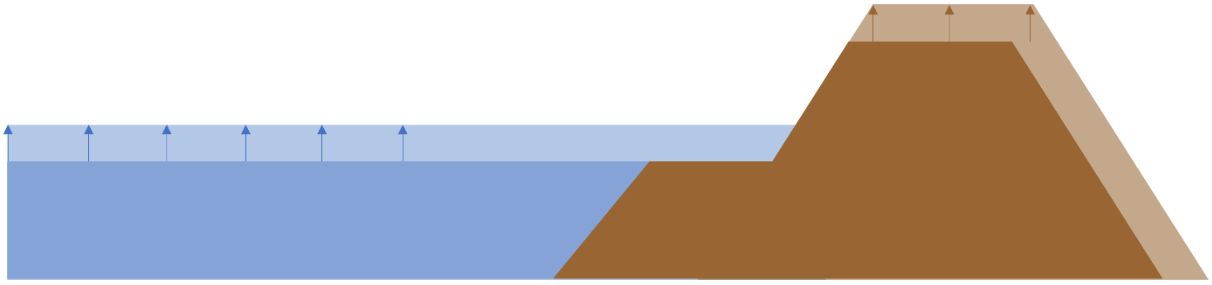


Figure E. 2 schematic representation of increasing the crest height on the sea defence

For the determination of the scale of the adaptation options, first the hydraulic boundary conditions are changed to determine the effects of sea level rise on overtopping. After that, the crest height for the design variants are changed in order to determine the crest heights required for the sea defence to meet the set overtopping requirements.

	Required crest level [m+NAP]		
	Variant 1	**Variant 2**	**Variant 3**
1 m SLR	16	16	16
2 m SLR	17.55	17.55	17.6
3 m SLR	19.2	19.35	19.55
4 m SLR	20.85	21.1	21.55
5 m SLR	22.55	22.95	23.65

Table E. 1 required crest level for various levels of sea level rise

Crest level adaptation for design variant 1

For design variant 1 the adaptation of the crest height will be performed in multitudes of 1.65 meters. The tipping point for each 1.65 meter of crest level increase is 1 meter. Crest increase to a level of NAP + 22.55 m means adaptation to 5 meters of sea level rise for design variant 1, which can be reached in 4 adaptation steps maximum.

Crest level adaptation for design variant 2

For design variant 2 the adaptation of the crest height will be performed in multitudes of 1.75 meters. The tipping point for each 1.75 meter of crest level increase is 1 meter. Crest increase to a level of NAP + 22.95 m means adaptation to 5 meters of sea level rise for design variant 2, which can be reached in 4 adaptation steps maximum.

Crest level adaptation for design variant 3

For design variant 3 the adaptation of the crest height will be performed in multitudes of 1.95 meters. The tipping point for each 1.95 meter of crest level increase is 1 meter. Crest increase to a level of NAP + 23.65 m means adaptation to 5 meters of sea level rise for design variant 3, which can be reached in 4 adaptation steps maximum.

This adaptational measure does not imply difficulties for the application of other adaptational measures mentioned in this chapter and can therefore also be applied as a combination with those.

E.4 Berm adaptation

In the three base designs for the adaptive pathway schemes a berm is present to restrict the amount of overtopping. Just like the crest height can be adapted, the geometry of the berm can be adapted as well. In this adaptational measure the berm will be widened and brought to the height of the new SWL after sea level rise.

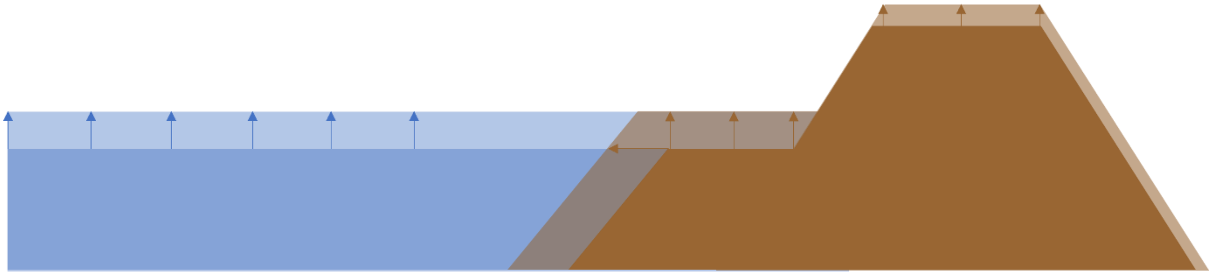


Figure E. 3 schematic representation of berm adaptation

The presence of a berm is integrated in the overtopping formula by the berm influence factor γ_b, which is a function of the berm width and the height of the berm with respect to SWL.

$$\gamma_b = 1 - r_b(1 - r_{dh}) \qquad (3)$$ (Van der Meer, et al., 2018).

In this calculation $r_b = \frac{B}{L_{berm}}$ with B the length of the berm and L_{berm} the length of the slope (between $R_{u2\%}$ and $2 * H_{m0}$) including the berm length.

The height of the berm with respect to the still water line is represented by the factor r_{dh}. For this factor three situations are determined:

$$r_{dh} = 0.5 - 0.5\cos\left(\pi \frac{d_b}{R_{u2\%}}\right) \qquad (5)$$ for a berm above still water line

$$r_{dh} = 0.5 - 0.5\cos\left(\pi \frac{d_b}{2 * H_{m0}}\right) \qquad (6)$$ for a berm below still water line

Otherwise, $r_{dh} = 1$ for berms outside the area of influence (between $R_{u2\%}$ and $2 * H_{m0}$).

In the case that the berm is situated on the still water line, $r_{dh} = 0$.

The influence of the berm is the largest when it is situated at SWL, however when the sea level rises this means that SWL rises as well. The length of the berm with respect to the wave length is the second parameters for the berm influence factor. The larger the wave length, the wider the berm has to be to dissipate wave energy. Therefore adaptation of the sea defence by altering the berm will be done by increasing the width and height of the berm.

For the determination of the scale of the adaptation options, first the hydraulic boundary conditions are changed to determine the effects of sea level rise on overtopping. After that, the berm width and height for the design variants are changed in order to determine the berm geometries required for the sea defence to meet the set overtopping requirements.

	Required berm width [m] and level [NAP+m]					
	Variant 1		**Variant 2**		**Variant 3**	
1 m SLR	24	6.52	22	6.52	23	6.52
2 m SLR	45	7.52	33	7.52	33	7.52
3 m SLR	71	8.52	46	8.52	47	8.52
4 m SLR	103	9.52	64	9.52	64	9.52
5 m SLR	145	10.52	87	10.52	85	10.52

Table E. 2 Required berm geometry for various levels of sea level rise

In order to be considered a berm, the maximum berm width is $0.25 * L_{m-1,0}$ with $L_{m-1,0}$ being the deep water wave length. In the case of the Delta21 sea defence, the deep water wave length is $L_{m-1,0} = \frac{gT_{m-1,0}^2}{2\pi} = \frac{9.81*13.85^2}{2\pi} = 299\ m$. Therefore the maximum berm width is approximately 75 meters, the measure of berm adaptation can not be used as a singular adaptation option to adapt the sea defence for 5 meters of sea level rise.

Since the width of the berm is not coupled to the top berm level, these two measures can be seen as individual adaptation options with different tipping points. These can also be used as and in a combination with other sea defence adaptation options.

Berm and crest level adaptation for design variant 1

The tipping points for the various berm adaptation combinations for design variant 1 are shown underneath in table E.3.

Berm level	**Berm width**		
	24	**50**	**75**
[NAP+m]	**[m]**	**[m]**	**[m]**
6.52	1	2.1	2.85
7.52	-	2.2	3
8.52	-	2.15	3.15
9.52	-	1.95	3.05
10.52	-	-	2.75

Table E. 3 Tipping points in meters above NAP for the various berm adaptation options for design variant 1

As can be seen in table E.3, solely increasing the berm level does not have a positive effect without increasing the berm width. Therefore the crest height will be increased in combination with an increase in berm width.

For variant 1 the adaptation options are the following:

- Berm width increase to a total width of 50 meters, berm height increase to NAP + 7.52 m. This has a tipping point at 2.2 meters of sea level rise.
- Berm width increase to a total width of 75 meters, berm height increase to NAP + 8.52 m. This has a tipping point at 3.15 meters of sea level rise.

Berm and crest level adaptation for design variant 2

The tipping points for the various berm adaptation combinations for design variant 1 are shown underneath in table E.4.

Berm level	**Berm width**		
	22	**50**	**75**
[NAP+m]	**[m]**	**[m]**	**[m]**
6.52	1	3	3.95
7.52	-	3.15	4.2
8.52	-	3.2	4.4
9.52	-	3.15	4.5
10.52	-	3.05	4.5

Table E. 4 Tipping points in meters above NAP for the various berm adaptation options for design variant 2

As can be seen in table E.4, solely increasing the berm level does not have a positive effect without increasing the berm width. Therefore the crest height will be increased in combination with an increase in berm width.

For variant 2 the adaptation options are the following:

- Berm width increase to a total width of 50 meters, berm height increase to NAP + 8.52 m. This has a tipping point at 3.2 meters of sea level rise.
- Berm width increase to a total width of 75 meters, berm height increase to NAP + 9.52 m. This has a tipping point at 4.5 meters of sea level rise.

Berm and crest level adaptation for design variant 3

The tipping points for the various berm adaptation combinations for design variant 1 are shown underneath in table E.5.

Berm level	**Berm width**		
	23	**50**	**75**
[NAP+m]	**[m]**	**[m]**	**[m]**
6.52	1	2.8	3.8
7.52	-	3.1	4
8.52	-	3.2	4.35
9.52	-	3	4.5
10.52	-	2.7	4.5

Table E. 5 Tipping points in meters above NAP for the various berm adaptation options for design variant 3

As can be seen in table E.3, solely increasing the berm level does not have a positive effect without increasing the berm width. Therefore the crest height will be increased in combination with an increase in berm width.

For variant 3 the adaptation options are the following:

- Berm width increase to a total width of 50 meters, berm height increase to NAP + 8.52 m. This has a tipping point at 3.1 meters of sea level rise.
- Berm width increase to a total width of 75 meters, berm height increase to NAP + 9.52 m. This has a tipping point at 4.5 meters of sea level rise.

Berm adaptation implies no complications for the use of other adaptational measures and can therefore be used in a combination.

E.5 Increasing the slope roughness

The slope roughness is determined by the type of revetment and the elements used to create the top layer of the slope. In the case of the Delta21 sea defence the outer slope is created by three segments: the lower slope, berm and upper slope, which do not necessarily have the same roughness of the top layer.

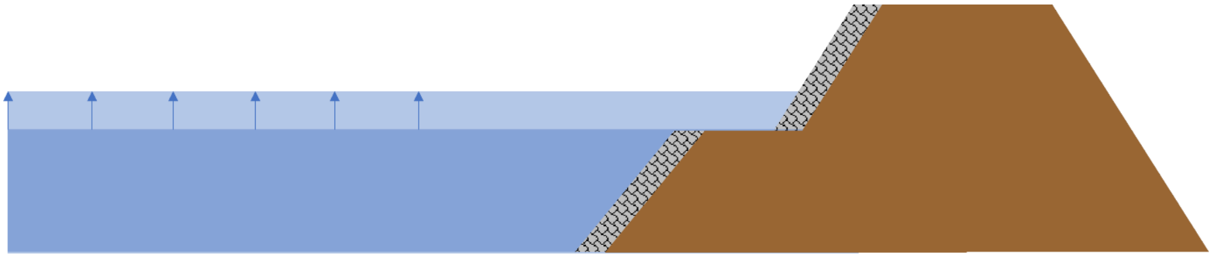


Figure E. 4 schematic representation of slope roughness adaptation

The roughness coefficient for a slope with different elements can be calculated using the following formula (Van der Meer, et al., 2018):

$$\gamma_f = \frac{\alpha_1*\gamma_{f1}*L_1+\alpha_2*\gamma_{f2}*L_2+\alpha_2*\gamma_{f3}*L_3}{\alpha_1*L_1+\alpha_2*L_2+\alpha_3*L_3} \qquad (8)$$

In which:

L_1 = length of slope until -0.25$z_{2\%}$ under the water line ($\sqrt{(1.5H_s*0.25)^2+(tan\alpha*1.5H_s*0.25)^2}$)
L_2 = length of the berm
L_1 = length of slope until +0.5$z_{2\%}$ above the water line ($\sqrt{(1.5H_s*0.5)^2+(tan\alpha*1.5H_s*0.5)^2}$)

The three different α_n factors are the influence factors of the position of the roughness elements on the overall outer slope ($\alpha_1 = 0.13$, $\alpha_2 = 0.22$ and $\alpha_3 = 0.65$). The roughness elements on the upper part of the outer slope have more influence on overtopping than the roughness elements on the lower slope and berm (Chen, Van Gent, Warmink, & Hulscher, 2020).

Using Formula 8 the roughness of the outer slope can be determined, however the use of material for the outer slope will have large consequences in this determination.

In this thesis, two types of outer slope are considered, both consider a berm with an asphalt top layer. However the top layer of the upper and lower slope differs:

1. An outer slope fully covered in an asphalt top layer, the overall roughness for the entire outer slope will then be $\gamma_f = 1$.
2. An outer slope with both the upper and lower slope build up from interlocking armour units. In this thesis it is assumed that X-Blocks are applied, which have a roughness factor of $\gamma_f = 0.44$.

Base design variant 1 and 3 both have an outer slope revetment created with concrete armour units and therefore above mentioned slope type 2. Design variant 2 is lined with asphalt and therefore has slope type 1. Transforming the outer slope from above mentioned slope type 1 to slope type 2 increases the roughness which decreases the occurring overtopping discharge.

This method of adaptation is only suitable for variant 2, which has a smooth outer slope and an inner slope with an asphalt layer below a clay and grass top layer. The smooth outer slope has a roughness coefficient $\gamma_f = 1$, this can be altered by applying interlocking armour units.

By changing the roughness of the second design variant and keeping the rest of the geometry the same, the effect of this roughness adaptation is determined. Applying this adaptation step to conceptual design variant 2 has the desired effect until 3.75 meters of sea level rise. Therefore 3.75 meters of sea level rise is the tipping point for this adaptation measure.

The use of concrete armour units is dependent on the steepness of the slope and cannot be performed for slopes milder than 1:3. Therefore this adaptation method cannot be applied in combination with the increase in slope angle as described in section 6.2.5.

Application of this adaptational measure poses no further issues in combination with the other adaptational measures as mentioned in this chapter.

E.6 Increasing the strength of the inner slope

The three conceptual designs for the Delta21 sea defence have an inner slope which has a grass top layer, this top layer has a maximum overtopping discharge of 5 l/m/s. The maximum allowable overtopping discharge for the Delta21 sea defence can be increased by covering the inner slope of the defence with a different material. Design variants 2 and 3 have an inner slope covered in an asphalt layer, on top of the asphalt layer is a thin soil layer with grass top layer. This way the sea defence looks like it is covered in grass, while having the strength of a sea defence covered with an asphalt top layer.

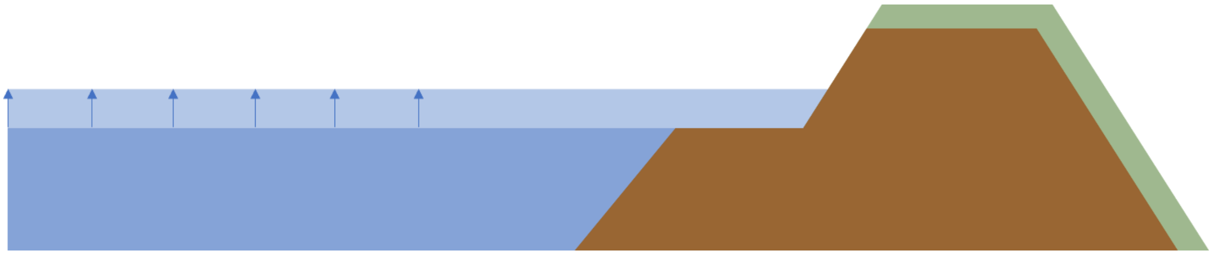


Figure E. 5 schematic representation of inner slope strength increase

Using this technique, the maximum allowable overtopping discharge is increased from 5 l/m/s to 125 l/m/s.

For the sea defence variant 1 with the inner slope covered solely in grass, this step can be taken once.

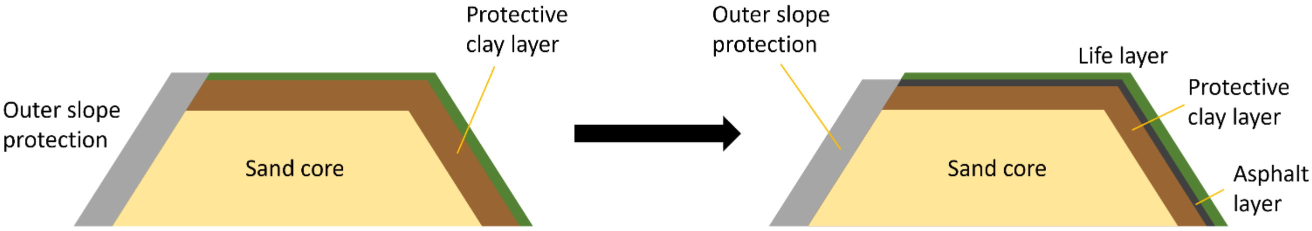


Figure E. 6 The new inner slope protection

Inner slope adaptation for design variant 1

The adaptation of the inner slope can be applied for base design variant 1. Applying an asphalt layer and keeping the geometry of the sea defence the same, increases the strength of the sea defence enough for it to fail at 3.90 meters of sea level rise. Therefore the tipping point of this adaptational measure is located at 3.90 meters of sea level rise.

The use of this adaptational measure has no implications for the use of the other adaptational measures mentioned in this chapter and can therefore be combined.

Inner slope adaptation for design variants 2 and 3

Since design variants 2 and 3 already have applied an asphalted inner slope, this design adaption method is not applicable for these design variants.

E.7 Adapting the slope angle of the dike

The adaptation of the slope angle has an effect on the occurring amount of overtopping, increasing the slope angle (and thereby making the slope less steep) decreases the amount of overtopping. However the adaptation of slope angle has large consequences for the geometry of the dike as is schematized in figure E.7 underneath.

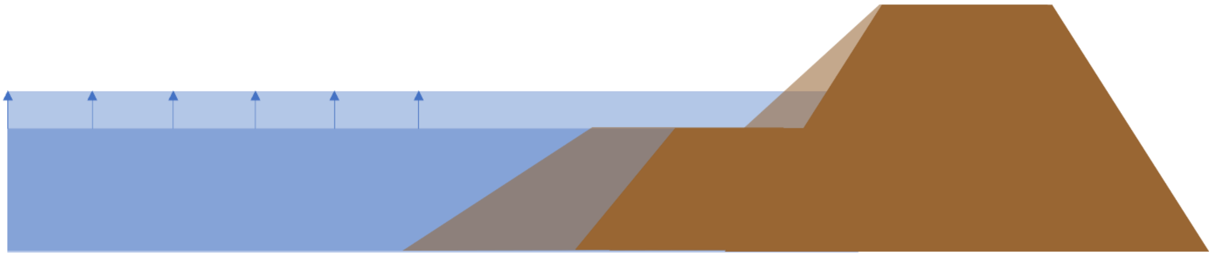


Figure E. 7 schematic representation of slope angle adaptation

The adaptation of the slope angle of the dike can be performed in two steps: from a slope of 1:1,5 to 1:3 and from a slope of 1:3 to 1:4. However, adapting the slope angle has limitations when interlocking armour units are used. armour units gain stability in slope steepness and therefore the slope angle cannot be increased without consequences when this revetment type is applied. The maximum slope steepness for the application of concrete armour units is 1:3.

Slope angle adaptation for design variant 1

For design variant 1 the applied revetment is created with the use of concrete armour units. Since these units gain stability for steep slopes, the slope angle cannot be increased further than 1:3. Therefore this adaptational measure cannot be applied for base design variant 1.

Slope angle adaptation for design variant 2

In the base design of variant 2 the outer slope is reinforced with the use of asphalt, this revetment type can be applied on mild slopes and therefore the increase in slope angle does not impose problems. Increasing the slope angle from 1:3 to 1:4 has an adaptation tipping point for 2.25 meters of sea level rise.

Since the maximum slope steepness for the use of concrete armour units is 1:3, the slope adaptation of variant 2 from 1:3 to 1:4 makes the increase of outer slope roughness as stated in section 7.3 impossible. Therefore these two adaptational measures cannot be performed as a combination.

Slope angle adaptation for design variant 3

The slope angle of base design variant 3 is 1:1,5. Since the maximum slope angle for interlocking armour units is 1:3, the slope angle can be increased for this design variant. However, the use of interlocking armour units on slopes milder than 1:1,5 causes necessity for heavier units. For slopes milder than 1:1,5, the weight correction factor is 1.25 and for slopes milder than 1:2 the weight correction factor is 1.5. The application of this adaptational measure for base design variant 3 has consequences for the applied interlocking armour unit weight, which makes it impossible for the units to be placed back on the slope after application of this adaptational measure.

Application of this adaptational measure for base design variant 3 has a tipping point at an extra 2,90 meters of sea level rise, therefore the tipping point for this adaptational measure is at 3,90 meters of sea level rise.

This measure can be applied in combination with the other design adaptation options.

E.8 Increasing foreshore level

By increasing the foreshore seawards of the sea defence, the waves will not break on the slopes of the sea defence but break due to depth induced breaking. This means that the waves present at the toe of the sea defence are significantly lower than they would be in the base design concept situations (where the water depth is 14 meters during normal situations but at least 20.52 meters during normative storm situations).

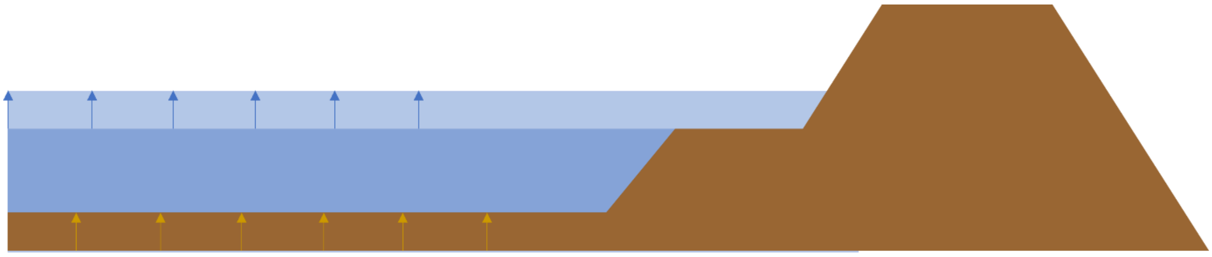


Figure E. 8 schematic representation of the foreshore level adaptation

In this adaptation option the assumption is made that the waves break according to a breaker parameter of $H_s/h = 0.5$ (Schiereck, 2019). However, a shallow foreshore is not only cause for the wave height at the toe of the sea defence to reduce but also for the wave period $T_{m-1,0}$ to increase.

An increase in wave period will also cause the breaker parameter to change, which has a direct influence on the overtopping as is shown in formula 2 in the main report.

The wave period changes under the influence of a shallow foreshore via the following formula (Hofland, Chen, Altomare, & Oosterlo, 2017):

$$T_{m-1.0,t} = \left(6\exp\left(-6\tilde{h}\right) + 0.25\exp\left(-0.75\tilde{h}\right) + 1\right) * T_{m-1,0,o} \qquad (E.1)$$

With

$$\tilde{h} = \frac{h_t}{H_{m0,o}}\left(\frac{cot\theta}{100}\right)^{0.2} \qquad (E.2)$$

In which:

$T_{m-1,0,t}$	=	The m-1 wave period at the toe of the sea defence	[s]
$T_{m-1,0,o}$	=	The m-1 wave period at deep water conditions	[s]
$\tilde{h}$	=	Relative water depth	[-]
h_t	=	The water depth at the toe of the sea defence	[m]
$H_{m0,o}$	=	The significant wave height in deep water conditions	[m]
θ	=	Slope angle of the foreshore	[°]

The water depth at the toe of the sea defence follows from the breaker parameter $H_s/h = 0.5$ and is different for each of the preferred significant wave heights which follows from the allowed overtopping discharge and variant roughness and geometry.

Using these variables and combining these with the offshore wave height for different levels of sea level rise the $T_{m-1,0}$ wave period at the toe of the sea defence can be determined. Via an iterative process the necessary adaptation options regarding foreshore adaptation are determined.

The length of the foreshore is a minimum of 1 deep water wave length $L_{m-1,0}$ (Van der Meer, et al., 2018). However, due to the large difference in incoming and broken waves, a minimum foreshore length of $2*L_{m-1,0}$ is considered in this adaptation measure.

Since the significant wave height and the $T_{m-1,0,t}$ wave period at the toe are fully dependent on the water depth at the toe, an optimum can be found in water depth. This causes a limitation in the positive effects of a shallow foreshore on overtopping and thereby a limit in the amount of sea level rise can be adapted to using this method.

Since the incoming wave period is the same for all three design variants, the length of the foreshore adaptation will be twice the deep water wave length: $2 * L_{m-1,0} = 2 * \frac{gT_{m-1,0}^2}{2\pi} = \frac{9.81*13.85^2}{\pi} = 599\ m.$

For approximately 600 meters the foreshore will have a slope of 1:100, after which the new water bed will go to the original NAP – 14 m bed level at a 1:12.5 slope.

Foreshore adaptation for design variant 1

For design variant 1 foreshore adaptation can be used to adapt the sea dike to up to 2.5 meters of sea level rise. This can be done in one large step or two smaller steps maximum.

The first step will be the increase of the foreshore by 12.26 meters to a level of NAP – 1.74 m. During storm conditions the depth at the toe of the dike will then be 9.2 meters (at the tipping point). This step has a tipping point at 2 meters of sea level rise.

The next step will be an extra increase of foreshore level with 1.96 meters to a level of NAP + 0.22 m, during storm conditions the depth at the toe of the dike will then be 7.8 meters (at the tipping point). This step has a tipping point at 2.5 meters of sea level rise.

Foreshore adaptation for design variant 2

For design variant 2 foreshore adaptation can be used to adapt the sea dike to up to 3 meters of sea level rise. This can be done in one large step or two smaller steps maximum.

The first step will be the increase of the foreshore by 10.92 meters to a level of NAP – 3.08 m. During storm conditions the depth at the toe of the dike will then be 10.6 meters (at the tipping point). This step has a tipping point at 2 meters of sea level rise.

The next step will be an extra increase of foreshore level with 3 meters to a level of NAP – 0.08 m, during storm conditions the depth at the toe of the dike will then be 8.6 meters (at the tipping point). This step has a tipping point at 3 meters of sea level rise.

Foreshore adaptation for design variant 3

For design variant 3 foreshore adaptation can be used to adapt the sea dike to up to 2.5 meters of sea level rise. This can be done in one large step or two smaller steps maximum.

The first step will be the increase of the foreshore 10.92 meters to a level of NAP – 3.08 m. During storm conditions the depth at the toe of the dike will then be 10.6 meters (at the tipping point). This step has a tipping point at 2 meters of sea level rise.

The next step will be an extra increase of foreshore level with 1.9 meters to a level of NAP – 1.18 m, during storm conditions the depth at the toe of the dike will then be 9.2 meters (at the tipping point). This step has a tipping point at 2.5 meters of sea level rise.

Due to the changing wave characteristics at the toe of the sea defence (as a consequence of depth induced breaking), this adaptation method will have consequences for the effectiveness of the other adaptational measures as mentioned in this chapter. For example a 1.65 meter increase in crest height for design variant 1 will not necessarily be enough to cope with the consequences of 1 meter of sea level rise after increasing the foreshore level.

However the increase in foreshore level does not pose structural consequences for the use of the other adaptation methods and can therefore be used in combinations.

Appendix F: Adaptational pathways for the Delta21 sea defence

In the primary conceptual design of the Delta21 sea defence, only one meter of sea level rise is taken into account in order to create 3 design variants. However, up to five meters of sea level rise might occur during the lifetime of the sea defence. In the main thesis report chapter 7 (supported by appendix E), multiple ways of adapting the sea defence to these rising sea levels have been created.

These adaptational measures cannot only be used as singular adaptations but also in combination with each other. The full overview of these adaptations will be presented in the form of an adaptational pathway scheme, which is created for each of the three base design variants.

The various adaptational measures which can be taken influence each other, this might cause that two measures which originally both adapt the sea defence for one meter of sea level rise, in combination only adapt the sea defence for one and a half meters (and not the to be expected two meters).

This appendix discusses the methodology of determining the combined effect of the several adaptation options as pathways and the adaptational pathways for design variants 1, 2 and 3.

F.1 Methodology of determination of sea level rise mitigating effect of pathways

Pathways are created as combinations of multiple adaptation options in a sequence and the effect of a pathway is expressed in the total amount of mitigated sea level rise. This section describes the steps which are taken to determine the total amount of mitigated sea level rise per pathway.

The mitigation of the effects of sea level rise is performed via the adaptational measures as described and elaborated in Chapter 6 of the main thesis report and Appendix E. Each of the adaptation options mitigate a certain amount of sea level rise for each of the base design concepts. For example, a 1.65 meters crest level increase for design variant 1 mitigates the effects of 1 meter of sea level rise. Therefore the tipping point of the design after implementing this adaptation option is 2 meters of sea level rise.

The calculation of the mitigated amount of sea level rise is performed using overtopping Formula 2 as presented on page 35 of the thesis report. The calculation is performed per base design variant, using the characteristics of the base design variant as starting point. These design variants are designed for 1 meter of sea level rise, which is therefore the base tipping point.

Adaptation via the adaptation options changes some of the characteristics of the sea defence, per adaptation option this is presented in Table F.1 underneath.

	Changed variable in overtopping formula							
Adaptation option	$tan\alpha$	$\xi_{m-1,0}$	R_c	H_s	γ_b	γ_f	γ_β	q
1. Crest level adaptation			Increase					
2. Berm adaptation					Decrease	Increase		
3. Slope roughness						Decrease		
4. Slope angle	Increase	Decrease			Increase	Decrease		
5. Inner slope strength								Increase
6. Foreshore adaptation		Increase		Decrease				

Table F. 1 Variables of the overtopping formula changed by multiple adaptation options

The mitigated amount of sea level rise is calculated via the following steps as presented in Figure F.1.

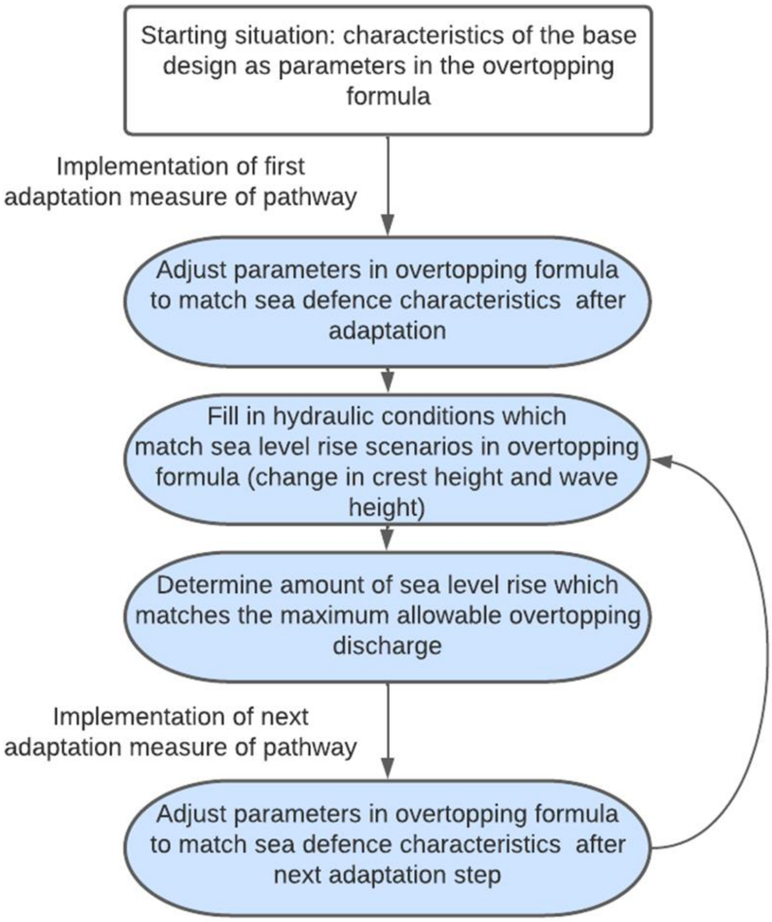


Figure F. 1 Flowchart presenting the steps taken to calculate the mitigated amount of sea level rise and tipping point per adaptive pathway

By applying the methodology presented in Figure F.1 the tipping point for each of the pathways and combination of adaptation options is determined per base design variant. These tipping points are presented in Sections F.2 to F.4 underneath.

F.2 Adaptational pathways for design variant 1

The first static sea defence design variant has an inner slope with a grass over clay top layer, the outer slopes are covered by interlocking armour units on a 1:3 slope. The crest height of the base design is NAP + 16 m and the berm width is 24 meters, covered in asphalt.

Since the roughness of the base design variant is already the maximum roughness the sea defence can have, this variable cannot be adapted in order to minimise overtopping. The use of interlocking armour units rules out the option of altering the slope angle.

Because of the fact that this variant has a solely grassy inner slope, the sea defence can be adapted by creating an inner slope with an asphalt layer topped by a clay and grass top layer.

The adaptation options for static sea defence variant 1 are the following:

- Crest height adaptation (in multitudes of 1.65 meters)
- Berm adaptation
- Inner slope adaptation
- Foreshore adaptation

These can be applied as stand-alone adaptations or in a package with other adaptation options. The effects of the combinations of these adaptational measures are presented in tables F.2 to F.10.

Tables F.2 to F.10 underneath show the amounts of sea level rise the various adaptational measure combinations protect against, in combination with base design variant 1.

The study is stopped once combinations reach a maximum of 5 meters sea level rise.

Berm	**Berm level**	**0**	**1,65**	**3,3**	**4,95**	**6,6**
24	**6,52**	Base	2	3	4	5
50	**7,52**	2,2	3,25	4,2	5	
75	**8,52**	3,15	4,2	5		

Table F. 2 Sea level rise mitigation by combinations of crest level increase and berm adaptation steps

	Crest	**0**	**1,65**	**3,3**	**4,95**	**6,6**
Foreshore	**-1,74**	2	2,75	3,45	4,2	5
	0,22	2,5	3,15	3,8	4,5	5

Table F. 3 Sea level rise mitigation by combinations of crest level increase and foreshore level increase

		Foreshore	
Berm	**Berm level**	**-1,74**	**0,22**
24	**6,52**	2	2,5
50	**7,52**	3,25	3,65
75	**8,52**	4,15	4,55

Table F. 4 Sea level rise mitigation by combinations of berm adaptation steps and foreshore level increase

	Foreshore	
	-1,74	**0,22**
Inner slope	4,15	4,4

Table F. 5 Sea level rise mitigation by combinations of inner slope adaptation and foreshore level increase

		Sea level rise		**Foreshore -1,74**		
Berm	**Berm level**	**0**	**1,65**	**3,3**	**4,95**	**6,6**
24	**6,52**	2	2,75	3,45	4,2	5
50	**7,52**	3,25	3,95	4,6	5	
75	**8,52**	4,15	4,9	5		

Table F. 6 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP - 1.74 m

Foreshore NAP + 0,22 m

Berm	Berm level	0	1,65	3,3	4,95	6,6
24	**6,52**	2,5	3,15	3,8	4,5	5
50	**7,52**	3,65	4,25	4,85	5	
75	**8,52**	4,55	4,9	5		

Table F. 7 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP +0.22 m

Inner slope adaptation

Berm	Berm level	0	1,65	3,3	4,95	6,6
24	**6,52**	3,9	5			
50	**7,52**	4,75				
75	**8,52**	5				

Table F. 8 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and inner slope adaptation

Inner slope + Foreshore NAP -1,74 m

Berm	Berm level	0	1,65	3,3	4,95	6,6
24	**6,52**	4,15	5			
50	**7,52**	5				
75	**8,52**					

Table F. 9 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP - 1.74 m and inner slope adaptation

Inner slope + Foreshore NAP +0,22 m

Berm	Berm level	0	1,65	3,3	4,95	6,6
24	**6,52**	4,4	5			
50	**7,52**	5				
75	**8,52**					

Table F. 10 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP + 0.22 m and inner slope adaptation

All these adaptational measures can be put together in various combinations to form adaptational pathways. The most direct pathways are shown in table F.11 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
0	1	0	-	-	-
1	2	1	Crest + 1,65 m		
2	2	1	Foreshore to -1,74 m		
3	2,2	1	Berm 50 m		
4	2,5	1	Foreshore to 0,22 m		
5	2,75	2	Foreshore to -1,74 m	Crest + 1,65 m	
6	**3**	1	Crest + 3,30 m		
7	3,15	2	Foreshore to 0,22 m	Crest + 1,65 m	
8	3,15	1	Berm 75 m		
9	3,25	2	Foreshore to -1,74 m	Berm 50 m	
10	3,25	2	Berm 50 m	Crest + 1,65 m	
11	3,45	2	Foreshore to -1,74 m	Crest + 3,30 m	
12	3,65	2	Foreshore to 0,22 m	Berm 50 m	
13	3,8	2	Foreshore to 0,22 m	Crest + 3,30 m	
14	3,9	1	Inner slope		
15	3,95	3	Foreshore to -1,74 m	Berm 50 m	Crest + 1,65 m
16	4	1	Crest + 4,95 m		
17	4,15	2	Foreshore to -1,74 m	Berm 75 m	
18	4,15	2	Foreshore to -1,74 m	Inner slope	
19	4,2	2	Crest + 3,30 m	Berm 50 m	
20	4,2	2	Crest + 1,65 m	Berm 75 m	
21	4,2	2	Foreshore to -1,74 m	Crest + 4,95 m	
22	4,25	3	Foreshore to 0,22 m	Berm 50 m	Crest + 1,65 m
23	4,4	2	Inner slope	Foreshore to 0,22 m	
24	4,5	2	Foreshore to 0,22 m	Crest + 4,95 m	
25	4,55	2	Foreshore to 0,22 m	Berm 75 m	
26	4,6	3	Foreshore to -1,74 m	Berm 50 m	Crest + 3,30 m
27	4,75	2	Inner slope	Berm 50 m	
28	4,85	3	Foreshore to 0,22 m	Berm 50 m	Crest + 3,30 m
29	4,9	3	Foreshore to -1,74 m	Berm 75 m	Crest + 1,65 m
30	4,9	3	Foreshore to 0,22 m	Berm 75 m	Crest + 1,65 m
31	5	1	Crest + 6,60 m		
32	5	2	Crest + 4,95 m	Berm 50 m	
33	5	2	Crest + 3,30 m	Berm 75 m	
34	5	2	Foreshore to -1,74 m	Berm + 6,60 m	
35	5	2	Foreshore to 0,22 m	Berm + 6,60 m	
36	5	2	Inner slope	Crest + 1,65 m	
37	5	2	Inner slope	Berm + 75 m	
38	5	3	Foreshore to -1,74 m	Crest + 4,95 m	Berm 50 m
39	5	3	Foreshore to -1,74 m	Crest + 3,30 m	Berm 75 m
40	5	3	Inner slope	Foreshore to -1,74 m	Crest + 1,65 m
41	5	3	Inner slope	Foreshore to -1,74 m	Berm 50 m
42	5	3	Foreshore to 0,22 m	Crest + 4,95 m	Berm 50 m
43	5	3	Foreshore to 0,22 m	Crest + 3,30 m	Berm 75 m
44	5	3	Inner slope	Foreshore to 0,22 m	Crest + 1,65 m
45	5	3	Inner slope	Foreshore to 0,22 m	Berm 50 m

Table F. 11 Adaptational pathways for design variant 1

As said, this table only presents the most ‘direct’ pathways with the preferred end results. However, the desired path can also be achieved in multiple different ways. As an example of this, table F.12 underneath shows the eight different ways pathway 28 can be achieved:

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4
31	**5**	**1**	**Crest + 6,60 m**			
31.2	5	*2*	*Crest + 1,65 m*	*Crest + 6,60 m*		
31.3	5	*2*	*Crest + 3,30 m*	*Crest + 6,60 m*		
31.4	5	*2*	*Crest + 4,95 m*	*Crest + 6,60 m*		
31.5	5	*3*	*Crest + 3,30 m*	*Crest + 4,95 m*	*Crest + 6,60 m*	
31.6	5	*3*	*Crest + 1,65 m*	*Crest + 3,30 m*	*Crest + 6,60 m*	
31.7	5	*3*	*Crest + 1,65 m*	*Crest + 4,95 m*	*Crest + 6,60 m*	
31.8	5	*4*	*Crest + 1,65 m*	*Crest + 3,30 m*	*Crest + 4,95 m*	*Crest + 6,60 m*

Table F. 12 Example: various ways in which pathway 28 can be achieved in multiple adaptation steps

In this thesis only the most direct way is regarded for the adaptive pathway schemes..

All adaptational pathways as presented in Table F.11, are visualized in one adaptational pathway as shown in Figure F.2 underneath. The numbers behind the pathways correspond to those in Table F.11.

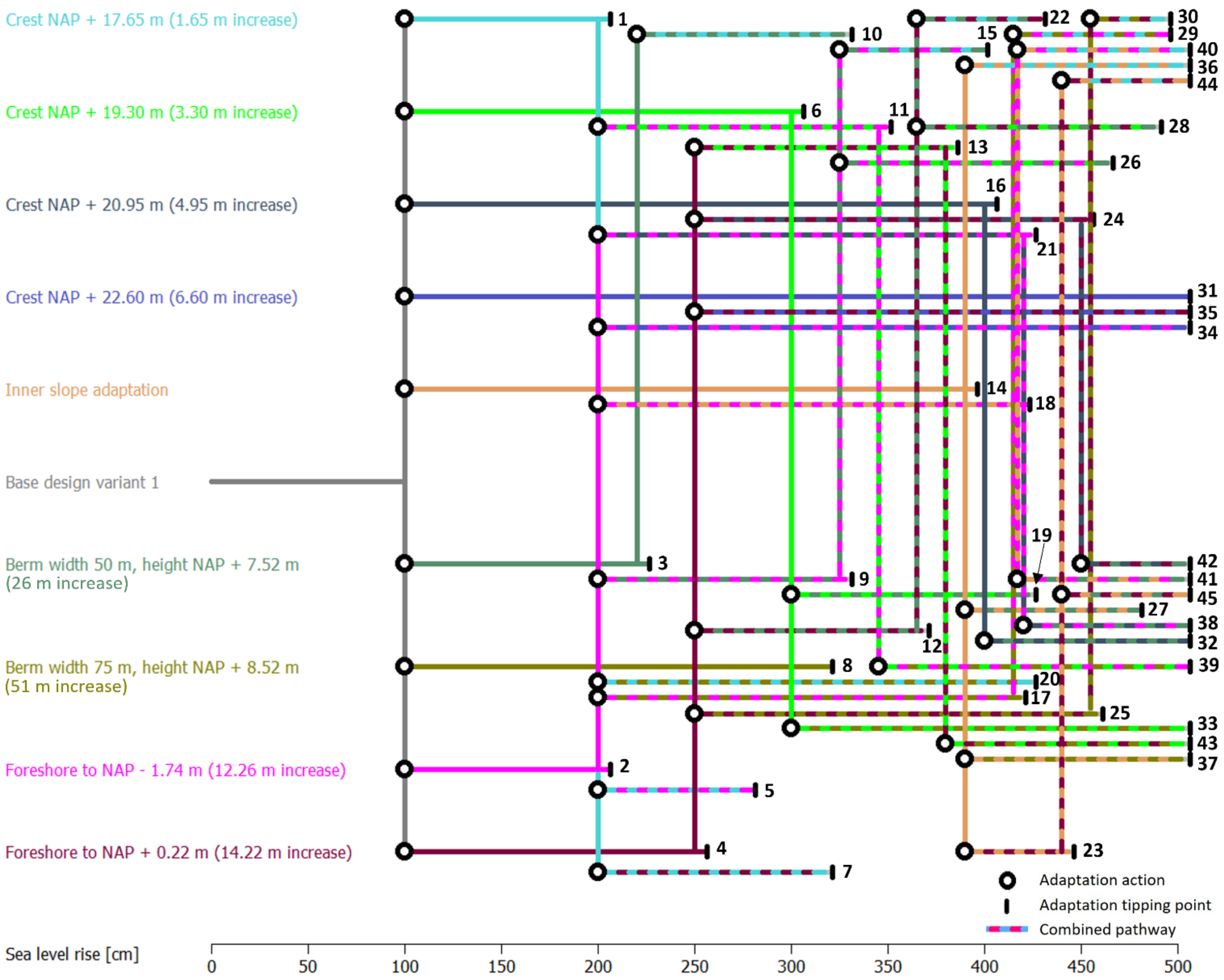


Figure F. 2 The adaptive pathway scheme showing possible adaptation options and combinations for sea defence variant 1

F.3 Adaptational pathways for design variant 2

The second sea defence design variant has a crest and inner slope protected for erosion by an asphalt layer, topped by a grass top layer. The outer slope is smooth, covered in asphalt concrete and has a roughness of $\gamma_f = 1$. The crest height of the base design is NAP + 16 m and the berm is 22 meters wide.

Because the inner slope of design variant 2 is already reinforced by asphalt, this adaptation option cannot be applied for design variant 2. However since the outer slope is covered in asphalt concrete with a roughness of $\gamma_f = 1$, the roughness can be adapted substituting this asphalt concrete layer on the slopes for Xbloc to lower the overtopping discharge.

The adaptation options for static sea defence variant 2 are the following:

- Crest height adaptation (in multitudes of 1.75 meters)
- Berm adaptation
- Slope angle adaptation
- Roughness adaptation
- Foreshore adaptation

The adaptation options altering the outer slope roughness and outer slope angle rule each other out as interlocking armour units are more effective on steep slopes. Therefore, Xbloc placed on a 1:4 slope is not taken into account in this thesis and this combination is not used. An adaptation pathway can only use one of these two adaptation options.

Tables F.13 to F.24 underneath show the amounts of sea level rise the various adaptational measure combinations protect against, in combination with base design variant 2.

The study is stopped once combinations reach a maximum of 5 meters sea level rise.

Berm	**Berm level**	**0**	**1,75**	**3,5**	**5,25**	**7**
22	**6,52**	Base	2	3	4	5
50	**8,52**	3,2	4,35	5		
75	**9,52**	4,5	5			

Table F. 13 Sea level rise mitigation by combinations of crest level increase and berm adaptation steps

Crest		**0**	**1,75**	**3,5**	**5,25**	**7**
Foreshore	**-3,08**	2	2,8	3,55	4,35	5
	-0,08	3	3,7	4,35	5	

Table F. 14 Sea level rise mitigation by combinations of crest level increase and foreshore level increase

		Foreshore	
Berm	**Berm level**	**-3,08**	**-0,08**
22	**6,52**	2	3
50	**8,52**	4,05	4,9
75	**9,52**	5	5

Table F. 15 Sea level rise mitigation by combinations of berm adaptation steps and foreshore level increase

	Foreshore	
	-3,08	**-0,08**
Slope angle	2,8	3,65
Slope roughness	3,85	4,3

Table F. 16 Sea level rise mitigation by combinations of inner slope adaptation and foreshore level increase

Sea level rise **Foreshore -3,08**

Berm	Berm level	0	1,75	3,5	5,25	7
22	**6,52**	2	2,8	3,55	4,35	5
50	**8,52**	4,05	4,9	5		
75	**9,52**	5				

Table F. 17 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP – 3.08m

Foreshore -0,08

Berm	Berm level	0	1,75	3,5	5,25	7
22	**6,52**	3	3,7	4,35	5	
50	**8,52**	4,9	5			
75	**9,52**	5				

Table F. 18 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP -0.08m

Slope angle

Berm	Berm level	0	1,75	3,5	5,25	7
22	**6,52**	2,25	3,4	4,5	5	
50	**8,52**	4	5			
75	**9,52**	5				

Table F. 19 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and slope angle adaptation

Slope roughness

Berm	Berm level	0	1,75	3,5	5,25	7
22	**6,52**	3,85	5			
50	**8,52**	4,9				
75	**9,52**	5				

Table F. 20 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and roughness adaptation

Slope roughness + Foreshore -3,08

Berm	Berm level	0	1,75	3,5	5,25	7
22	**6,52**	3,85	4,85	5		
50	**8,52**	5				
75	**9,52**					

Table F. 21 Sea level rise mitigation by combinations of crest level increase, berm adaptation, a foreshore level increase to NAP – 3.08 m and roughness adaptation

Slope angle + Foreshore -3,08

Berm	Berm level	0	1,75	3,5	5,25	7
22	**6,52**	2,8	3,7	4,65	5	
50	**8,52**	4,5	5			
75	**9,52**	5				

Table F. 22 Sea level rise mitigation by combinations of crest level increase, berm adaptation, a foreshore level increase to NAP – 3.08 m and slope angle adaptation

Slope roughness + Foreshore -0,08

Berm	Berm level	0	1,75	3,5	5,25	7
22	**6,52**	4,3	5			
50	**8,52**	5				
75	**9,52**					

Table F. 23 Sea level rise mitigation by combinations of crest level increase, berm adaptation, a foreshore level increase to NAP – 0.08 m and roughness adaptation

		Slope angle + Foreshore -0,08				
Berm	**Berm level**	**0**	**1,75**	**3,5**	**5,25**	**7**
22	**6,52**	3,65	4,5	5		
50	**8,52**	5				
75	**9,52**					

Table F. 24 Sea level rise mitigation by combinations of crest level increase, berm adaptation, a foreshore level increase to NAP – 0.08 m and slope angle adaptation

All these adaptational measures are put together in various combinations to form adaptational pathways. The most direct pathways are shown in table F.25 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4
1	2	1	Crest + 1,75 m			
2	2	1	Foreshore to -3,08 m			
3	2,25	1	Slope angle			
4	2,8	2	Foreshore to -3,08 m	Crest + 1,75 m		
5	2,8	2	Slope angle	Foreshore to -3,08 m		
6	3	1	Crest + 3,5 m			
7	3	1	Foreshore to -0,08 m			
8	3,2	1	Berm 50 m			
9	3,4	2	Slope angle	Crest + 1,75 m		
10	3,55	2	Foreshore to -3,08 m	Crest + 3,50 m		
11	3,65	2	Slope angle	Foreshore to -0,08		
12	3,7	2	Foreshore to -0,08 m	Crest + 1,75 m		
13	3,7	3	Slope angle	Foreshore to -3,08 m	Crest + 1,75 m	
14	3,85	1	Slope roughness			
15	3,85	2	Foreshore to -3,08 m	Slope roughness		
16	4	1	Crest + 5,25 m			
17	4	2	Slope angle	Berm 50 m		
18	4,05	2	Foreshore to -3,08 m	Berm 50 m		
19	4,3	2	Foreshore to -0,08 m	Slope roughness		
20	4,35	2	Crest + 1,75 m	Berm 50 m		
21	4,35	2	Foreshore to -3,08 m	Crest + 5,25 m		
22	4,35	2	Foreshore to -0,08 m	Crest + 3,50 m		
23	4,5	1	Berm 75 m			
24	4,5	2	Slope angle	Crest + 3,50 m		
25	4,5	3	Slope angle	Foreshore to -3,08 m	Berm 50 m	
26	4,5	3	Slope angle	Foreshore to -0,08	Crest + 1,75 m	
27	4,65	3	Slope angle	Foreshore to -3,08 m	Crest + 3,50 m	
28	4,85	3	Slope roughness	Foreshore to -3,08 m	Crest + 1,75 m	
29	4,9	2	Foreshore to -0,08 m	Berm 50 m		
30	4,9	2	Slope roughness	Berm 50 m		
31	4,9	3	Foreshore to -3,08 m	Crest + 1,75 m	Berm 50 m	
32	5	1	Crest + 7,00 m			
33	5	2	Crest + 1,75 m	Berm 75 m		
34	5	2	Crest + 3,5 m	Berm 50 m		
35	5	2	Foreshore to -3,08 m	Crest + 7,00 m		
36	5	2	Slope angle	Crest + 5,25 m		
37	5	2	Slope angle	Berm 75 m		
38	5	2	Foreshore to -0,08 m	Crest + 5,25 m		
39	5	2	Foreshore to -0,08 m	Berm 75 m		
40	5	2	Slope roughness	Crest + 1,75 m		
41	5	2	Slope roughness	Berm 75 m		
42	5	2	Foreshore to -3,08 m	Berm 75 m		
43	5	3	Foreshore to -3,08 m	Crest + 3,50 m	Berm 50 m	
44	5	3	Slope angle	Crest + 1,75 m	Berm 50 m	
45	5	3	Slope roughness	Foreshore to -3,08 m	Berm 50 m	
46	5	3	Slope roughness	Foreshore to -3,08 m	Crest + 3,50 m	

47	5	3	Slope angle	Foreshore to -3,08 m	Crest + 5,25 m	
48	5	3	Slope angle	Foreshore to -3,08 m	Berm 75 m	
49	5	3	Foreshore to -0,08 m	Crest + 1,75 m	Berm 50 m	
50	5	3	Slope roughness	Foreshore to -0,08 m	Crest + 1,75 m	
51	5	3	Slope roughness	Foreshore to -0,08 m	Berm 50 m	
52	5	3	Slope angle	Foreshore to -0,08 m	Crest + 3,50 m	
53	5	3	Slope angle	Foreshore to -0,08 m	Berm 50 m	
54	5	4	Slope angle	Foreshore to -3,08 m	Crest + 1,75 m	Berm 50 m

Table F. 25 Adaptational pathways for design variant 2

All adaptational pathways as presented in Table F.25, are visualized in one adaptational pathway as shown in Figure F.3 underneath. The numbers behind the pathways correspond to those in Table F.25.

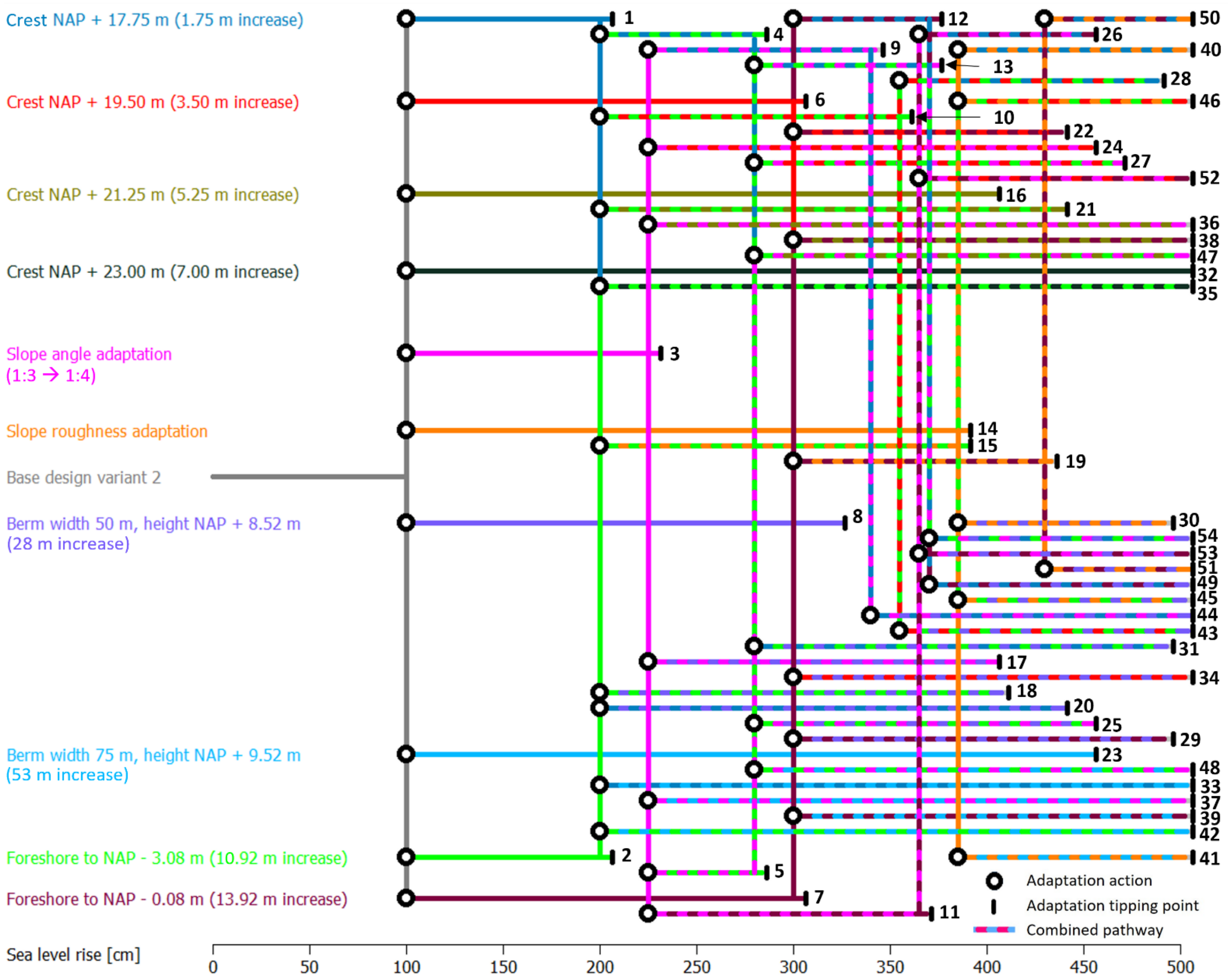


Figure F. 3 The adaptive pathway scheme showing possible adaptation options and combinations for sea defence variant 2

F.4 Adaptational pathways for design variant 3

The third static sea defence design variant has an inner slope with an asphalt layer topped by a clay and grass top layer. The outer slope is covered by interlocking armour units, the crest height of the base design is NAP+16 m and the berm width is 23 meters wide.

Because the inner slope of base design variant 3 is already reinforced by asphalt and the outer slope is covered in concrete armour units, the adaptation options of inner slope reinforcement and outer slope roughness adaptation cannot be applied for this design variant.

The adaptation options for static sea defence variant 3 are the following:

- Crest height adaptation (in multitudes of 1.95 meters)
- Berm adaptation
- Slope angle adaptation
- Foreshore adaptation

These can be applied as stand-alone adaptations or in a package with other adaptation options.

Tables F.26 to F.34 underneath show the amounts of sea level rise the various adaptational measure combinations protect against, in combination with base design variant 1.

The study is stopped once combinations reach a maximum of 5 meters sea level rise.

Berm	**Berm level**	**0**	**1,95**	**3,9**	**5,85**	**7,8**
23	**6,52**	Base	2	3	4	5
50	**8,52**	3,2	4,35	5		
75	**9,52**	4,55	5			

Table F. 26 Sea level rise mitigation by combinations of crest level increase and berm adaptation steps

	Crest	**0**	**1,95**	**3,9**	**5,85**	**7,8**
Foreshore level [NAP + m]	**-3.08**	2	2,75	3,45	4,15	4,8
	-1.18	2,5	3,15	3,8	4,4	5

Table F. 27 Sea level rise mitigation by combinations of crest level increase and foreshore level increase

		Foreshore [NAP+m]	
Berm	**Crest**	**-3.08**	**-1.18**
23	**6,52**	2	2,5
50	**8,52**	4	4,45
75	**9,52**	5	5

Table F. 28 Sea level rise mitigation by combinations of berm adaptation steps and foreshore level increase

	Foreshore [NAP+m]	
	-3.08	**-1.18**
Slope angle	3,85	4,2

Table F. 29 Sea level rise mitigation by combinations of slope angle adaptation and foreshore level increase

Foreshore NAP -3.08 m

Berm	**Berm level**	**0**	**1,95**	**3,9**	**5,85**	**7,8**
23	**6,52**	2	2,75	3,45	4,15	4,8
50	**8,52**	4	4,8	5		
75	**9,52**	5				

Table F. 30 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP – 3.08 m

Foreshore NAP -1.18 m

Berm	Berm level	0	1,95	3,9	5,85	7,8
23	**6,52**	2,5	3,15	3,8	4,4	5
50	**8,52**	4,45	5			
75	**9,52**	5				

Table F. 31 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP -1.18 m

Slope angle adaptation

Berm	Berm level	0	1,95	3,9	5,85	7,8
23	**6,52**	3,85	5			
50	**8,52**	4,9				
75	**9,52**	5				

Table F. 32 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and slope angle adaptation

Slope angle + Foreshore NAP -3.08 m

Berm	Berm level	0	1,95	3,9	5,85	7,8
23	**6,52**	3,85	5			
50	**8,52**	5				
75	**9,52**					

Table F. 33 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP – 3.08 m and slope angle adaptation

Slope angle + Foreshore NAP -1.18 m

Berm	Berm level	0	1,95	3,9	5,85	7,8
23	**6,52**	4,2	5			
50	**8,52**	5				
75	**9,52**					

Table F. 34 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and a foreshore level increase to NAP -1.18 m and slope angle adaptation

All these adaptational measures can be put together in various combinations to form adaptational pathways. The most direct pathways are shown in table F.35 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
0	1	0	-	-	-
1	2	1	Crest + 1,95 m		
2	2	1	Foreshore to -3,08 m		
3	2,5	1	Foreshore to -1,18 m		
4	2,75	2	Foreshore to -3,08 m	Crest + 1,95 m	
5	3	1	Crest + 3,90 m		
6	3,15	2	Foreshore to -1,18 m	Crest + 1,95 m	
7	3,2	1	Berm 50 m		
8	3,45	2	Foreshore to -3,08 m	Crest + 3,90 m	
9	3,8	2	Foreshore to -1,18 m	Crest + 3,90 m	
10	3,85	1	Slope angle		
11	3,85	2	Foreshore to -3,08 m	Slope angle	
12	4	1	Crest + 5,85 m		
13	4	2	Foreshore to -3,08 m	Berm 50 m	
14	4,15	2	Foreshore to -3,08 m	Crest + 5,85 m	
15	4,2	2	Foreshore to -1,18 m	Slope angle	
16	4,35	2	Crest + 1,95 m	Berm 50 m	
17	4,4	2	Foreshore to -1,18 m	Crest + 5,85 m	
18	4,45	2	Foreshore to -1,18 m	Berm 50 m	
19	4,55	1	Berm 75 m		
20	4,8	2	Foreshore to -3,08 m	Crest + 7,80 m	
21	4,8	3	Foreshore to -3,08 m	Crest + 1,95 m	Berm 50 m
22	4,9	2	Slope angle	Berm 50 m	
23	5	1	Crest + 7,80 m		
24	5	2	Crest + 3,90 m	Berm 50 m	
25	5	2	Crest + 1,95 m	Berm 75 m	
26	5	2	Foreshore to -3,08 m	Berm 75 m	
27	5	2	Slope angle	Crest + 1,95 m	
28	5	2	Slope angle	Berm 75 m	
29	5	2	Foreshore to -1,18 m	Crest + 7,80 m	
30	5	2	Foreshore to -1,18 m	Berm 75 m	
31	5	3	Foreshore to -3,08 m	Crest + 3,90 m	Berm 50 m
32	5	3	Foreshore to -1,18 m	Crest + 1,95 m	Berm 50 m
33	5	3	Slope angle	Foreshore to -3,08 m	Crest + 1,95 m
34	5	3	Slope angle	Foreshore to -3,08 m	Berm 50 m
35	5	3	Slope angle	Foreshore to -1,18 m	Crest + 1,95 m
36	5	3	Slope angle	Foreshore to -1,18 m	Berm 50 m

Table F. 35 Adaptational pathways for design variant 3

All adaptational pathways as presented in Table F.35, are visualized in one adaptational pathway as shown in Figure F.4 underneath. The numbers behind the pathways correspond to those in Table F.35.

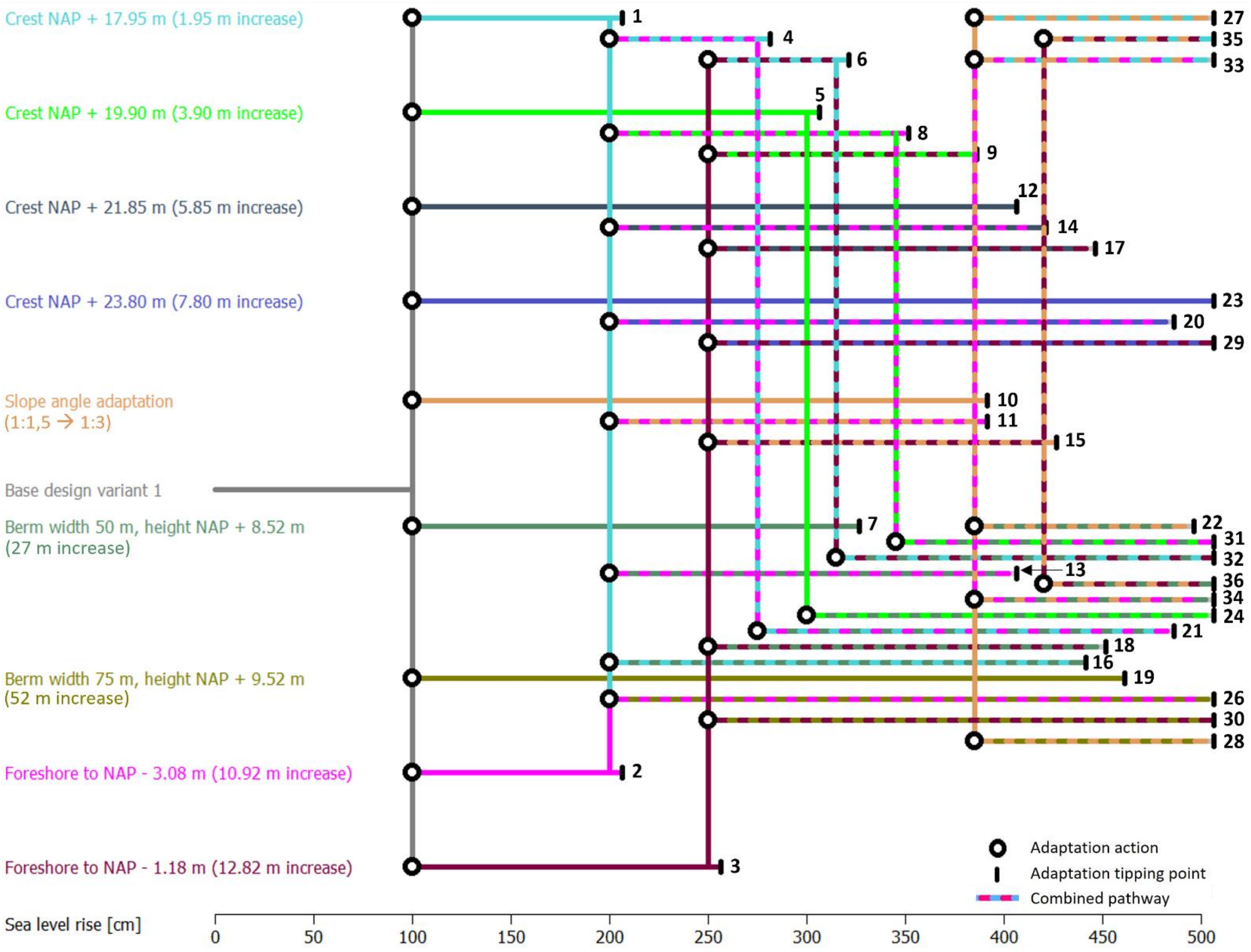


Figure F. 4 The adaptive pathway scheme showing possible adaptation options and combinations for sea defence variant 3

Appendix G: Adaptive pathway schemes without the use of foreshore adaptation in a combination

As discussed in Section 7.4 in the main thesis report, the use of foreshore adaptation is not considered to be a viable base design adaptation option in combination with other adaptation methods. Not only due to the large amounts of foreshore suppletion which has to be performed (at least 10.92 meters of sand has to be brought in place, this is in the case of design variants 2 and 3), the use of foreshore adaptation also reduces the effectivity of other adaptation options which are to be implemented in the future.

On top of that, foreshore adaptation has large consequences on the Natura2000 area which is located in the North Sea right at the outer toe of the new Delta21 sea defence.

Because of the removal of foreshore adaptation, the adaptive pathway schemes change and a lot of adaptation combinations are not available anymore. In this Appendix the new adaptation pathway schemes are presented for base design variants 1, 2 and 3.

G.1 The adaptive pathway scheme for base design variant 1

The first static sea defence design variant has an inner slope with a grass over clay top layer, the outer slopes are covered by interlocking armour units on a 1:3 slope. The crest height of the base design is NAP + 16 m and the berm width is 24 meters, covered in asphalt.

Since the roughness of the base design variant is already the maximum roughness the sea defence can have, this variable cannot be adapted in order to minimise overtopping. The use of interlocking armour units rules out the option of altering the slope angle.

Because of the fact that this variant has a solely grassy inner slope, the sea defence can be adapted by creating an inner slope with an asphalt layer topped by a clay and grass top layer.

The adaptation options which can be used in a combination for sea defence variant 1 are the following:

- Crest height adaptation (in multitudes of 1.65 meters)
- Berm adaptation
- Inner slope adaptation

These can be applied as stand-alone adaptations or in a package with other adaptation options. The effects of the combinations of these adaptational measures are presented in tables G.1 to G.3.

Foreshore adaptation can still be used, however not in a combination with the other options.

For each of the combinations a calculation is made for the amount of sea level rise the adaptational measure mitigates. For example: the base situation for variant 1 is designed for one meter of sea level rise. When 1.65 meters is added to the crest (the crest level is than NAP + 17.65 m), the sea defence is able to guarantee water safety until 2 meters of sea level rise is reached.

Tables G.1 to G.3 underneath show the amounts of sea level rise the various adaptational measure combinations protect against, in combination with base design variant 1.

The study is stopped once combinations reach a maximum of 5 meters sea level rise.

		Sea level rise				
Berm	**Berm level**	**0**	**1,65**	**3,3**	**4,95**	**6,6**
24	**6,52**	Base	2	3	4	5
50	**7,52**	2,2	3,25	4,2	5	
75	**8,52**	3,15	4,2	5		

Table G. 1 Sea level rise mitigation by combinations of crest level increase and berm adaptation steps

		Sea level rise		Inner slope		
Berm	**Berm level**	**0**	**1,65**	**3,3**	**4,95**	**6,6**
24	**6,52**	3,9	5			
50	**7,52**	4,75				
75	**8,52**	5				

Table G. 2 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and inner slope adaptation

All these adaptational measures can be put together in various combinations to form adaptational pathways. The most direct pathways are shown in table G.3 underneath, the pathway numbering is the same as in chapter 7 of the main thesis report.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4
1	2	1	Crest + 1,65 m			
2	2	1	Foreshore to -1,74 m			
3	2,2	1	Berm 50 m			
4	2,5	1	Foreshore to 0,22 m			
4.2		2	Foreshore to -1,74 m	Foreshore to 0,22 m		
6	3	1	Crest + 3,30 m			
6.2		2	Crest + 1,65 m	Crest + 3,30 m		
8	3,15	1	Berm 75 m			
8.2		2	Berm 50 m	Berm 75 m		
10	3,25	2	Berm 50 m	Crest + 1,65 m		
14	3,9	1	Inner slope			
16	4	1	Crest + 4,95 m			
16.2		2	Crest + 1,65 m	Crest + 4,95 m		
16.3		2	Crest + 3,30 m	Crest + 4,95 m		
16.4		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	
19	4,2	2	Crest + 3,30 m	Berm 50 m		
19.2		3	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m	
20	4,2	2	Crest + 1,65 m	Berm 75 m		
20.2		3	Crest + 1,65 m	Berm 50 m	Berm 75 m	
27	4,75	2	Inner slope	Berm 50 m		
31	5	1	Crest + 6,60 m			
31.2		2	Crest + 1,65 m	Crest + 6,60 m		
31.3		2	Crest + 3,30 m	Crest + 6,60 m		
31.4		2	Crest + 4,95 m	Crest + 6,60 m		
31.5		3	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m	
31.6		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 6,60 m	
31.7		3	Crest + 1,65 m	Crest + 4,95 m	Crest + 6,60 m	
31.8		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m
32	5	2	Crest + 4,95 m	Berm 50 m		
32.2		3	Crest + 1,65 m	Crest + 4,95 m	Berm 50 m	
32.3		3	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m	
32.4		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m
33	5	2	Crest + 3,30 m	Berm 75 m		
33.2		3	Crest + 3,30 m	Berm 50 m	Berm 75 m	
33.3		3	Crest + 1,65 m	Crest + 3,30 m	Berm 75 m	

33.4		4	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m	Berm 75 m
36	5	2	Inner slope	Crest + 1,65 m		
37	5	2	Inner slope	Berm 75 m		
37.2		3	Inner slope	Berm 50 m	Berm 75 m	

Table G. 3 Adaptational pathways for design variant 1 without the use of foreshore adaptation in a combination

Table G.3 also shows the different ways a pathway can be achieved in multiple steps (for example pathway 33 which divides in 33.2, 33.3 and 33.4 in multiple steps). These pathways are not shown in Figure G.1 underneath, only most direct pathways are shown in this figure.

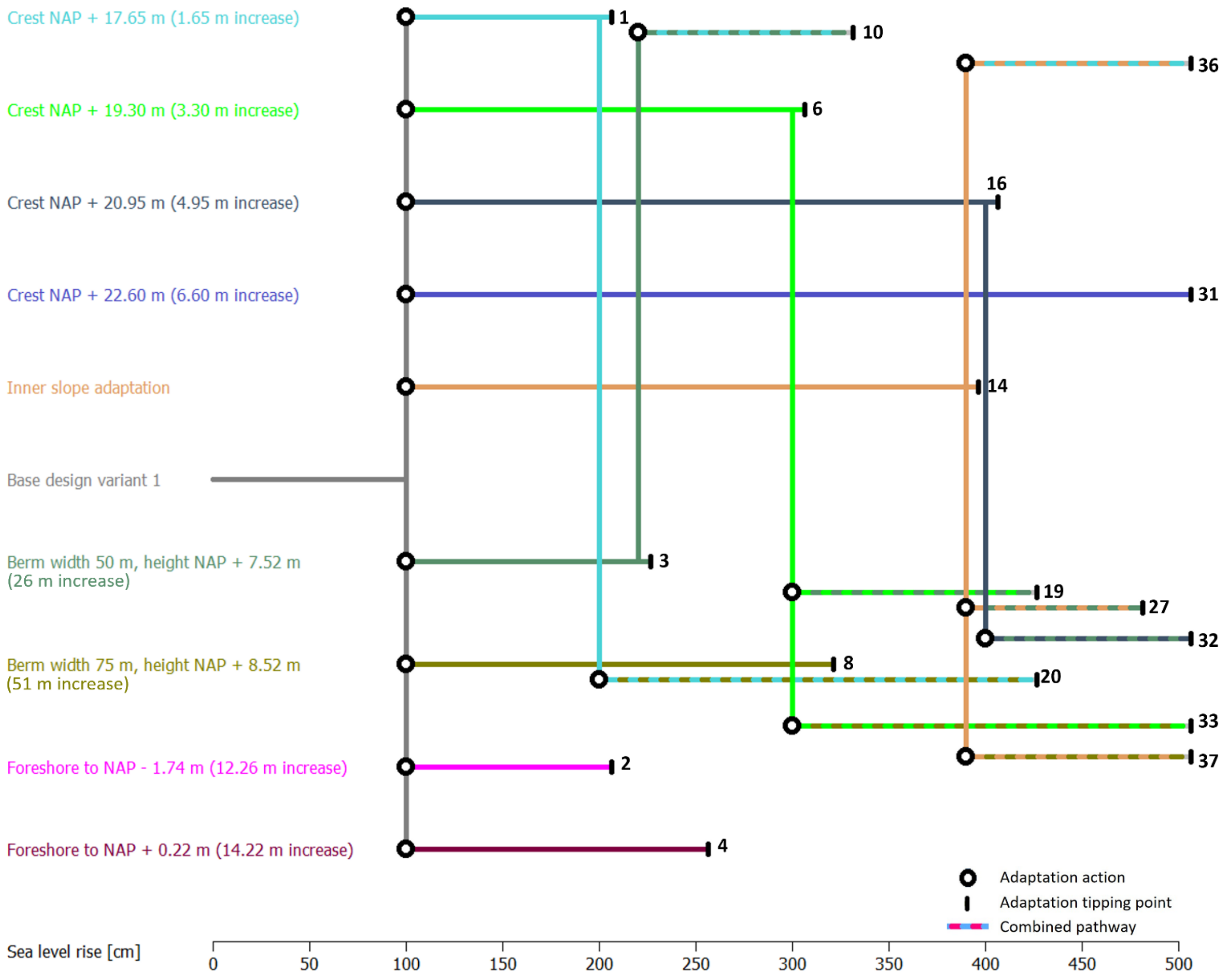


Figure G. 1 Adaptive pathway scheme of design variant 1 without the use of foreshore adaptation in a combination

G.2 The adaptive pathway scheme for base design variant 2

The second base design variant has an inner slope with an asphalt reinforcement, the outer slopes are covered by asphalt concrete on a 1:3 slope. The crest height of the base design is NAP + 16 m and the berm width is 22 meters, covered in asphalt concrete.

The adaptation options for static sea defence variant 2 are the following:

- Crest height adaptation (in multitudes of 1.75 meters)
- Berm adaptation
- Outer slope angle adaptation
- Outer slope roughness adaptation

These can be applied as stand-alone adaptations or in a package with other adaptation options. The effects of the combinations of these adaptational measures are presented in Tables G.4 to G.7.

Foreshore adaptation can still be used, however not in a combination with the other options.

For each of the combinations a calculation is made for the amount of sea level rise the adaptational measure mitigates. For example: the base situation for variant 2 is designed for one meter of sea level rise. When 1.75 meters is added to the crest (the crest level is than NAP + 17.75 m), the sea defence is able to guarantee water safety until 2 meters of sea level rise is reached.

Tables G.4 to G.7 underneath show the amounts of sea level rise the various adaptational measure combinations protect against, in combination with base design variant 2.

The study is stopped once combinations reach a maximum of 5 meters sea level rise.

		Sea level rise				
Berm	**Berm level**	**0**	**1,75**	**3,5**	**5,25**	**7**
22	**6,52**	Base	2	3	4	5
50	**8,52**	3,2	4,35	5		
75	**9,52**	4,5	5			

Table G. 4 Sea level rise mitigation by combinations of crest level increase and berm adaptation steps

		Sea level rise		**Slope angle**		
Berm	**Berm level**	**0**	**1,75**	**3,5**	**5,25**	**7**
22	**6,52**	2,25	3,4	4,5	5	
50	**8,52**	4	5			
75	**9,52**	5				

Table G. 5 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and slope angle adaptation

		Sea level rise		**Slope roughness**		
Berm	**Berm level**	**0**	**1,75**	**3,5**	**5,25**	**7**
22	**6,52**	3,85	5			
50	**8,52**	4,9				
75	**9,52**	5				

Table G. 6 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and outer slope roughness adaptation

All these adaptational measures can be put together in various combinations to form adaptational pathways. The most direct pathways are shown in table G.7 underneath, the pathway numbering is the same as in chapter 7 of the main thesis report.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4
1	2	1	Crest + 1,75 m			
2	2	1	Foreshore to -3,08 m			
3	2,25	1	Slope angle			
6	3	1	Crest + 3,50 m			
6.2		2	Crest + 1,75 m	Crest + 3,50 m		
7	3	1	Foreshore to -0,08 m			
7.2		2	Foreshore to -3,08 m	Foreshore to -0,08 m		
8	3,2	1	Berm 50 m			
9	3,4	2	Slope angle	Crest + 1,75 m		
14	3,85	1	Slope roughness			
16	4	1	Crest + 5,25 m			
16.2		2	Crest + 1,75 m	Crest + 5,25 m		
16.3		2	Crest + 3,50 m	Crest + 5,25 m		
16.4		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	
17	4	2	Slope angle	Berm 50 m		
20	4,35	2	Crest + 1,75 m	Berm 50 m		
23	4,5	1	Berm 75 m			
23.2		2	Berm 50 m	Berm 75 m		
24	4,5	2	Slope angle	Crest + 3,50 m		
24.2		3	Slope angle	Crest + 1,75 m	Crest + 3,50 m	
30	4,9	2	Slope roughness	Berm 50 m		
32	5	1	Crest + 7,00 m			
32.2		2	Crest + 1,75 m	Crest + 7,00 m		
32.3		2	Crest + 3,50 m	Crest + 7,00 m		
32.4		2	Crest + 5,25 m	Crest + 7,00 m		
32.5		3	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m	
32.6		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 7,00 m	
32.7		3	Crest + 1,75 m	Crest + 5,25 m	Crest + 7,00 m	
32.8		4	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m
33	5	2	Crest + 1,75 m	Berm 75 m		
33.2		3	Crest + 1,75 m	Berm 50 m	Berm 75 m	
34	5	2	Crest + 3,50 m	Berm 50 m		
34.2		3	Crest + 1,75 m	Crest + 3,50 m	Berm 50 m	
36	5	2	Slope angle	Crest + 5,25 m		
36.2		3	Slope angle	Crest + 1,75 m	Crest + 5,25 m	
36.3		3	Slope angle	Crest + 3,50 m	Crest + 5,25 m	
36.4		4	Slope angle	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m
37	5	2	Slope angle	Berm 75 m		
37.2		3	Slope angle	Berm 50 m	Berm 75 m	
40	5	2	Slope roughness	Crest + 1,75 m		
41	5	2	Slope roughness	Berm 75 m		
41.2		3	Slope roughness	Berm 50 m	Berm 75 m	
44	5	3	Slope angle	Crest + 1,75 m	Berm 50 m	

Table G. 7 Adaptational pathways for design variant 2 without the use of foreshore adaptation in a combination

Table G.7 also shows the different ways a pathway can be achieved in multiple steps (for example pathway 36 which divides in 36.2, 36.3 and 36.4 in multiple steps). These pathways are not shown in Figure G.2 underneath, only most direct pathways are shown in this figure.

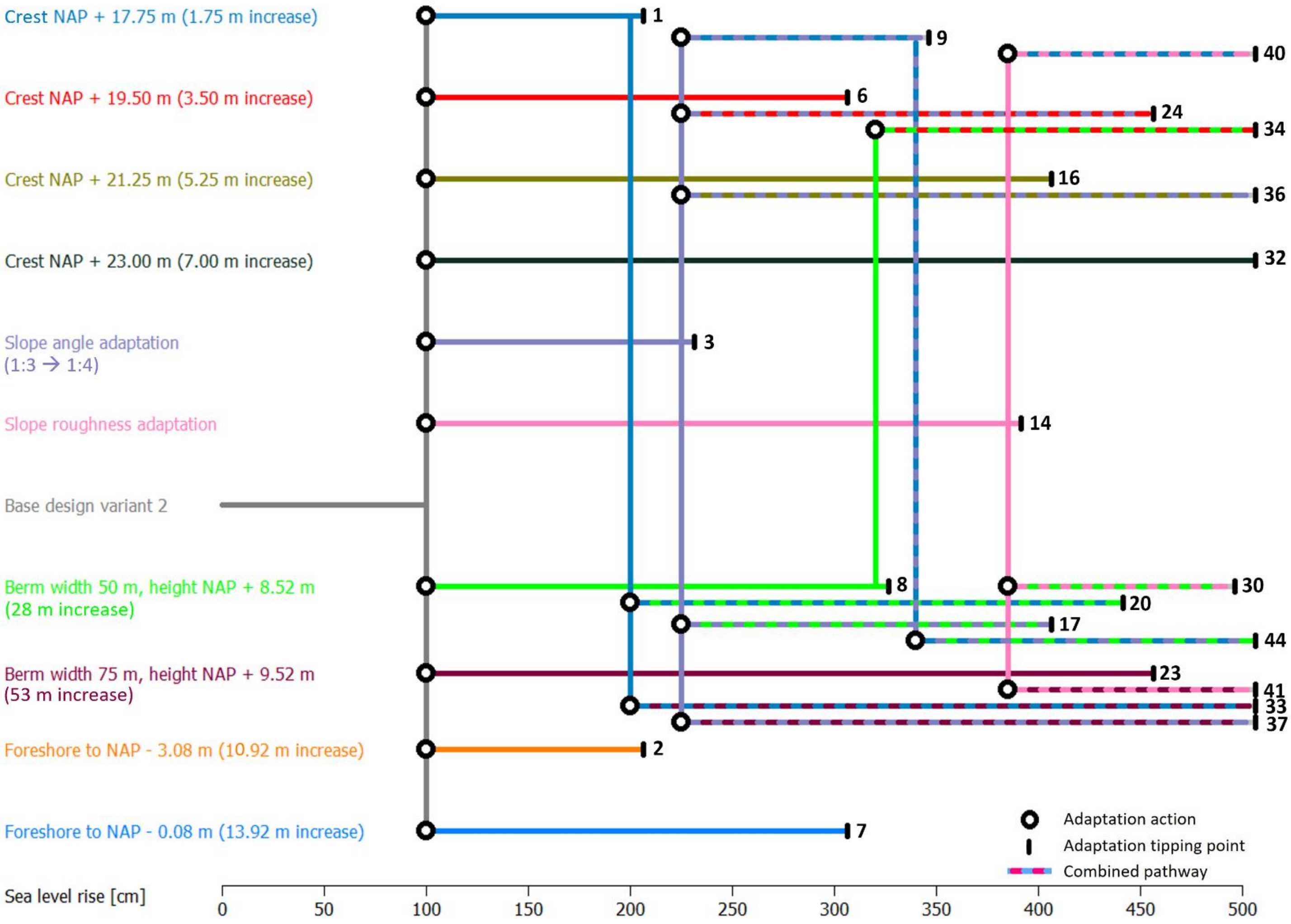


Figure G. 2 Adaptive pathway scheme of design variant 2 without the use of foreshore adaptation in a combination

G.3 The adaptive pathway scheme for base design variant 3

The third base design variant has an inner slope with an asphalt reinforcement, the outer slopes are covered by a single layer of interlocking armour units on a 1:1,5 slope. The crest height of the base design is NAP + 16 m and the berm width is 23 meters, covered in asphalt concrete.

The adaptation options for static sea defence variant 3 are the following:

- Crest height adaptation (in multitudes of 1.95 meters)
- Berm adaptation
- Outer slope angle adaptation

These can be applied as stand-alone adaptations or in a package with other adaptation options. The effects of the combinations of these adaptational measures are presented in tables G.8 to G.10.

For each of the combinations a calculation is made for the amount of sea level rise the adaptational measure mitigates. For example: the base situation for variant 3 is designed for one meter of sea level rise. When 1.95 meters is added to the crest (the crest level is than NAP + 17.95 m), the sea defence is able to guarantee water safety until 2 meters of sea level rise is reached.

Tables G.8 to G.10 underneath show the amounts of sea level rise the various adaptational measure combinations protect against, in combination with base design variant 3.

The study is stopped once combinations reach a maximum of 5 meters sea level rise.

		Sea level rise				
Berm	**Berm level**	**0**	**1,95**	**3,9**	**5,85**	**7,8**
23	**6,52**	Base	2	3	4	5
50	**8,52**	3,2	4,35	5		
75	**9,52**	4,55	5			

Table G. 8 Sea level rise mitigation by combinations of crest level increase and berm adaptation steps

		Sea level rise		**Slope angle**		
Berm	**Berm level**	**0**	**1,95**	**3,9**	**5,85**	**7,8**
23	**6,52**	3,85	5			
50	**8,52**	4,9				
75	**9,52**	5				

Table G. 9 Sea level rise mitigation by combinations of crest level increase, berm adaptation steps and slope angle adaptation

All these adaptational measures can be put together in various combinations to form adaptational pathways. The most direct pathways are shown in Table G.10 underneath, the pathway numbering is the same as in Chapter 7 of the main thesis report.

Pathway number	**Tipping point [mSLR]**	**Number of adaptation steps**	**Adaptation step 1**	**Adaptation step 2**	**Adaptation step 3**	**Adaptation step 4**
1	2	1	Crest + 1,95 m			
2	2	1	Foreshore to -3,08 m			
3	2,5	1	Foreshore to -1,18 m			
3.2		2	Foreshore to -3,08 m	Foreshore to -1,18 m		
5	3	1	Crest + 3,90 m			
5.2		2	Crest + 1,95 m	Crest + 3,90 m		
7	3,2	1	Berm 50 m			
10	3,85	1	Slope angle			
12	4	1	Crest + 5,85 m			
12.2		2	Crest + 1,95 m	Crest + 5,85 m		
12.3		2	Crest + 3,90 m	Crest + 5,85 m		
12.4		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m	
16	4,35	2	Crest + 1,95 m	Berm 50 m		
19	4,55	1	Berm 75 m			
19.2		2	Berm 50 m	Berm 75 m		
22	4,9	2	Slope angle	Berm 50 m		
23	5	1	Crest + 7,80 m			
23.2		2	Crest + 1,95 m	Crest + 7,80 m		
23.3		2	Crest + 3,90 m	Crest + 7,80 m		
23.4		2	Crest + 5,85 m	Crest + 7,80 m		
23.5		3	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m	
23.6		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 7,80 m	
23.7		3	Crest + 1,95 m	Crest + 5,85 m	Crest + 7,80 m	
23.8		4	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m
24	5	2	Crest + 3,90 m	Berm 50 m		
24.2		3	Crest + 1,95 m	Crest + 3,90 m	Berm 50 m	
25	5	2	Crest + 1,95 m	Berm 75 m		
25.2		3	Crest + 1,95 m	Berm 50 m	Berm 75 m	
27	5	2	Slope angle	Crest + 1,95 m		
28	5	2	Slope angle	Berm 75 m		
28.2		3	Slope angle	Berm 50 m	Berm 75 m	

Table G. 10 Adaptational pathways for design variant 3 without the use of foreshore adaptation in a combination

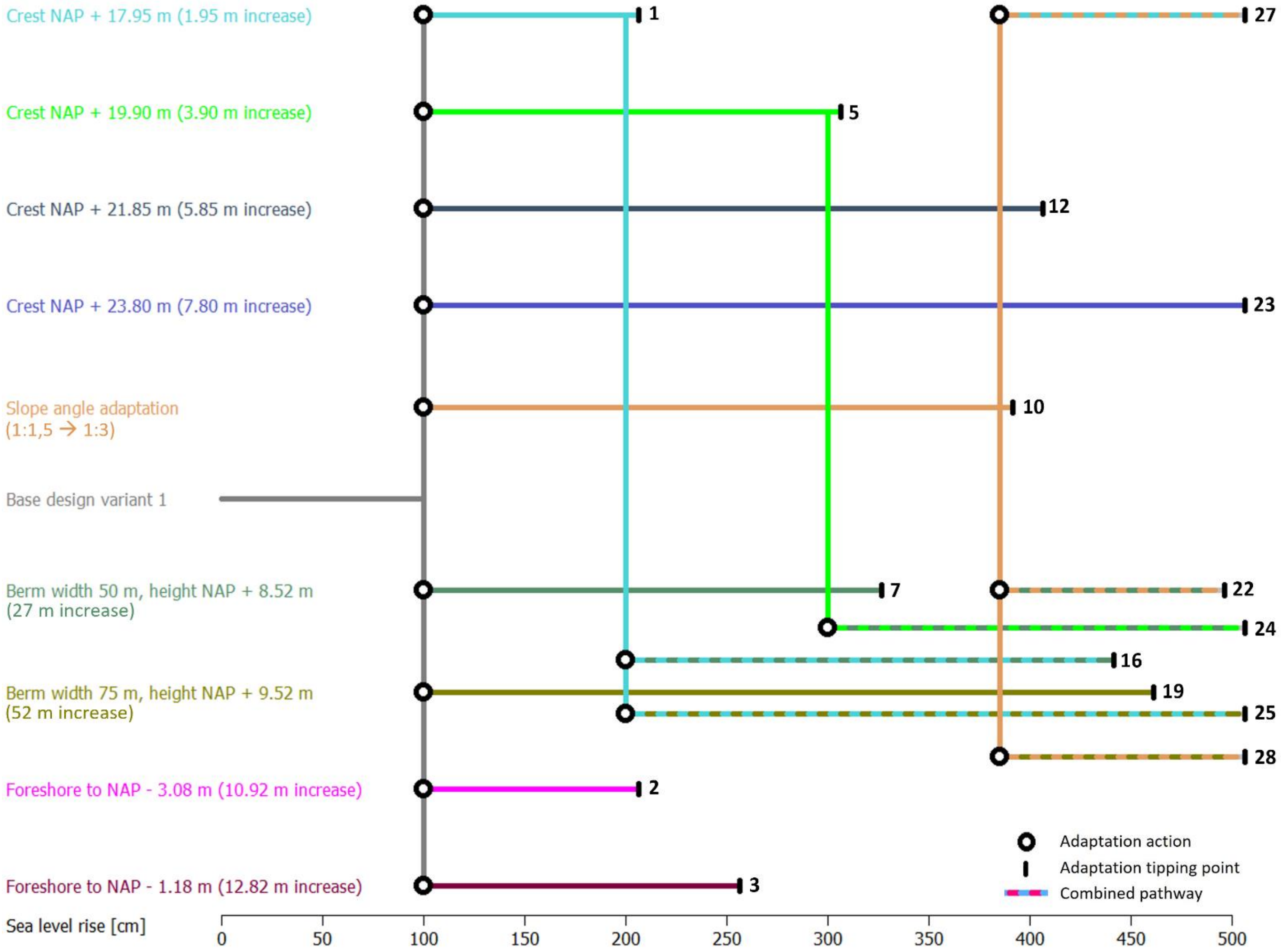


Figure G. 3 Adaptive pathway scheme of design variant 3 without the use of foreshore adaptation in a combination

Appendix H: Determination of amount of construction material

In this appendix the amount of construction material which is necessary for the adaptation of the three sea defence variants is determined. First the general amounts of construction material for the sea defence are elaborated on, followed by the construction processes for the various adaptation methods. Finally the construction materials for the three design variants and the extra materials for every pathway are calculated.

H.1 General construction materials for the Delta21 sea defence

Since the sea defence is created with a sandy core, a very large part of the dike will be formed out of sand, which will be dredged from the energy storage lake. However, other construction materials will be used as well.

Since the thesis in the main report speaks of a conceptual design, the various transition constructions between the slope angles and different materials are not detailed. The same goes for filter layers, eventual geotextiles and toe constructions of the slopes.

This thesis will regard the use of asphalt on the inner slope (open stone asphalt) and outer slope (hydraulic asphalt), a clay layer on the inner slope and the use of interlocking armour units on the outer slope.

Asphalt

Two types of asphalt will be discussed: open stone asphalt (as a protective layer on the inner slope) and hydraulic asphalt (as a protective layer on the slopes of the design variant 2 and the berm of all three the variants). For the use of open stone asphalt on the inner slope a thickness of 0,2 meters is assumed (Deltares, 2015), this asphalt type has a volumetric weight of 2100 kg/m^3.

For hydraulic asphalt on the berm or slope a thickness of 0,5 meters is assumed (Deltares, 2015), this asphalt type has a volumetric weight of 2400 kg/m^3. This assumption is based on the size of the incoming waves. In this assumption however the influence of water overpressure and front slope stability are not regarded, which will influence the necessary layer thickness.

Clay

In all variants a clay layer will be present on the inner slope of the sea defence. In the base version of variant 1 this layer has a protective function for water safety, for variants 2 and 3 the clay layer will provide water tightness of the dike which prevents large amounts of flow through the dike.

In both cases this clay layer will be 1 meter thick, of which the top 0,2 meters will consist of a vegetation layer (TAW, 1996).

Interlocking armour units

The third top layer which can be defined in the sea defence variants is the use of interlocking armour units on the slopes, in this thesis the use of XBloc is regarded. These units gain stability by locking into each other, a process which is dependent on slope steepness and unit weight.

Volume of X-Bloc per unit

The base volume for X-Blocs is determined via formula H.1:

$$V_{XBloc} = \left(\frac{H_s}{2.77 * \Delta}\right)^3 \qquad (H.1)$$

In which

$$\Delta = \frac{\rho_c - \rho_w}{\rho_w} \qquad (H.2)$$

The density of concrete for these armour units is maximum 2500 kg/m^3.

The required X-Bloc volume is also influenced by the core permeability and slope steepness.

For impermeable cores (which is the case for the Delta21 sea defence), the X-Bloc volume will be multiplied by 2. For slopes steeper than 1:1.5 (which is the case for variant 1 and adapted variant 3), this volume will have to be multiplied by 1.5 (Delta Marine Consultants, 2018).

Using a concrete density of 2500 kg/m^3 and a salt water density of 1025 kg/m^3, the following required X-Bloc volumes can be determined for significant wave heights of 7.87 and 8.97 meters:

Significant wave height [m]	Slope steepness 1:1.5	Slope steepness 1:3
7.87	15.39 m^3	23.09 m^3
8.97	22.79 m^3	34.19 m^3

Table H. 1 Required volume for X-Bloc under the influence of wave height and slope steepness

Armour layer thickness

For the required X-Bloc volumes, the layer thickness of the armour layer will be as represented in Figure H.1 and Table H.2 underneath:

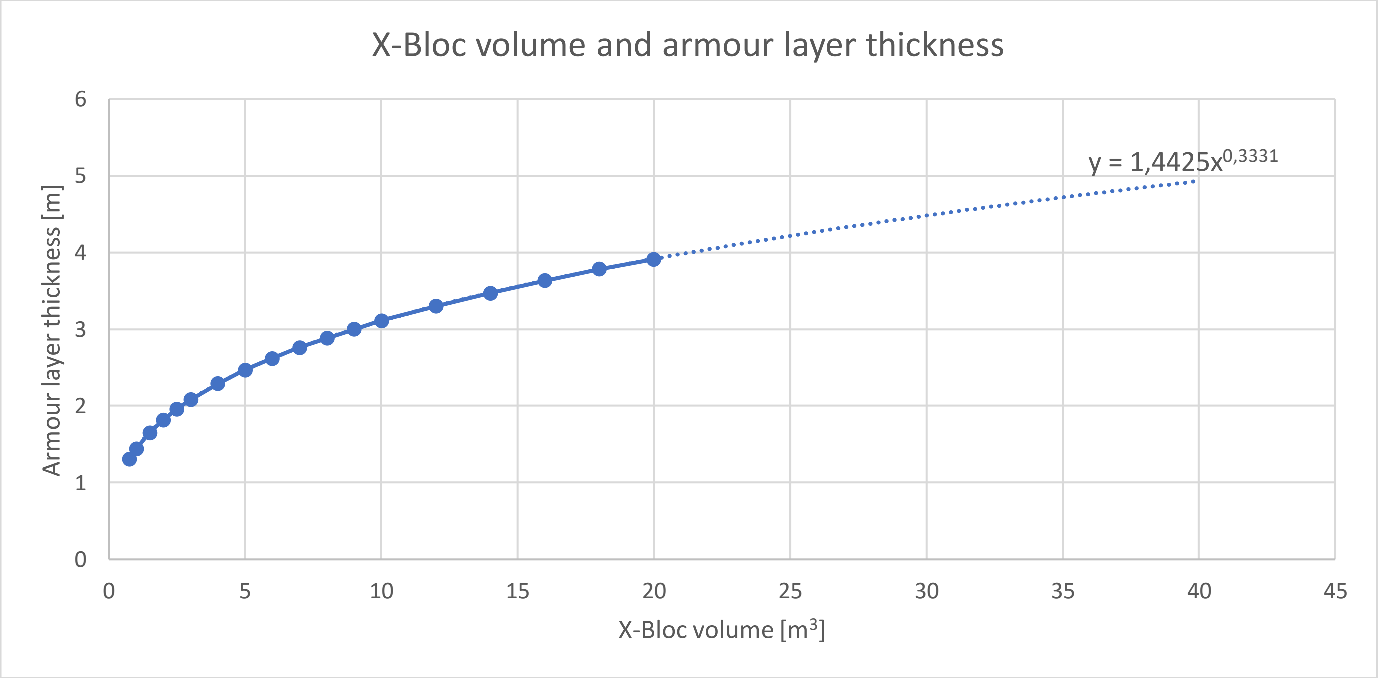


Figure H. 1 Relationship between X-Bloc volume and armour layer thickness

Significant wave height [m]	Slope steepness 1:1.5	Slope steepness 1:3
7.87	3.59 m	4.10 m
8.97	4.09 m	4.68 m

Table H. 2 armour layer thickness for X-Bloc under the influence of wave height and slope steepness

Since X-Bloc have lifetime of 100 years, it is assumed that the X-Blocs do only have to be purchased once at the start of the project and re-used at every adaptation step. Therefore X-Blocs with a volume of 34.19 m^3 and a unit height (and similar armour layer thickness) of 4.68 m will be used in the Delta21 sea defence.

Packing density of the X-Bloc units

The packing density of X-Bloc units can be determined based on the unit volume as well and is characterized as a number of interlocking armour units per 100 square meters. The relationship between these two values is graphically presented in Figure H.2 underneath.

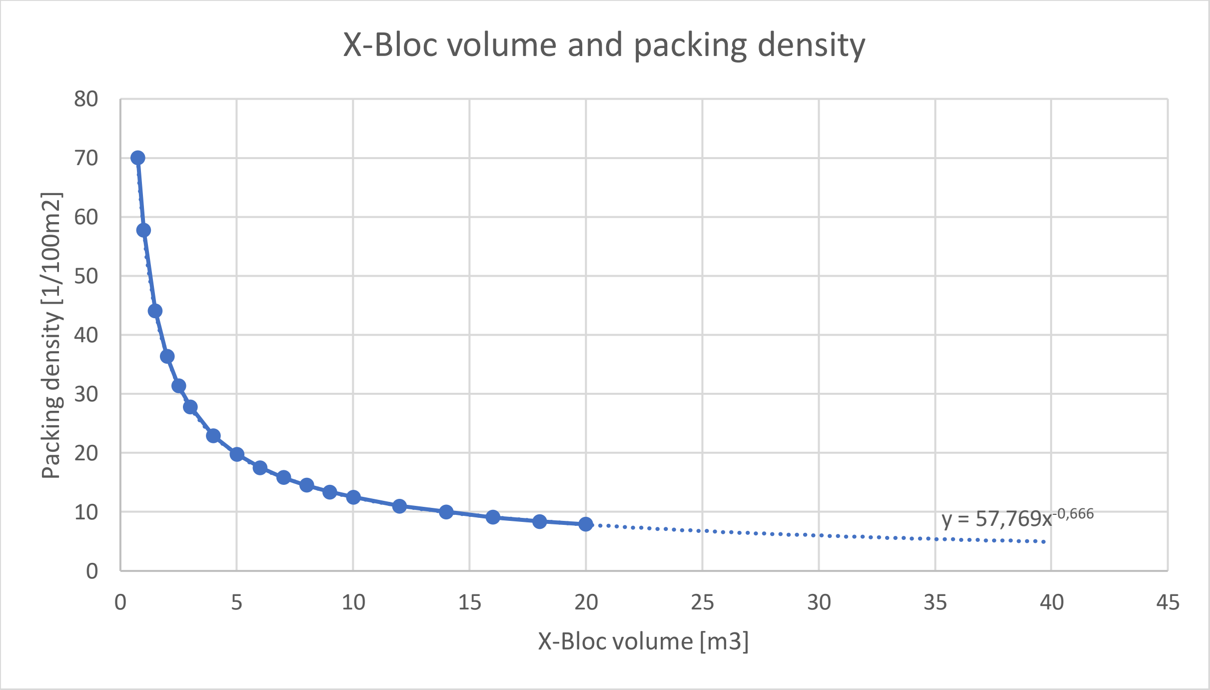


Figure H. 2 Relationship between X-Bloc volume and packing density

Significant wave height [m]	Slope steepness 1:1.5	Slope steepness 1:3
7.87	9.34	7.13
8.97	7.19	5.49

Table H. 3 packing density for X-Bloc under the influence of wave height and slope steepness

H.2 Constructions processes for the adaptation methods

Crest level increase

Four steps of crest height adaptation are defined for each of the design variants. For crest height adaptation the amount of sand in the cross-section changes. It is assumed that the top clay layer of the base sea dike is removed and the new profile is formed in sand. After this the removed inner slope protection is placed back on the slope.

Since the length of the outer slope lengthens as well for crest level increase, the outer slope protection increases in length as well.

For design variant 1 each step in crest height increase requires the following steps:

- Removal of clay from the inner slope
- Addition of sand to the core
- Addition of one row of X-Blocs on the front slope
- Replacement of clay on the inner slope

For design variant 2 each step in crest height increase requires the following steps:

- Removal of life layer from the inner slope
- Removal of asphalt layer from the inner slope
- Removal of lower clay layer from the inner slope
- Addition of sand to the core
- Replacement of clay on the inner slope
- Placement of new asphalt on the inner slope
- Replacement of life layer on the inner slope
- Addition of extra asphalt length on the outer slope

For design variant 1 each step in crest height increase requires the following steps:

- Removal of life layer from the inner slope
- Removal of asphalt layer from the inner slope
- Removal of lower clay layer from the inner slope
- Addition of sand to the core
- Replacement of clay on the inner slope
- Placement of new asphalt on the inner slope
- Replacement of life layer on the inner slope
- Addition of one row of X-Blocs on the front slope

Berm with increase

Berm adaptation with Xbloc units on the slopes

For berm adaption first all layers of Xbloc are removed from the slopes and the asphalt is removed from the berm. After this sand is applied on the berm to bring it to sufficient height and width. Last, the rows of X-Bloc are placed back and a new asphalt berm is put in place.

Berm adaptation requires the following steps:

- Removal of all X-Bloc from the outer slope
- Removal of hydraulic asphalt from the berm
- Addition of sand to the berm
- Replacement of all X-Bloc on the outer slope
- Placement of new hydraulic asphalt on the berm

Berm adaptation with hydraulic asphalt on the slopes

For berm adaption first hydraulic asphalt is removed from the berm and slopes. After this sand is applied on the berm to bring it to sufficient height and width. Finally new asphalt is put in place on the outer slopes and berm again.

Berm adaptation requires the following steps:

- Removal of hydraulic asphalt
- Addition of sand to the berm and lower slope
- Placement of new hydraulic asphalt

Inner slope adaptation

For the adaptation of the inner slope an asphalt layer is applied on the inner slope. This requires the removal of the inner slope clay layer, the replacement of this clay layer with sufficient thickness, placement of the new asphalt layer and the placement of a life layer on top.

Inner slope adaptation requires the following steps:

- Removal of the inner slope clay layer
- Replacement of a clay layer with sufficient thickness
- Placement of an asphalt layer
- Placement of a life layer

Outer slope roughness adaptation

The adaptation of roughness of the outer slope will only be applied for design variant 2 which has an asphalted outer slope. This requires the removing of this asphalt top layer and the placement of Xbloc units.

Outer slope roughness adaptation requires the following steps:

- Removal of hydraulic asphalt
- Placement of Xbloc units on the upper and lower slope
- Replacement of hydraulic asphalt on the berm

Outer slope angle adaptation

Outer slope angle adaptation knows two variants:

1. from 1:3 to 1:4 for an asphalt slope
2. from 1:1,5 to 1:3 for a slope covered in concrete armour units.

Case 1 requires the following steps:

- Removal of hydraulic asphalt
- Addition of sand to the slopes and berm to form the new geometry
- Placement of new hydraulic asphalt

Case 2 requires the following steps:

- Removal of Xbloc from lower and upper slopes
- Removal of hydraulic asphalt from berm
- Addition of sand to the slopes and berm to form the new geometry
- Replacement of Xbloc on lower and upper slopes
- Placement of new hydraulic asphalt on the berm

Foreshore adaptation

In total two steps of foreshore adaptation can be identified for every design variant.

All foreshores will be approximately 700 meters long and will be mainly be created by sand nourishment.

Due to the increase in foreshore level some erosion might occur, which will have to be prevented by an armour layer. However this layer is not in the scope of this thesis and will have to be dimensioned in further studies.

H.3 Construction materials per adaptational pathway design variant 1

Using the adaptational pathways as presented in Chapter 7 of the main report, the construction materials and processes necessary to complete the adaptation pathway can be determined. The construction materials and processes for the adaptational pathways for design variant 1 can be found underneath in table H.4.

Pathway number	Clay			Sand	Open stone asphalt		Hydraulic asphalt		Interlocking Armour Units		
	New	Removal	Replacement	Placement	New	Removal	New	Removal	New	Removal	Replacement
	[m3]	[m3]	[m3]	[m3]	[m3]	[m3]	[m3]	[m3]	[Pcs.]	[Pcs.]	[Pcs.]
0	94,9	0	0	2761,6	0	0	12,0	0	5,2	0	0
1	5,2	94,9	94,9	282,1	0,0	0,0	0,0	0	0,3	0,0	0,0
2	0,0	0,0	0,0	5801,0	0,0	0,0	0,0	0	0,0	0,0	0,0
3	0,0	0,0	0,0	570,5	0,0	0,0	13,0	12	0,0	5,2	5,2
4	0,0	0,0	0,0	7155,0	0,0	0,0	0,0	0	0,0	0,0	0,0
4.2	0,0	0,0	0,0	7155,0	0,0	0,0	0,0	0	0,0	0,0	0,0
6	10,4	94,9	94,9	580,6	0,0	0,0	0,0	0	0,6	0,0	0,0
6.2	10,4	195,0	195,0	580,6	0,0	0,0	0,0	0	0,6	0,0	0,0
8	0,0	0,0	0,0	1171,0	0,0	0,0	25,5	12	0,0	5,2	5,2
8.2	0,0	0,0	0,0	1171,0	0,0	0,0	25,5	49,5	0,0	10,4	10,4
10	5,2	94,9	94,9	852,7	0,0	0,0	13,0	12	0,3	5,2	5,2
14	0,0	94,9	94,9	0,0	19,0	0,0	0,0	0	0,0	0,0	0,0
16	15,7	94,9	94,9	895,4	0,0	0,0	0,0	0	0,9	0,0	0,0
16.2	15,7	197,6	197,6	895,4	0,0	0,0	0,0	0	0,9	0,0	0,0
16.3	15,7	197,6	197,6	895,4	0,0	0,0	0,0	0	0,9	0,0	0,0
16.4	15,7	295,0	295,0	895,4	0,0	0,0	0,0	0	0,9	0,0	0,0
19	10,4	94,9	94,9	1151,1	0,0	0,0	13,0	12	0,6	5,2	5,2
19.2	10,4	195,0	195,0	1151,1	0,0	0,0	13,0	12	0,6	5,2	5,2
20	5,2	94,9	94,9	1453,2	0,0	0,0	25,5	12	0,3	5,2	5,2
20.2	5,2	94,9	94,9	1453,2	0,0	0,0	25,5	49,5	0,3	10,4	10,4
27	0,0	94,9	94,9	551,5	19,0	0,0	13,0	12	0,0	5,2	5,2
31	20,9	94,9	94,9	1226,5	0,0	0,0	0,0	0	1,1	0,0	0,0
31.2	20,9	200,2	200,2	1226,5	0,0	0,0	0,0	0	1,1	0,0	0,0
31.3	20,9	200,2	200,2	1226,5	0,0	0,0	0,0	0	1,1	0,0	0,0
31.4	20,9	200,2	200,2	1226,5	0,0	0,0	0,0	0	1,1	0,0	0,0
31.5	20,9	298,5	298,5	1226,5	0,0	0,0	0,0	0	1,1	0,0	0,0
31.6	20,9	298,5	298,5	1226,5	0,0	0,0	0,0	0	1,1	0,0	0,0
31.7	20,9	298,5	298,5	1226,5	0,0	0,0	0,0	0	1,1	0,0	0,0
31.8	20,9	395,1	395,1	1226,5	0,0	0,0	0,0	0	1,1	0,0	0,0
32	15,7	94,9	94,9	1465,9	0,0	0,0	13,0	12	0,9	5,2	5,2
32.2	15,7	197,6	197,6	1465,9	0,0	0,0	13,0	12	0,9	5,2	5,2
32.3	15,7	197,6	197,6	1465,9	0,0	0,0	13,0	12	0,9	5,2	5,2
32.4	15,7	295,0	295,0	1465,9	0,0	0,0	13,0	12	0,9	5,2	5,2
33	10,4	94,9	94,9	1751,6	0,0	0,0	25,5	12	0,6	5,2	5,2
33.2	10,4	94,9	94,9	1751,6	0,0	0,0	25,5	49,5	0,6	10,4	10,4
33.3	10,4	195,0	195,0	1751,6	0,0	0,0	25,5	12	0,6	5,2	5,2
33.4	10,4	195,0	195,0	1751,6	0,0	0,0	25,5	49,5	0,6	10,4	10,4
36	5,2	192,3	192,3	262,1	39,0	19,0	0,0	0	0,3	0,0	0,0
37	0,0	94,9	94,9	1152,0	19,0	0,0	25,5	12	0,0	5,2	5,2
37.2	0,0	94,9	94,9	1152,0	19,0	0,0	25,5	49,5	0,0	10,4	10,4

Table H. 4 Construction materials for the lifecycle of design variant 1

H.4 Construction materials per adaptational pathway design variant 2

Using the adaptational pathways as presented in Chapter 7 of the main report, the construction materials and processes necessary to complete the adaptation pathway can be determined. The construction materials and processes for the adaptational pathways for design variant 2 can be found underneath in table H.5.

Pathway number	Clay			Sand	Open stone asphalt		Hydraulic asphalt		Interlocking Armour Units		
	New	Removal	Replacement	Placement	New	Removal	New	Removal	New	Removal	Replacement
	[m3]	[m3]	[m3]	[m3]	[m3]	[m3]	[m3]	[m3]	[Pcs.]	[Pcs.]	[Pcs.]
0	94,9	0	0	3099,2	19,0	0	58,4	0,0	0,0	0	0
1	5,5	94,9	94,9	321,8	20,1	19,0	2,8	0,0	0,0	0,0	0,0
2	0,0	0,0	0,0	5571,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
3	0,0	0,0	0,0	435,6	0,0	0,0	73,3	58,4	0,0	0,0	0,0
6	11,1	94,9	94,9	661,9	21,2	19,0	5,5	0,0	0,0	0,0	0,0
6.2	11,1	195,3	195,3	661,9	40,2	37,9	5,5	0,0	0,0	0,0	0,0
7	0,0	0,0	0,0	7056,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
7.2	0,0	0,0	0,0	7056,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
8	0,0	0,0	0,0	560,6	0,0	0,0	86,4	58,4	0,0	0,0	0,0
9	5,5	94,9	94,9	810,6	20,1	19,0	94,5	58,4	0,0	0,0	0,0
14	0,0	0,0	0,0	0,0	0,0	0,0	11,0	58,4	5,2	0,0	0,0
16	16,6	94,9	94,9	1020,5	22,3	19,0	8,3	0,0	0,0	0,0	0,0
16.2	16,6	198,0	198,0	1020,5	41,3	37,9	8,3	0,0	0,0	0,0	0,0
16.3	16,6	198,0	198,0	1020,5	41,3	37,9	8,3	0,0	0,0	0,0	0,0
16.4	16,6	295,7	295,7	1020,5	60,2	56,9	8,3	0,0	0,0	0,0	0,0
17	0,0	0,0	0,0	1096,1	0,0	0,0	202,1	145,3	0,0	0,0	0,0
20	5,5	94,9	94,9	982,3	20,1	19,0	92,0	58,4	0,0	0,0	0,0
23	0,0	0,0	0,0	1286,1	0,0	0,0	111,4	58,4	0,0	0,0	0,0
23.2	0,0	0,0	0,0	1286,1	0,0	0,0	196,4	143,4	0,0	0,0	0,0
24	11,1	94,9	94,9	1207,0	21,2	19,0	101,7	58,4	0,0	0,0	0,0
24.2	11,1	195,3	195,3	1207,0	40,2	37,9	101,7	58,4	0,0	0,0	0,0
30	0,0	0,0	0,0	264,0	0,0	0,0	22,0	116,9	5,2	5,2	5,2
32	22,1	94,9	94,9	1397,4	23,4	19,0	11,1	0,0	0,0	0,0	0,0
32.2	22,1	200,8	200,8	1397,4	42,4	37,9	11,1	0,0	0,0	0,0	0,0
32.3	22,1	200,8	200,8	1397,4	42,4	37,9	11,1	0,0	0,0	0,0	0,0
32.4	22,1	200,8	200,8	1397,4	42,4	37,9	11,1	0,0	0,0	0,0	0,0
32.5	22,1	299,4	299,4	1397,4	61,3	56,9	11,1	0,0	0,0	0,0	0,0
32.6	22,1	299,4	299,4	1397,4	61,3	56,9	11,1	0,0	0,0	0,0	0,0
32.7	22,1	299,4	299,4	1397,4	61,3	56,9	11,1	0,0	0,0	0,0	0,0
32.8	22,1	396,1	396,1	1397,4	80,3	75,9	11,1	0,0	0,0	0,0	0,0
33	5,5	94,9	94,9	1607,8	20,1	19,0	117,0	58,4	0,0	0,0	0,0
33.2	5,5	94,9	94,9	1607,8	20,1	19,0	204,7	146,1	0,0	0,0	0,0
34	11,1	94,9	94,9	1322,5	21,2	19,0	97,5	58,4	0,0	0,0	0,0
34.2	11,1	195,3	195,3	1322,5	40,2	37,9	97,5	58,4	0,0	0,0	0,0
36	16,6	94,9	94,9	1624,8	22,3	19,0	108,9	11,0	0,0	0,0	0,0
36.2	16,6	198,0	198,0	1624,8	41,3	37,9	108,9	58,4	0,0	0,0	0,0
36.3	16,6	198,0	198,0	1624,8	41,3	37,9	108,9	58,4	0,0	0,0	0,0
36.4	16,6	295,7	295,7	1624,8	60,2	56,9	108,9	58,4	0,0	0,0	0,0
37	0,0	0,0	0,0	1721,6	0,0	0,0	239,6	157,8	0,0	0,0	0,0
37.2	0,0	0,0	0,0	1721,6	0,0	0,0	339,0	257,1	0,0	0,0	0,0
40	5,5	94,9	94,9	0,0	20,1	19,0	11,0	58,4	5,5	0,0	0,0
41	0,0	0,0	0,0	889,5	0,0	0,0	22,0	116,9	5,2	5,2	5,2
41.2	0,0	0,0	0,0	889,5	0,0	0,0	33,0	175,3	5,2	10,4	10,4
44	5,5	94,9	94,9	1471,1	20,1	19,0	212,9	148,9	0,0	0,0	0,0

Table H. 5 Construction materials for the lifecycle of design variant 2

H.5 Construction materials per adaptational pathway design variant 3

Using the adaptational pathways as presented in Chapter 7 of the main report, the construction materials and processes necessary to complete the adaptation pathway can be determined. The construction materials and processes for the adaptational pathways for design variant 3 can be found underneath in table H.6.

Pathway number	**Clay**			**Sand**	**Open stone asphalt**		**Hydraulic asphalt**		**Interlocking Armour Units**		
	New	**Removal**	**Replacement**	**Placement**	**New**	**Removal**	**New**	**Removal**	**New**	**Removal**	**Replacement**
	[m3]	**[m3]**	**[m3]**	**[m3]**	**[m3]**	**[m3]**	**[m3]**	**[m3]**	**[Pcs.]**	**[Pcs.]**	**[Pcs.]**
0	94,9	0	0	2238,5	19,0	0	11,5	0	3,0	0	0
1	6,2	94,9	94,9	255,8	20,2	19,0	0,0	0	0,2	0,0	0,0
2	0,0	0,0	0,0	5571,0	0,0	0,0	0,0	0	0,0	0,0	0,0
3	0,0	0,0	0,0	6429,0	0,0	0,0	0,0	0	0,0	0,0	0,0
3.2	0,0	0,0	0,0	6429,0	0,0	0,0	0,0	0	0,0	0,0	0,0
5	12,3	94,9	94,9	528,6	21,4	19,0	0,0	0	0,4	0,0	0,0
5.2	12,3	195,9	195,9	528,6	40,4	37,9	0,0	0	0,4	0,0	0,0
7	0,0	0,0	0,0	640,5	0,0	0,0	13,5	11,5	0,0	3,0	3,0
10	0,0	0,0	0,0	484,1	0,0	0,0	0,0	11,5	2,2	3,0	3,0
12	18,5	94,9	94,9	818,6	22,7	19,0	0,0	0	0,6	0,0	0,0
12.2	18,5	199,0	199,0	818,6	41,6	37,9	0,0	0	0,6	0,0	0,0
12.3	18,5	199,0	199,0	818,6	41,6	37,9	0,0	0	0,6	0,0	0,0
12.4	18,5	296,9	296,9	818,6	60,6	56,9	0,0	0	0,6	0,0	0,0
16	6,2	94,9	94,9	896,3	20,2	19,0	13,5	11,5	0,2	3,0	3,0
19	0,0	0,0	0,0	1266,0	0,0	0,0	26,0	11,5	0,0	3,0	3,0
19.2	0,0	0,0	0,0	1266,0	0,0	0,0	26,0	49	0,0	5,9	5,9
22	0,0	0,0	0,0	1124,7	0,0	0,0	13,5	36,5	2,2	5,9	5,9
23	24,7	94,9	94,9	1125,7	23,9	19,0	0,0	0	0,8	0,0	0,0
23.2	24,7	202,1	202,1	1125,7	42,9	37,9	0,0	0	0,8	0,0	0,0
23.3	24,7	202,1	202,1	1125,7	42,9	37,9	0,0	0	0,8	0,0	0,0
23.4	24,7	202,1	202,1	1125,7	42,9	37,9	0,0	0	0,8	0,0	0,0
23.5	24,7	301,0	301,0	1125,7	61,9	56,9	0,0	0	0,8	0,0	0,0
23.6	24,7	301,0	301,0	1125,7	61,9	56,9	0,0	0	0,8	0,0	0,0
23.7	24,7	301,0	301,0	1125,7	61,9	56,9	0,0	0	0,8	0,0	0,0
23.8	24,7	398,0	398,0	1125,7	80,8	75,9	0,0	0	0,8	0,0	0,0
24	12,3	94,9	94,9	1169,2	21,4	19,0	13,5	11,5	0,4	3,0	3,0
24.2	12,3	195,9	195,9	1169,2	40,4	37,9	13,5	11,5	0,4	3,0	3,0
25	6,2	94,9	94,9	1521,8	20,2	19,0	26,0	11,5	0,2	3,0	3,0
25.2	6,2	94,9	94,9	1521,8	20,2	19,0	26,0	49	0,2	5,9	5,9
27	6,2	94,9	94,9	818,1	20,2	19,0	0,0	11,5	2,6	3,0	3,0
28	0,0	0,0	0,0	1750,2	0,0	0,0	26,0	49	2,2	5,9	5,9
28.2	0,0	0,0	0,0	1750,2	0,0	0,0	26,0	86,5	2,2	8,9	8,9

Table H. 6 Construction materials for the lifecycle of design variant 3

Appendix I: Determination of Environmental Cost Indicator

This appendix describes the appliance of the Environmental Costs Indicator (ECI) as used in the main report about the Delta21 sea defence.

Sustainability, circularity and environmental awareness are gaining importance in society and thereby also in large infrastructural projects in the Netherlands. Because of this the outcomes of Life-Cycle-Analysis (LCA) are taken into account for these project more regularly. For the different products and suppliers which come together in a large product, the lifecycle analysis is typically performed using various different methods. This causes the outcomes of these analysis to differ widely over the market as well. In order to be able to compare the different impacts products and processes have, the more general environmental costs indicator (ECI) or in Dutch “milieu kosten indicator” is created.

The environmental costs indicator is a single score unit which bundles various different environmental impacts in a single score, expressed in Euros. The various different impacts are defined as presented in Table I.1 underneath.

Impact category	Unit	Weighting factor (€/unit)
Global warming	kg CO_2-eq	0,05 €
Ozone depletion	kg CFC-11-eq	30,00 €
Acidification of soil and water	kg SO_2-eq	4,00 €
Eutrophication	kg PO_4^3-eq	9,00 €
Depletion of abiotic resources – elements	kg Sb-eq	0,16 €
Depletion of abiotic resources – fossil fuels	kg Sb-eq	0,16 €
Human toxicity	kg 1,4 DB-eq	0,09 €
Freshwater toxicity	kg 1,4 DB-eq	0,03 €
Marine water toxicity	kg 1,4 DB-eq	0,0001 €
Terrestrial toxicity	kg 1,4 DB-eq	0,06 €
Photochemical oxidant creation (smog)	kg C_2H_4-eq	2,00 €

Table I. 1 Weighting factors [€] of the various impact categories of the ECI

The environmental costs indicator is created out of a materials life cycle analysis. For every product the impact of the raw materials and processes that lead to the used material are listed and the impact is reviewed. By translating the different impacts to an amount of Euros, the different kinds of environmental impacts of materials and processes be compared. This results in a method to compare the environmental impact of vastly different design variants.

This method is visualized in Figure I.1 underneath.

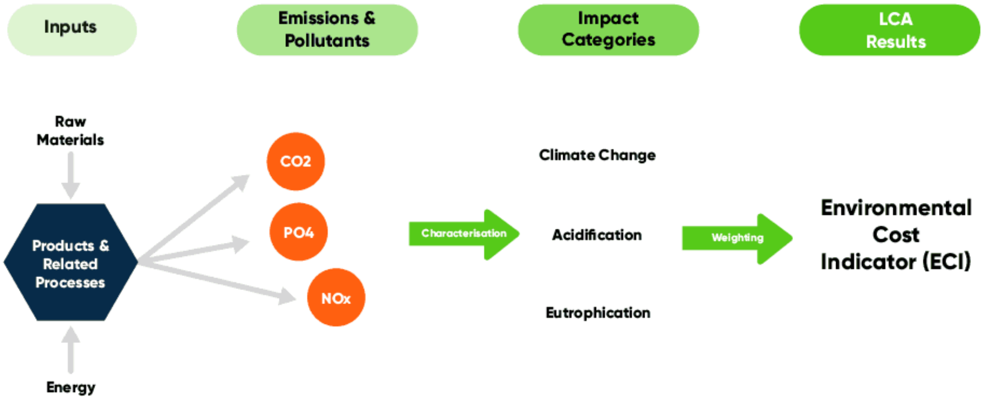


Figure I. 1 The ECI workflow

The environmental cost indicator is not only used to compare different design variants in one project, but also to review different tender bids from various contractors. In this process a low environmental costs indicator means that the tender bid has a low impact on the environment. Since this is an important factor in the modern day infrastructure market a low ECI value can lead to a discount in tender offer, resulting in a process in which a higher bid can still win due to a low ECI value, as shown in Figure I.2 underneath.

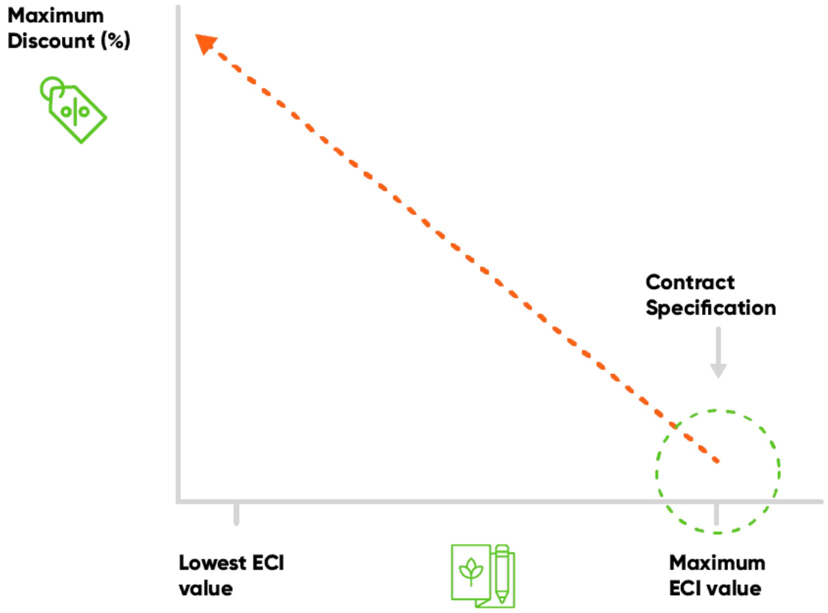


Figure I. 2 Tender bid discount coupled to ECI values

Environmental cost indicator in the Delta21 project

In the main report, the environmental cost indicator is uses to create an assessment and compare different sea defence adaptation strategies. The different measures which can be taken to adapt the sea defence to future levels of sea level rise all have different environmental cost indicator, which can be used as a criteria to pick the preferred adaptation method.

In the determination of the ECI of the different adaptation options, firstly the ECI of the different construction materials is determined. In this thesis the values for the different materials are used as indicated in DuboCalc, which is general software created to determine the ECI value for infrastructural projects.

The ECI values for the different construction materials and processes come from the “Hoog Water Beschermingsprogramma (HWBP)” database as created by Rijkswaterstaat and the national environmental database or “Nationale milieudatabase”. The values per unit as used in this thesis are listed in Table I.2 underneath.

Material or process	Unit	ECI – value per unit [€]
Delivering and applying clay	m^3	4,438944
Delivering and applying sand for base design	m^3	1,504201
Delivering and applying sand for adaptation options	m^3	3,880376
Delivering and applying sand for foreshore adaptation	m^3	0,936752
Delivering and applying Hydraulic Asphalt	tonnes	46,499576
Delivering and applying Open stone Asphalt	tonnes	20,432396
Delivering and applying X-Block	Pcs.	647,149215
Removing clay layer	m^3	0,103650
Removing Hydraulic Asphalt	tonnes	2,89954
Removing Open stone Asphalt	tonnes	1,052232
Removing X-Block	Pcs.	3,228821
Replacing clay layer	m^3	0,148147
Replacing X-Block	Pcs.	3,228821

Table I. 2 ECI-values for applied materials and processes

Using the ECI-values for each of the materials and processes as mentioned in Table I.2 above, the eventual environmental cost indicators for the design variants and their adaption options can be determined.

Assumptions in determination of Environmental cost indicators

For the determination of the ECI-values of the various processes and materials, multiple assumptions have been made. The most important assumptions for each of the categories are listed underneath.

Clay

It is assumed that the clay is brought to the project by inland shipping. After arrival on the project site it is handled by excavators.

Removal of the clay is handled by excavators as well, after which it is brought to a depot on the project site by truck. This clay is later placed back on the dike in the same way.

Sand

The sand which is used in the dike for the base variants is assumed to be acquired by dredging and later put in place by bulldozers and excavators. However for the adaptation methods it is assumed that sand is brought to the project site by inland shipping, after which it is put in place by excavators.

Foreshore adaptation however is performed by sand suppletion by rainbowing.

Asphalt

The ECI-values of both the types of asphalt (OSA and hydraulic asphalt) are based on asphalt concretes with densities of 2100 and 2400 kg/m^3 respectively.

X-Bloc

For X-Bloc the assumption has been made that, even though the volume of the units is very large, the blocks can still be created without reinforcement steel. As this is common practice for X-Bloc units. The blocks will be casted nearby the project site and transported by inland shipping vessel. Upon arrival the blocks will be put in place by an hydraulic excavator.

Removal and re-use of the X-Bloc units will be performed by inland shipping vessels and hydraulic excavators as well. During operation the blocks will be stored in a depot on site.

I.1 Environmental costs indicator of Delta21 sea defence variant 1

The required materials for the adaptation options of Delta21 sea defence variant 1 are presented in Appendix H: Determination of amount of construction material. Using this information and coupling it to the information in Table I.2 above, the ECI-value for the different adaptation pathways for design variant 1 are determined. The ECI-values for the different adaptation pathways for design variant 1 are presented in Table I.3 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Environmental cost indicator [€/m]
1	2	1	Crest + 1,65 m				1188
2	2	1	Foreshore to -1,74 m				5434
3	2,2	1	Berm 50 m				3501
4	2,5	1	Foreshore to 0,22 m				6702
4.2		2	Foreshore to -1,74 m	Foreshore to 0,22 m			6702
6	3	1	Crest + 3,30 m				2408
6.2		2	Crest + 1,65 m	Crest + 3,30 m			2433
8	3,15	1	Berm 75 m				6930
8.2		2	Berm 50 m	Berm 75 m			7225
10	3,25	2	Berm 50 m	Crest + 1,65 m			4689
14	3,9	1	Inner slope				838
16	4	1	Crest + 4,95 m				3683
16.2		2	Crest + 1,65 m	Crest + 4,95 m			3709
16.3		2	Crest + 3,30 m	Crest + 4,95 m			3709
16.4		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m		3734
19	4,2	2	Crest + 3,30 m	Berm 50 m			5909
19.2		3	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m		5934
20	4,2	2	Crest + 1,65 m	Berm 75 m			8119
20.2		3	Crest + 1,65 m	Berm 50 m	Berm 75 m		8413
27	4,75	2	Inner slope	Berm 50 m			4275
31	5	1	Crest + 6,60 m				5014
31.2		2	Crest + 1,65 m	Crest + 6,60 m			5040
31.3		2	Crest + 3,30 m	Crest + 6,60 m			5040
31.4		2	Crest + 4,95 m	Crest + 6,60 m			5040
31.5		3	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m		5065
31.6		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 6,60 m		5065
31.7		3	Crest + 1,65 m	Crest + 4,95 m	Crest + 6,60 m		5065
31.8		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m	5089
32	5	2	Crest + 4,95 m	Berm 50 m			7184
32.2		3	Crest + 1,65 m	Crest + 4,95 m	Berm 50 m		7210
32.3		3	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m		7210
32.4		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m	7234
33	5	2	Crest + 3,30 m	Berm 75 m			9338
33.2		3	Crest + 3,30 m	Berm 50 m	Berm 75 m		9633
33.3		3	Crest + 1,65 m	Crest + 3,30 m	Berm 75 m		9364
33.4		4	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m	Berm 75 m	9658
36	5	2	Inner slope	Crest + 1,65 m			2860
37	5	2	Inner slope	Berm 75 m			7704
37.2		3	Inner slope	Berm 50 m	Berm 75 m		7999

Table I. 3 ECI-values for the different pathways for conceptual design variant 1

I.2 Environmental costs indicator of Delta21 sea defence variant 2

The required materials for the adaptation options of Delta21 sea defence variant 2 are presented in Appendix H: Determination of amount of construction material. Using this information and coupling it to the information in Table I.2 above, the ECI-value for the different adaptation pathways for design variant 2 are determined. The ECI-values for the different adaptation pathways for design variant 2 are presented in Table I.4 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Environmental cost indicator [€/m]
1	2	1	Crest + 1,75 m				2351
2	2	1	Foreshore to -3,08 m				5219
3	2,25	1	Slope angle				3491
6	3	1	Crest + 3,50 m				3884
6.2		2	Crest + 1,75 m	Crest + 3,50 m			4766
7	3	1	Foreshore to -0,08 m				6610
7.2		2	Foreshore to -3,08 m	Foreshore to -0,08 m			6610
8	3,2	1	Berm 50 m				3868
9	3,4	2	Slope angle	Crest + 1,75 m			6116
14	3,85	1	Slope roughness				5777
16	4	1	Crest + 5,25 m				5480
16.2		2	Crest + 1,75 m	Crest + 5,25 m			6362
16.3		2	Crest + 3,50 m	Crest + 5,25 m			6362
16.4		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m		7243
17	4	2	Slope angle	Berm 50 m			7896
20	4,35	2	Crest + 1,75 m	Berm 50 m			6558
23	4,5	1	Berm 75 m				7721
23.2		2	Berm 50 m	Berm 75 m			8312
24	4,5	2	Slope angle	Crest + 3,50 m			7934
24.2		3	Slope angle	Crest + 1,75 m	Crest + 3,50 m		8815
30	4,9	2	Slope roughness	Berm 50 m			7112
32	5	1	Crest + 7,00 m				7138
32.2		2	Crest + 1,75 m	Crest + 7,00 m			8020
32.3		2	Crest + 3,50 m	Crest + 7,00 m			8020
32.4		2	Crest + 5,25 m	Crest + 7,00 m			8020
32.5		3	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m		8901
32.6		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 7,00 m		8901
32.7		3	Crest + 1,75 m	Crest + 5,25 m	Crest + 7,00 m		8901
32.8		4	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m	9782
33	5	2	Crest + 1,75 m	Berm 75 m			10072
33.2		3	Crest + 1,75 m	Berm 50 m	Berm 75 m		10683
34	5	2	Crest + 3,50 m	Berm 50 m			8091
34.2		3	Crest + 1,75 m	Crest + 3,50 m	Berm 50 m		8973
36	5	2	Slope angle	Crest + 5,25 m			9494
36.2		3	Slope angle	Crest + 1,75 m	Crest + 5,25 m		10706
36.3		3	Slope angle	Crest + 3,50 m	Crest + 5,25 m		10706
36.4		4	Slope angle	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	11587
37	5	2	Slope angle	Berm 75 m			11497
37.2		3	Slope angle	Berm 50 m	Berm 75 m		12188
40	5	2	Slope roughness	Crest + 1,75 m			7926
41	5	2	Slope roughness	Berm 75 m			9231
41.2		3	Slope roughness	Berm 50 m	Berm 75 m		9671
44	5	3	Slope angle	Crest + 1,75 m	Berm 50 m		10546

Table I. 4 ECI-values for the different pathways for conceptual design variant 2

I.3 Environmental costs indicator of Delta21 sea defence variant 3

The required materials for the adaptation options of Delta21 sea defence variant 3 are presented in Appendix H: Determination of amount of construction material. Using this information and coupling it to the information in Table I.2 above, the ECI-value for the different adaptation pathways for design variant 3 are determined. The ECI-values for the different adaptation pathways for design variant 3 are presented in Table I.5 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Environmental cost indicator [€/m]
1	2	1	Crest + 1,95 m				1952
2	2	1	Foreshore to -3,08 m				5219
3	2,5	1	Foreshore to -1,18 m				6022
3.2		2	Foreshore to -3,08 m	Foreshore to -1,18 m			6022
5	3	1	Crest + 3,90 m				3081
5.2		2	Crest + 1,95 m	Crest + 3,90 m			3963
7	3,2	1	Berm 50 m				3776
10	3,85	1	Slope angle				3188
12	4	1	Crest + 5,85 m				4269
12.2		2	Crest + 1,95 m	Crest + 5,85 m			5151
12.3		2	Crest + 3,90 m	Crest + 5,85 m			5151
12.4		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m		6032
16	4,35	2	Crest + 1,95 m	Berm 50 m			5428
19	4,55	1	Berm 75 m				7290
19.2		2	Berm 50 m	Berm 75 m			7570
22	4,9	2	Slope angle	Berm 50 m			7058
23	5	1	Crest + 7,80 m				5515
23.2		2	Crest + 1,95 m	Crest + 7,80 m			6398
23.3		2	Crest + 3,90 m	Crest + 7,80 m			6398
23.4		2	Crest + 5,85 m	Crest + 7,80 m			6398
23.5		3	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m		7279
23.6		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 7,80 m		7279
23.7		3	Crest + 1,95 m	Crest + 5,85 m	Crest + 7,80 m		7279
23.8		4	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m	8159
24	5	2	Crest + 3,90 m	Berm 50 m			6857
24.2		3	Crest + 1,95 m	Crest + 3,90 m	Berm 50 m		7039
25	5	2	Crest + 1,95 m	Berm 75 m			9242
25.2		3	Crest + 1,95 m	Berm 50 m	Berm 75 m		9522
27	5	2	Slope angle	Crest + 1,95 m			5499
28	5	2	Slope angle	Berm 75 m			10660
28.2		3	Slope angle	Berm 50 m	Berm 75 m		10940

Table I. 5 ECI-values for the different pathways for conceptual design variant 3

Appendix J: Determination of the Direct Construction Costs

This appendix regards the determination of the direct construction costs, which is one of the evaluation criteria in the determination of the preferable design variant and adaptation methodology for the Delta21 sea defence.

J.1 The standard methodology for cost estimation

In every infrastructural project the costs are an important factor in the determination of the preferable design variant. In the Netherlands the standard methodology for cost estimation or "Standaardsystematiek Kostenraming" (from now on SSK-methodology) has been developed to standardize the way costs for large construction projects are estimated. This creates the possibility to make a fair comparison between different design variants and, for example, bids on a tender.

In the SSK-methodology the total investment costs are build up using the direct construction costs and various percentage factors to get to the final investment costs. The SSK-methodology determines the investment costs using the following buildup:

1. Foreseen construction costs
    a. Direct construction costs
    b. Indirect construction costs
2. Risk in the construction costs
3. Real estate costs
4. Foreseen direct engineering costs
5. Unforeseen engineering costs
6. Extra costs
    a. Insurances
    b. Fees and charges
    c. Underground infrastructure
    d. Unforeseen extra costs

Of these, only the direct construction costs (1.a) are fully (quantitively) determined. All other expense items are determined as percentages of the direct construction costs.

During the conceptual phase of the project, a lot of the costs are still unknown or undefined. During every stage later in the project, more materials and therefore costs will be defined which makes the estimation more accurate.

J.2 Determining the direct construction costs for the Delta21 sea defence

The thesis in the main report only handles the conceptual design of the Delta21 sea defence and the methodology of adaptation to the consequences of climate change.

Since the total investment costs are a sum of several expense items which are a percentage product of the direct construction costs, only the determination of the direct construction costs is enough to create a comparison between the different design variants and adaptational pathways.

The study does not require a precise estimation of the direct construction costs, it does however require an estimation of the direct construction costs for the parts in which the variants and pathways differ from one another. For example the costs of filter layers, detailed transition constructions between slopes and berms, the use of geotextiles, etc. will be used in each of the variants and adaptation methods and can be defined as a percentage of the construction costs. However the amounts of clay, sand, asphalt concrete and interlocking armour units do differ over the different variants and adaptation methods.

The most important costs that are determined are presented underneath in table J.1.

Material or process	**Unit**	**Direct construction costs per unit [€]**
Delivering and applying clay	m^3	25,00
Delivering and applying sand	m^3	7,50
Delivering and applying Hydraulic Asphalt	tonnes	70,00
Delivering and applying Open stone Asphalt	tonnes	75,00
Delivering and applying X-Block	Pcs.	6700,00
Removing clay layer	m^3	2,50
Removing sand	m^3	2,50
Removing Hydraulic Asphalt	tonnes	10,00
Removing Open stone Asphalt	tonnes	10,00
Removing X-Block	Pcs.	750,00
Replacing clay layer	m^3	5,00
Replacing X-Block	Pcs.	750,00

Table J. 1 Direct construction costs for various materials and processes used in the Delta21 sea defence

Using the processes and material costs as mentioned in the table above, the direct construction costs required for the comparison between the different conceptual design variants and their adaptation pathways can be estimated.

J.3 Delta21 sea defence design variant 1

The required materials for the adaptation options of Delta21 sea defence variant 1 are presented in appendix H: Determination of amount of construction material. Using this information and coupling it to the information in table J.1 above, the direct construction costs for the different adaptation pathways for design variant 1 are determined. The direct construction costs for the different adaptation pathways for design variant 1 are presented in table J.2 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Direct construction costs [€/m]
1	2	1	Crest + 1,65 m				4877
2	2	1	Foreshore to -1,74 m				43508
3	2,2	1	Berm 50 m				14563
4	2,5	1	Foreshore to 0,22 m				53663
4.2		2	Foreshore to -1,74 m	Foreshore to 0,22 m			53663
6	3	1	Crest + 3,30 m				9165
6.2		2	Crest + 1,65 m	Crest + 3,30 m			9916
8	3,15	1	Berm 75 m				21167
8.2		2	Berm 50 m	Berm 75 m			29879
10	3,25	2	Berm 50 m	Crest + 1,65 m			19440
14	3,9	1	Inner slope				3558
16	4	1	Crest + 4,95 m				13576
16.2		2	Crest + 1,65 m	Crest + 4,95 m			14346
16.3		2	Crest + 3,30 m	Crest + 4,95 m			14346
16.4		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m		15077
19	4,2	2	Crest + 3,30 m	Berm 50 m			23729
19.2		3	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m		24479
20	4,2	2	Crest + 1,65 m	Berm 75 m			26044
20.2		3	Crest + 1,65 m	Berm 50 m	Berm 75 m		34757
27	4,75	2	Inner slope	Berm 50 m			18121
31	5	1	Crest + 6,60 m				18109
31.2		2	Crest + 1,65 m	Crest + 6,60 m			18899
31.3		2	Crest + 3,30 m	Crest + 6,60 m			18899
31.4		2	Crest + 4,95 m	Crest + 6,60 m			18899
31.5		3	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m		19637
31.6		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 6,60 m		19637
31.7		3	Crest + 1,65 m	Crest + 4,95 m	Crest + 6,60 m		19637
31.8		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m	20361
32	5	2	Crest + 4,95 m	Berm 50 m			28139
32.2		3	Crest + 1,65 m	Crest + 4,95 m	Berm 50 m		28910
32.3		3	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m		28910
32.4		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m	29641
33	5	2	Crest + 3,30 m	Berm 75 m			30332
33.2		3	Crest + 3,30 m	Berm 50 m	Berm 75 m		39045
33.3		3	Crest + 1,65 m	Crest + 3,30 m	Berm 75 m		31083
33.4		4	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m	Berm 75 m	39795
36	5	2	Inner slope	Crest + 1,65 m			11998
37	5	2	Inner slope	Berm 75 m			24725
37.2		3	Inner slope	Berm 50 m	Berm 75 m		33437

Table J. 2 Direct construction costs for the different pathways for conceptual design variant 1

J.4 Delta21 sea defence design variant 2

The required materials for the adaptation options of Delta21 sea defence variant 2 are presented in appendix H: Determination of amount of construction material. Using this information and coupling it to the information in table J.1 above, the direct construction costs for the different adaptation pathways for design variant 1 are determined. The direct construction costs for the different adaptation pathways for design variant 1 are presented in table J.3 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Direct construction costs [€/m]
1	2	1	Crest + 1,75 m				7289
2	2	1	Foreshore to -3,08 m				41783
3	2,25	1	Slope angle				7091
6	3	1	Crest + 3,50 m				10618
6.2		2	Crest + 1,75 m	Crest + 3,50 m			14758
7	3	1	Foreshore to -0,08 m				52920
7.2		2	Foreshore to -3,08 m	Foreshore to -0,08 m			52920
8	3,2	1	Berm 50 m				7959
9	3,4	2	Slope angle	Crest + 1,75 m			14920
14	3,85	1	Slope roughness				53324
16	4	1	Crest + 5,25 m				14084
16.2		2	Crest + 1,75 m	Crest + 5,25 m			18245
16.3		2	Crest + 3,50 m	Crest + 5,25 m			18245
16.4		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m		22364
17	4	2	Slope angle	Berm 50 m			16481
20	4,35	2	Crest + 1,75 m	Berm 50 m			15998
23	4,5	1	Berm 75 m				15500
23.2		2	Berm 50 m	Berm 75 m			17538
24	4,5	2	Slope angle	Crest + 3,50 m			18812
24.2		3	Slope angle	Crest + 1,75 m	Crest + 3,50 m		22952
30	4,9	2	Slope roughness	Berm 50 m			67493
32	5	1	Crest + 7,00 m				17689
32.2		2	Crest + 1,75 m	Crest + 7,00 m			21870
32.3		2	Crest + 3,50 m	Crest + 7,00 m			21870
32.4		2	Crest + 5,25 m	Crest + 7,00 m			21870
32.5		3	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m		25996
32.6		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 7,00 m		25996
32.7		3	Crest + 1,75 m	Crest + 5,25 m	Crest + 7,00 m		25996
32.8		4	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m	30108
33	5	2	Crest + 1,75 m	Berm 75 m			22789
33.2		3	Crest + 1,75 m	Berm 50 m	Berm 75 m		24894
34	5	2	Crest + 3,50 m	Berm 50 m			19326
34.2		3	Crest + 1,75 m	Crest + 3,50 m	Berm 50 m		23466
36	5	2	Slope angle	Crest + 5,25 m			21726
36.2		3	Slope angle	Crest + 1,75 m	Crest + 5,25 m		27025
36.3		3	Slope angle	Crest + 3,50 m	Crest + 5,25 m		27025
36.4		4	Slope angle	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	31144
37	5	2	Slope angle	Berm 75 m			23572
37.2		3	Slope angle	Berm 50 m	Berm 75 m		25957
40	5	2	Slope roughness	Crest + 1,75 m			62010
41	5	2	Slope roughness	Berm 75 m			72184
41.2		3	Slope roughness	Berm 50 m	Berm 75 m		81399
44	5	3	Slope angle	Crest + 1,75 m	Berm 50 m		24397

Table J. 3 Direct construction costs for the different pathways for conceptual design variant 2

J.5 Delta21 sea defence design variant 3

The required materials for the adaptation options of Delta21 sea defence variant 3 are presented in appendix H: Determination of amount of construction material. Using this information and coupling it to the information in table J.1 above, the direct construction costs for the different adaptation pathways for design variant 1 are determined. The direct construction costs for the different adaptation pathways for design variant 1 are presented in table J.4 underneath.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Direct construction costs [€/m]
1	2	1	Crest + 1,95 m				7658
2	2	1	Foreshore to -3,08 m				41783
3	2,5	1	Foreshore to -1,18 m				48218
3.2		2	Foreshore to -3,08 m	Foreshore to -1,18 m			48218
5	3	1	Crest + 3,90 m				11346
5.2		2	Crest + 1,95 m	Crest + 3,90 m			15490
7	3,2	1	Berm 50 m				11802
10	3,85	1	Slope angle				23363
12	4	1	Crest + 5,85 m				15162
12.2		2	Crest + 1,95 m	Crest + 5,85 m			19330
12.3		2	Crest + 3,90 m	Crest + 5,85 m			19330
12.4		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m		23451
16	4,35	2	Crest + 1,95 m	Berm 50 m			18460
19	4,55	1	Berm 75 m				18593
19.2		2	Berm 50 m	Berm 75 m			23947
22	4,9	2	Slope angle	Berm 50 m			35488
23	5	1	Crest + 7,80 m				19107
23.2		2	Crest + 1,95 m	Crest + 7,80 m			23298
23.3		2	Crest + 3,90 m	Crest + 7,80 m			23298
23.4		2	Crest + 5,85 m	Crest + 7,80 m			23298
23.5		3	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m		27427
23.6		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 7,80 m		27427
23.7		3	Crest + 1,95 m	Crest + 5,85 m	Crest + 7,80 m		27427
23.8		4	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m	31541
24	5	2	Crest + 3,90 m	Berm 50 m			23148
24.2		3	Crest + 1,95 m	Crest + 3,90 m	Berm 50 m		26292
25	5	2	Crest + 1,95 m	Berm 75 m			26251
25.2		3	Crest + 1,95 m	Berm 50 m	Berm 75 m		31605
27	5	2	Slope angle	Crest + 1,95 m			32582
28	5	2	Slope angle	Berm 75 m			42580
28.2		3	Slope angle	Berm 50 m	Berm 75 m		47933

Table J. 4 Direct construction costs for the different pathways for conceptual design variant 3

Appendix K: Evaluation of toe relocation and adaptability

The design process of the conceptual design of the Delta21 sea defence makes use of the adaptive pathway approach to pick the preferred conceptual design with adaptability to climate change in mind. For the three base design variants, adaptational pathways have been created to gain insight in the different ways the Delta21 sea defence can be adapted to sea level rise.

In order to pick the preferred adaptational pathway, multiple evaluation criteria have been created:

- Environmental Cost Indicator (ECI)
- Direct construction costs
- Changes in dike geometry
- Adaptability after implementing the adaptation measure

The first two evaluation criteria are discussed in Appendices I and J respectively. In this appendix the shift in outer toe position and the amount of possible pathways to form after the earlier applied adaptation methods are presented.

K.1 Values for the evaluation criteria for design variant 1

The shifts in toe position per adaptive pathway and the amount of possible effective adaptive pathways after application of the mentioned one are shown underneath in Tables K.1 and K.2.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Shift in outer toe position
1	2	1	Crest + 1,65 m				0,0
2	2	1	Foreshore to -1,74 m				678
3	2,2	1	Berm 50 m				26,0
4	2,5	1	Foreshore to 0,22 m				706
4.2		2	Foreshore to -1,74 m	Foreshore to 0,22 m			706
6	3	1	Crest + 3,30 m				0,0
6.2		2	Crest + 1,65 m	Crest + 3,30 m			0,0
8	3,15	1	Berm 75 m				51
8.2		2	Berm 50 m	Berm 75 m			51
10	3,25	2	Berm 50 m	Crest + 1,65 m			26
14	3,9	1	Inner slope				0,0
16	4	1	Crest + 4,95 m				0,0
16.2		2	Crest + 1,65 m	Crest + 4,95 m			0,0
16.3		2	Crest + 3,30 m	Crest + 4,95 m			0,0
16.4		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m		0,0
19	4,2	2	Crest + 3,30 m	Berm 50 m			26
19.2		3	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m		26
20	4,2	2	Crest + 1,65 m	Berm 75 m			51
20.2		3	Crest + 1,65 m	Berm 50 m	Berm 75 m		51
27	4,75	2	Inner slope	Berm 50 m			26
31	5	1	Crest + 6,60 m				0,0
31.2		2	Crest + 1,65 m	Crest + 6,60 m			0,0
31.3		2	Crest + 3,30 m	Crest + 6,60 m			0,0
31.4		2	Crest + 4,95 m	Crest + 6,60 m			0,0
31.5		3	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m		0,0
31.6		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 6,60 m		0,0
31.7		3	Crest + 1,65 m	Crest + 4,95 m	Crest + 6,60 m		0,0
31.8		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m	0,0
32	5	2	Crest + 4,95 m	Berm 50 m			26
32.2		3	Crest + 1,65 m	Crest + 4,95 m	Berm 50 m		26
32.3		3	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m		26
32.4		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m	26

33	5	2	Crest + 3,30 m	Berm 75 m			51
33.2		3	Crest + 3,30 m	Berm 50 m	Berm 75 m		51
33.3		3	Crest + 1,65 m	Crest + 3,30 m	Berm 75 m		51
33.4		4	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m	Berm 75 m	51
36	5	2	Inner slope	Crest + 1,65 m			0,0
37	5	2	Inner slope	Berm 75 m			51
37.2		3	Inner slope	Berm 50 m	Berm 75 m		51

Table K. 1 Shift in outer toe position at the end of the application of the adaptive pathway for design variant 1

Pathway number	**Tipping point [mSLR]**	**Number of adaptation steps**	**Adaptation step 1**	**Adaptation step 2**	**Adaptation step 3**	**Adaptation step 4**	**Number of possible pathways after**
1	2	1	Crest + 1,65 m				16
2	2	1	Foreshore to -1,74 m				1
3	2,2	1	Berm 50 m				12
4	2,5	1	Foreshore to 0,22 m				-
4.2		2	Foreshore to -1,74 m	Foreshore to 0,22 m			-
6	3	1	Crest + 3,30 m				7
6.2		2	Crest + 1,65 m	Crest + 3,30 m			7
8	3,15	1	Berm 75 m				4
8.2		2	Berm 50 m	Berm 75 m			4
10	3,25	2	Berm 50 m	Crest + 1,65 m			5
14	3,9	1	Inner slope				4
16	4	1	Crest + 4,95 m				2
16.2		2	Crest + 1,65 m	Crest + 4,95 m			2
16.3		2	Crest + 3,30 m	Crest + 4,95 m			2
16.4		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m		2
19	4,2	2	Crest + 3,30 m	Berm 50 m			2
19.2		3	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m		2
20	4,2	2	Crest + 1,65 m	Berm 75 m			1
20.2		3	Crest + 1,65 m	Berm 50 m	Berm 75 m		1
27	4,75	2	Inner slope	Berm 50 m			1
31	5	1	Crest + 6,60 m				-
31.2		2	Crest + 1,65 m	Crest + 6,60 m			-
31.3		2	Crest + 3,30 m	Crest + 6,60 m			-
31.4		2	Crest + 4,95 m	Crest + 6,60 m			-
31.5		3	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m		-
31.6		3	Crest + 1,65 m	Crest + 3,30 m	Crest + 6,60 m		-
31.7		3	Crest + 1,65 m	Crest + 4,95 m	Crest + 6,60 m		-
31.8		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Crest + 6,60 m	-
32	5	2	Crest + 4,95 m	Berm 50 m			-
32.2		3	Crest + 1,65 m	Crest + 4,95 m	Berm 50 m		-
32.3		3	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m		-
32.4		4	Crest + 1,65 m	Crest + 3,30 m	Crest + 4,95 m	Berm 50 m	-
33	5	2	Crest + 3,30 m	Berm 75 m			-
33.2		3	Crest + 3,30 m	Berm 50 m	Berm 75 m		-
33.3		3	Crest + 1,65 m	Crest + 3,30 m	Berm 75 m		-
33.4		4	Crest + 1,65 m	Crest + 3,30 m	Berm 50 m	Berm 75 m	-
36	5	2	Inner slope	Crest + 1,65 m			-
37	5	2	Inner slope	Berm 75 m			-
37.2		3	Inner slope	Berm 50 m	Berm 75 m		-

Table K. 2 Number of possible efficient pathways after the application of the mentioned adaptive pathway for design variant 1

K.2 Values for the evaluation criteria for design variant 2

The shifts in toe position per adaptive pathway and the amount of possible effective adaptive pathways after application of the mentioned one are shown underneath in Tables K.3 and K.4.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Shift in outer toe position
1	2	1	Crest + 1,75 m				0,0
2	2	1	Foreshore to -3,08 m				678
3	2,25	1	Slope angle				30
6	3	1	Crest + 3,50 m				0,0
6.2		2	Crest + 1,75 m	Crest + 3,50 m			0,0
7	3	1	Foreshore to -0,08 m				703
7.2		2	Foreshore to -3,08 m	Foreshore to -0,08 m			703
8	3,2	1	Berm 50 m				28,0
9	3,4	2	Slope angle	Crest + 1,75 m			30,0
14	3,85	1	Slope roughness				0,0
16	4	1	Crest + 5,25 m				0,0
16.2		2	Crest + 1,75 m	Crest + 5,25 m			0,0
16.3		2	Crest + 3,50 m	Crest + 5,25 m			0,0
16.4		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m		0,0
17	4	2	Slope angle	Berm 50 m			58,0
20	4,35	2	Crest + 1,75 m	Berm 50 m			28,0
23	4,5	1	Berm 75 m				53,0
23.2		2	Berm 50 m	Berm 75 m			53,0
24	4,5	2	Slope angle	Crest + 3,50 m			30,0
24.2		3	Slope angle	Crest + 1,75 m	Crest + 3,50 m		30,0
30	4,9	2	Slope roughness	Berm 50 m			28,0
32	5	1	Crest + 7,00 m				0,0
32.2		2	Crest + 1,75 m	Crest + 7,00 m			0,0
32.3		2	Crest + 3,50 m	Crest + 7,00 m			0,0
32.4		2	Crest + 5,25 m	Crest + 7,00 m			0,0
32.5		3	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m		0,0
32.6		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 7,00 m		0,0
32.7		3	Crest + 1,75 m	Crest + 5,25 m	Crest + 7,00 m		0,0
32.8		4	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m	0,0
33	5	2	Crest + 1,75 m	Berm 75 m			53,0
33.2		3	Crest + 1,75 m	Berm 50 m	Berm 75 m		53,0
34	5	2	Crest + 3,50 m	Berm 50 m			28,0
34.2		3	Crest + 1,75 m	Crest + 3,50 m	Berm 50 m		28,0
36	5	2	Slope angle	Crest + 5,25 m			30,0
36.2		3	Slope angle	Crest + 1,75 m	Crest + 5,25 m		30,0
36.3		3	Slope angle	Crest + 3,50 m	Crest + 5,25 m		30,0
36.4		4	Slope angle	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	30,0
37	5	2	Slope angle	Berm 75 m			83,0
37.2		3	Slope angle	Berm 50 m	Berm 75 m		83,0
40	5	2	Slope roughness	Crest + 1,75 m			0,0
41	5	2	Slope roughness	Berm 75 m			53,0
41.2		3	Slope roughness	Berm 50 m	Berm 75 m		53,0
44	5	3	Slope angle	Crest + 1,75 m	Berm 50 m		58

Table K. 3 Shift in outer toe position at the end of the application of the adaptive pathway for design variant 2

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Number of possible pathways after
1	2	1	Crest + 1,75 m				17
2	2	1	Foreshore to -3,08 m				1
3	2,25	1	Slope angle				11
6	3	1	Crest + 3,50 m				6
6.2		2	Crest + 1,75 m	Crest + 3,50 m			6
7	3	1	Foreshore to -0,08 m				-
7.2		2	Foreshore to -3,08 m	Foreshore to -0,08 m			-
8	3,2	1	Berm 50 m				9
9	3,4	2	Slope angle	Crest + 1,75 m			4
14	3,85	1	Slope roughness				4
16	4	1	Crest + 5,25 m				2
16.2		2	Crest + 1,75 m	Crest + 5,25 m			2
16.3		2	Crest + 3,50 m	Crest + 5,25 m			2
16.4		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m		2
17	4	2	Slope angle	Berm 50 m			2
20	4,35	2	Crest + 1,75 m	Berm 50 m			3
23	4,5	1	Berm 75 m				3
23.2		2	Berm 50 m	Berm 75 m			3
24	4,5	2	Slope angle	Crest + 3,50 m			1
24.2		3	Slope angle	Crest + 1,75 m	Crest + 3,50 m		1
30	4,9	2	Slope roughness	Berm 50 m			1
32	5	1	Crest + 7,00 m				-
32.2		2	Crest + 1,75 m	Crest + 7,00 m			-
32.3		2	Crest + 3,50 m	Crest + 7,00 m			-
32.4		2	Crest + 5,25 m	Crest + 7,00 m			-
32.5		3	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m		-
32.6		3	Crest + 1,75 m	Crest + 3,50 m	Crest + 7,00 m		-
32.7		3	Crest + 1,75 m	Crest + 5,25 m	Crest + 7,00 m		-
32.8		4	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m	-
33	5	2	Crest + 1,75 m	Berm 75 m			-
33.2		3	Crest + 1,75 m	Berm 50 m	Berm 75 m		-
34	5	2	Crest + 3,50 m	Berm 50 m			-
34.2		3	Crest + 1,75 m	Crest + 3,50 m	Berm 50 m		-
36	5	2	Slope angle	Crest + 5,25 m			-
36.2		3	Slope angle	Crest + 1,75 m	Crest + 5,25 m		-
36.3		3	Slope angle	Crest + 3,50 m	Crest + 5,25 m		-
36.4		4	Slope angle	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	-
37	5	2	Slope angle	Berm 75 m			-
37.2		3	Slope angle	Berm 50 m	Berm 75 m		-
40	5	2	Slope roughness	Crest + 1,75 m			-
41	5	2	Slope roughness	Berm 75 m			-
41.2		3	Slope roughness	Berm 50 m	Berm 75 m		-
44	5	3	Slope angle	Crest + 1,75 m	Berm 50 m		-

Table K. 4 Number of possible efficient pathways after the application of the mentioned adaptive pathway for design variant 2

K.3 Values for the evaluation criteria for design variant 3

The shifts in toe position per adaptive pathway and the amount of possible effective adaptive pathways after application of the mentioned one are shown underneath in Tables K.5 and K.6.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Shift in outer toe position
1	2	1	Crest + 1,95 m				0,0
2	2	1	Foreshore to -3,08 m				678,3
3	2,5	1	Foreshore to -1,18 m				702,8
3.2		2	Foreshore to -3,08 m	Foreshore to -1,18 m			702,8
5	3	1	Crest + 3,90 m				0,0
5.2		2	Crest + 1,95 m	Crest + 3,90 m			0,0
7	3,2	1	Berm 50 m				27,0
10	3,85	1	Slope angle				45,0
12	4	1	Crest + 5,85 m				0,0
12.2		2	Crest + 1,95 m	Crest + 5,85 m			0,0
12.3		2	Crest + 3,90 m	Crest + 5,85 m			0,0
12.4		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m		0,0
16	4,35	2	Crest + 1,95 m	Berm 50 m			27,0
19	4,55	1	Berm 75 m				52,0
19.2		2	Berm 50 m	Berm 75 m			52,0
22	4,9	2	Slope angle	Berm 50 m			72,0
23	5	1	Crest + 7,80 m				0,0
23.2		2	Crest + 1,95 m	Crest + 7,80 m			0,0
23.3		2	Crest + 3,90 m	Crest + 7,80 m			0,0
23.4		2	Crest + 5,85 m	Crest + 7,80 m			0,0
23.5		3	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m		0,0
23.6		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 7,80 m		0,0
23.7		3	Crest + 1,95 m	Crest + 5,85 m	Crest + 7,80 m		0,0
23.8		4	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m	0,0
24	5	2	Crest + 3,90 m	Berm 50 m			27,0
24.2		3	Crest + 1,95 m	Crest + 3,90 m	Berm 50 m		27,0
25	5	2	Crest + 1,95 m	Berm 75 m			52,0
25.2		3	Crest + 1,95 m	Berm 50 m	Berm 75 m		52,0
27	5	2	Slope angle	Crest + 1,95 m			45,0
28	5	2	Slope angle	Berm 75 m			98
28.2		3	Slope angle	Berm 50 m	Berm 75 m		98

Table K. 5 Shift in outer toe position at the end of the application of the adaptive pathway for design variant 3

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4	Number of possible pathways after
1	2	1	Crest + 1,95 m				12
2	2	1	Foreshore to -3,08 m				1
3	2,5	1	Foreshore to -1,18 m				-
3.2		2	Foreshore to -3,08 m	Foreshore to -1,18 m			-
5	3	1	Crest + 3,90 m				4
5.2		2	Crest + 1,95 m	Crest + 3,90 m			4
7	3,2	1	Berm 50 m				7
10	3,85	1	Slope angle				4
12	4	1	Crest + 5,85 m				1
12.2		2	Crest + 1,95 m	Crest + 5,85 m			1
12.3		2	Crest + 3,90 m	Crest + 5,85 m			1
12.4		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m		1
16	4,35	2	Crest + 1,95 m	Berm 50 m			2
19	4,55	1	Berm 75 m				2
19.2		2	Berm 50 m	Berm 75 m			2
22	4,9	2	Slope angle	Berm 50 m			1
23	5	1	Crest + 7,80 m				-
23.2		2	Crest + 1,95 m	Crest + 7,80 m			-
23.3		2	Crest + 3,90 m	Crest + 7,80 m			-
23.4		2	Crest + 5,85 m	Crest + 7,80 m			-
23.5		3	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m		-
23.6		3	Crest + 1,95 m	Crest + 3,90 m	Crest + 7,80 m		-
23.7		3	Crest + 1,95 m	Crest + 5,85 m	Crest + 7,80 m		-
23.8		4	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m	-
24	5	2	Crest + 3,90 m	Berm 50 m			-
24.2		3	Crest + 1,95 m	Crest + 3,90 m	Berm 50 m		-
25	5	2	Crest + 1,95 m	Berm 75 m			-
25.2		3	Crest + 1,95 m	Berm 50 m	Berm 75 m		-
27	5	2	Slope angle	Crest + 1,95 m			-
28	5	2	Slope angle	Berm 75 m			-
28.2		3	Slope angle	Berm 50 m	Berm 75 m		-

Table K. 6 Number of possible efficient pathways after the application of the mentioned adaptive pathway for design variant 3

Appendix L: Pathway evaluation for design variants 2 and 3

In this appendix the evaluation of the adaptive pathways for design variants 2 and 3 is considered. As discussed in the thesis main report, this evaluation is performed for four sea level rise scenarios: 2, 3, 4 and 5 meters of sea level rise.

L.1 Determination of the preferred adaptation strategy for design variant 2

The first considered design variant is design variant 2, of which the adaptive pathway scheme is presented in Appendix G. As discussed in Section 8.1 the adaptive pathways are evaluated per meter sea level rise, starting at 2 meters of sea level rise to a maximum of 5 meters of sea level rise. Using this evaluation the preferred adaptation strategy for design variant 2 is determined per sea level rise scenario.

In the evaluation, the pathway numbers as presented in the tables and Chapter 7 are mentioned between brackets behind the individual adaptation options.

Pathway evaluation for 2 meters of sea level rise

The first considered sea level rise scenario is one in which 2 meters of sea level rise occurs, the adaptation pathways which are formed in Sections 7.1 to 7.3 are evaluated for this scenario. All pathways considered for design variant 2 can be found in Appendix G.

In this section all pathways adapting the sea defence to 2 meters of sea level rise are evaluated. In addition to this, also the singular adaptation steps which adapt the sea defence to more than 2 meters of sea level rise are taken into account as these are also options to be applied as a first adaptation step at the moment the base design variant does not meet the water safety requirements anymore. An exception to this is the case in which the first step of an adaptation option (or whole adaptation pathway) is sufficient to adapt the sea defence to 2 meters of sea level rise. An example of this is for example the case in which a berm width increase to 50 meters is sufficient, in this case a berm width increase to 75 meters is not included.

All considered pathways in this evaluation step are shown underneath in Table L.1.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
1	2	1	Crest + 1,75 m		
2	2	1	Foreshore to -3,08 m		
3	2,25	1	Slope angle		
8	3,2	1	Berm 50 m		
14	3,85	1	Slope roughness		

Table L.1 adaptive pathways which adapt sea defence base design variant 2 to 2 meters of sea level rise

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. The scores of the different paths for these criteria are indicated in Table L.2 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
1	2	1	2351	7289	0	17
2	2	1	5219	41783	674	1
3	2,25	1	3491	7091	30	11
8	3,2	1	3868	7959	28	10
14	3,85	1	5777	53324	0	4

Table L.2 Values of the various adaptation pathways for the four selection criteria

Environmental cost indicator

Crest level increase (1) has the lowest value ECI-value and is therefore the preferred option. Both an adaptation of the slope angle (3) and berm width (8) have low to mid ECI-values as well. The ECI-value for foreshore adaptation (2) is approximately twice that of crest level increase (1). This also holds for an increase in slope roughness (14); the implementation of Xbloc imposes a high ECI-value due to the large concrete demand.

Direct construction costs

The direct construction costs for crest level increase (1) are slightly higher than those for a slope angle adaptation (3) due to the handling of clay and asphalt on the inner slope which should be done when performing crest level increase. Berm adaptation (8) is a factor 1.2 more expensive than the first two mentioned adaptation options. The two outliers in this category are foreshore adaptation (2) (due to the very large amount of sand which is used) and roughness adaptation (14) (due to the large amount of Xbloc which are required). When only looking at the direct construction costs, slope angle (3) adaptation is the preferred adaptation option.

Shift in toe location

Both roughness increase (14) and a crest level increase (1) do not impose a shift in toe location. The shifts due to berm adaptation (8) and slope angle adaptation (3) are approximately 30 meters. Same as for design variant 1, an adaptation of the foreshore (2) imposes a very large shift in toe location by 674 meters.

Flexibility and adaptability

Slope roughness (14) and slope angle (3) adaptation cannot be combined which gives less freedom in available adaptation options after implementing these as a first adaptation step. Berm width increase (8) results in less adaptation pathways to form due to the high tipping point. Crest level adaption (1) can be combined with every other adaptation option and has a low tipping point, therefore a lot of adaptation pathways can still be formed after implementing this a first adaptation step.

Foreshore adaptation (2) cannot be combined with other pathways and does rule out further (efficient) adaptation of the Delta21 sea defence.

Conclusion

Due to the low ECI-value, fairly low construction costs and lack of outer toe relocation, crest level increase (1) is the preferred adaptation option for base design variant 2 for 2 meters of sea level rise.

Pathway evaluation for 3 meters of sea level rise

Not every pathway in Appendix G is required to mitigate the effects of 3 meters of sea level rise, all considered pathways in this evaluation are shown underneath in Table L.3.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
6	3	1	Crest + 3,50 m		
6.2	3	2	Crest + 1,75 m	Crest + 3,50 m	
7	3	1	Foreshore to -0,08 m		
7.2	3	2	Foreshore to -3,08 m	Foreshore to -0,08 m	
8	3,2	1	Berm 50 m		
9	3,4	2	Slope angle	Crest + 1,75 m	
14	3,85	1	Slope roughness		

Table L.3 adaptive pathways which adapt sea defence base design variant 2 to 3 meters of sea level rise

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. The scores of the different paths for these criteria are indicated in Table L.4 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
6	3	1	3884	10618	0	6
6.2	3	2	4766	14758	0	6
7	3	1	6610	52920	703	-
7.2	3	2	6610	52920	703	-
8	3,2	1	3868	7959	28	10
9	3,4	2	6116	14920	30	4
14	3,85	1	5777	53324	0	4

Table L.4 Values of the various adaptation pathways for the four selection criteria

Environmental cost indicator

The ECI-values for crest level increase (6) and berm width increase (8) are more or less equal when the first is performed in a single 3,50 meter increase. However, when the crest level is increased in more than a single step (6.2) (two steps of 1,75 meters), the required berm width increase has a lower ECI-value (comparing 6.2 and 8). The adaptation of the foreshore (7), slope angle (9) and roughness (14) have significantly larger ECI-value, therefore it can be said that these are not the preferred adaptation methods according to this evaluation criterium.

Direct construction costs

The direct construction costs for berm adaptation (8) are lower than a crest level increase (6) sufficient to adapt the sea defence to 3 meters of sea level rise. Slope angle adaptation (9) is slightly more expensive than crest level increase (6), however foreshore level increase (7) and slope roughness adaptation (14) are a factor 5 more expensive. Using the direct construction costs as evaluation criterium it can be said that berm width increase (8) is the preferred adaptation method.

Shift in toe location

Foreshore level increase (7), berm width increase (8) and slope angle adaptation (9) impose a shift of outer toe location into the North Sea. Therefore crest level increase (6) and outer slope roughness increase (14) are preferred according to this criterium.

Flexibility and adaptability

The use of berm adaptation (8) occurs in a lot of efficient combinations in the adaptive pathway scheme for design variant 2, therefore this adaptational measure also gives a lot of flexibility in the selection of adaptational measures in the future. Due to the fact that slope angle (9) and roughness adaptation (14) cannot be combined, and slope roughness increase (14) already has a high tipping point, both of these measures grant less flexibility than the earlier mentioned berm adaptation.

Foreshore adaptation (7) cannot be combined with other pathways and does therefore rule out further (efficient) adaptation of the Delta21 sea defence.

Conclusion

Due to the low ECI-value and direct construction costs, in combination with large flexibility for the future, a berm increase with 28 meters (to a total width of 50 meters) (8) is the preferrable adaptation measure with 3 meters of sea level rise in mind. This means however that during early planning phase at least 28 meters of space should be reserved as a buffer between the sea defence and the Natura2000 area.

Pathway evaluation for 4 meters of sea level rise

Not every pathway in Appendix G is required to mitigate the effects of 4 meters of sea level rise, all considered pathways in this evaluation are shown underneath in Table L.5.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
16	4	1	Crest + 5,25 m		
16.2	4	2	Crest + 1,75 m	Crest + 5,25 m	
16.3	4	2	Crest + 3,50 m	Crest + 5,25 m	
16.4	4	3	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m
17	4	2	Slope angle	Berm 50 m	
20	4,35	2	Crest + 1,75 m	Berm 50 m	
23	4,5	1	Berm 75 m		
23.2	4,5	2	Berm 50 m	Berm 75 m	
24	4,5	2	Slope angle	Crest + 3,50 m	
24.2	4,5	3	Slope angle	Crest + 1,75 m	Crest + 3,50 m
30	4,9	2	Slope roughness	Berm 50 m	

Table L.5 adaptive pathways which adapt sea defence base design variant 2 to 4 meters of sea level rise

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. The scores of the different paths for these criteria are indicated in Table L.6 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
16	4	1	5480	14084	0	2
16.2	4	2	6362	18245	0	2
16.3	4	2	6362	18245	0	2
16.4	4	3	7243	22364	0	2
17	4	2	7896	16481	58	2
20	4,35	2	6558	15998	28	3
23	4,5	1	7721	15500	53	3
23.2	4,5	2	8312	17538	53	3
24	4,5	2	7934	18812	30	1
24.2	4,5	3	8815	22952	30	1
30	4,9	2	7112	67493	28	1

Table L.6 Values of the various adaptation pathways for the four selection criteria

Environmental cost indicator

The ECI-value for an increase in crest level is the lowest of all pathways adapting sea defence variant 2 to 4 meters of sea level rise, when implemented in either one or two adaptation steps (pathways 16, 16.2 and 16.3). Because of the inner slope reinforcement of design variant 2, every crest level increase requires the removal and re-appliance of the asphalt protection layer on the inner slope. Removing this layer 3 times imposes a higher ECI-value than the removal and re-appliance of the asphalt concrete on the outer slopes which is necessary for berm width increase. Therefore, when increasing the crest level in 3 steps (16.4), it is preferred to adapt the crest level with one small step in combination with berm width increase (20).

Pathways which include slope angle and roughness adaptation induce a large ECI-value (17, 24, 30).

Direct construction costs

The direct construction costs for only crest adaptation are the lowest when performed in a single step of 5,25 meters (16). However when multiple steps (of 1,75 m) of crest level increase are used (16.2, 16.3, 16.4), a berm width increase in combination with a small crest level increase is preferred (20).

The use of a combination of outer slope roughness and berm width increase cause the highest direct construction costs (30). While all direct construction costs are in the same order, slope roughness increase in combination with berm adaptation is a factor 4 more expensive than crest level increase.

Shift in toe location

The increase in berm width (23) shifts the location of the inner toe to the Natura2000 area in in the North Sea. For a berm width increase to 50 meters this is 28 meters and for a berm width increase to 75 meters this is 53 meters. Slope angle adaptation shifts the toe with 30 meters.

Flexibility and adaptability

Pathways 20 and 23, which make use of a large berm width increase or a combination of small crest level and berm width increases can be followed up in more efficient ways than the other pathways which adapt sea defence base variant 2 to 4 meters of sea level rise. Therefore these two are preferred with adaptability in mind. For maximum flexibility it is advised to start this pathway with a berm width increase, since this gives the most options after the first adaptation step.

Conclusion

From the outcomes of the various evaluation criteria as discussed above, it can be concluded that a combination between crest level increase to NAP+17,75 m in combination with a berm width increase of 28 meters is the preferred adaptation method as this is has a comparable ECI-value and lower direct construction costs. Also there are more available adaptation pathways to be formed after implementation. This does however mean that 28 meters of empty space should be reserved in front of the sea defence for adaptation in the future.

Pathway evaluation for 5 meters of sea level rise

Not every pathway in Appendix G mitigates the effects of 5 meters of sea level rise, all considered pathways in this evaluation are shown underneath in Table L.7.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4
32	5	1	Crest + 7,00 m			
32.2	5	2	Crest + 1,75 m	Crest + 7,00 m		
32.3	5	2	Crest + 3,50 m	Crest + 7,00 m		
32.4	5	2	Crest + 5,25 m	Crest + 7,00 m		
32.5	5	3	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m	
32.6	5	3	Crest + 1,75 m	Crest + 3,50 m	Crest + 7,00 m	
32.7	5	3	Crest + 1,75 m	Crest + 5,25 m	Crest + 7,00 m	
32.8	5	4	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m	Crest + 7,00 m
33	5	2	Crest + 1,75 m	Berm 75 m		
33.2	5	3	Crest + 1,75 m	Berm 50 m	Berm 75 m	
34	5	2	Crest + 3,50 m	Berm 50 m		
34.2	5	3	Crest + 1,75 m	Crest + 3,50 m	Berm 50 m	
36	5	2	Slope angle	Crest + 5,25 m		
36.2	5	3	Slope angle	Crest + 1,75 m	Crest + 5,25 m	
36.3	5	3	Slope angle	Crest + 3,50 m	Crest + 5,25 m	
36.4	5	4	Slope angle	Crest + 1,75 m	Crest + 3,50 m	Crest + 5,25 m
37	5	2	Slope angle	Berm 75 m		
37.2	5	3	Slope angle	Berm 50 m	Berm 75 m	
40	5	2	Slope roughness	Crest + 1,75 m		
41	5	2	Slope roughness	Berm 75 m		

41.2	5	3	Slope roughness	Berm 50 m	Berm 75 m	
44	5	3	Slope angle	Crest + 1,75 m	Berm 50 m	

Table L.7 adaptive pathways which adapt sea defence base design variant 2 to 5 meters of sea level rise

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. The scores of the different paths for these criteria are indicated in Table L.8 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
32	5	1	7138	17689	0	-
32.2	5	2	8020	21870	0	-
32.3	5	2	8020	21870	0	-
32.4	5	2	8020	21870	0	-
32.5	5	3	8901	25996	0	-
32.6	5	3	8901	25996	0	-
32.7	5	3	8901	25996	0	-
32.8	5	4	9782	30108	0	-
33	5	2	10072	22789	53	-
33.2	5	3	10683	24894	53	-
34	5	2	8091	19326	28	-
34.2	5	3	8973	23466	28	-
36	5	2	9494	21726	30	-
36.2	5	3	10706	27025	30	-
36.3	5	3	10706	27025	30	-
36.4	5	4	11587	31144	30	-
37	5	2	11497	23572	83	-
37.2	5	3	12188	25957	83	-
40	5	2	7926	62010	0	-
41	5	2	9231	72184	53	-
41.2	5	3	9671	81399	53	-
44	5	3	10546	24397	58	-

Table L.8 Values of the various adaptation pathways for the four selection criteria

Environmental cost indicator

The same behaviour can be seen for 5 meters of sea level rise as for 4 meters (Section 8.5.2). An increase in crest level in a single step of 7 meters (32) has a lower ECI-value than a combination of berm and crest adaptation (33, 34), however when performing the crest level increase in multiple steps (32.2 – 32.8) it is more efficient to combine crest level increase and berm width increase. Because of the inner slope reinforcement of design variant 2, every crest level increase requires the removal and re-appliance of the asphalt protection layer on the inner slope. Removing this layer 3 or 4 times imposes a higher ECI-value than the removal and re-appliance of the asphalt concrete on the outer slopes which is necessary for berm width increase.

Combining a slope angle adaptation with a berm width increase (37) results in a higher ECI-value than combining this with a crest level increase (36) due to the required amount of sand and extra asphalt on the longer outer slope. Combining a crest level increase to a berm width increase adaptation (33, 34) results in a lower ECI-value than both of these combinations.

The preferred adaptational measure to adapt sea defence base design variant 2 to 5 meters of sea level rise is a crest level increase of 3,50 meters in combination with a berm width increase of 28 meters (34).

Direct construction costs

The direct construction costs for a crest level increase with 7 meters in a single step (32) are the lowest, however when performing the crest level increase in multiple steps (32.2 – 32.8) it is less expensive to combine crest level increase and berm width increase (33, 34).

By far the most expensive adaptational measures are those which make use of outer slope roughness adaptation which are at least a factor three to four more expensive (40, 41).

The preferred adaptational measure to adapt sea defence base design variant 2 to 5 meters of sea level rise is a crest level increase of 3,50 meters, combined with a berm width increase of 28 meters, when performed in multiple steps (34, 34.2). Only when applied in a single step, a crest level increase of 7 meters (32) is a less expensive way to adapt the sea defence to 5 meters of sea level rise.

Shift in toe location

The shift in toe location for base design variant 2 has a maximum of 83 meters, which is the case for the combination of slope angle adaptation in combination with a berm width increase to a total width of 75 meters. A berm width increase to 50 meters imposes a 28 meter shift in toe location. Pathways which do not make use of either of these adaptation measures do not impose a shift in toe location and are therefore preferred.

Flexibility and adaptability

Most of the pathways include an increase of crest level, which makes this a first adaptation step which gives the most flexibility as it can be expanded with all available adaptation methods.

Conclusion

Due to the lower ECI-value, direct construction costs and the absence of an outer toe shift, the increase of crest level with 7 meters in a single step is the preferred pathway for base design variant 2 for 5 meters of sea level rise. However with the possibility that 5 meters of sea level rise might not occur during the lifetime of the sea defence, it is preferred to adapt the sea defence in multiple steps. Then, a combination of a crest level increase with 3,50 meters and a berm width increase with 28 meters is preferred.

Therefore a crest level increase of 3,50 meters and a berm width increase of 28 meters is the advised method to adapt sea defence variant 2 to 5 meters of sea level rise. This is in line with the preferred adaptation methods for 2, 3 and 4 meters of sea level rise.

L.2 Determination of the preferred adaptation strategy for design variant 3

The second considered design variant is design variant 3, of which the adaptive pathway scheme is presented in Appendix G. As discussed in Section 8.1 the adaptive pathways are evaluated per meter sea level rise, starting at 2 meters of sea level rise to a maximum of 5 meters of sea level rise. Using this evaluation the preferred adaptation strategy for design variant 3 is determined per sea level rise scenario.

In the evaluation, the pathway numbers as presented in the tables and Chapter 7 are mentioned between brackets behind the individual adaptation options.

Pathway evaluation for 2 meters of sea level rise

The first considered sea level rise scenario is one in which 2 meters of sea level rise occurs, the adaptation pathways which are formed in Sections 7.1 to 7.3 are evaluated for this scenario. All pathways considered for design variant 3 can be found in Appendix G.

In this section all pathways adapting the sea defence to 2 meters of sea level rise are evaluated. In addition to this, also the singular adaptation steps which adapt the sea defence to more than 2 meters of sea level rise are taken into account as these are also options to be applied as a first adaptation step at the moment the base design variant does not meet the water safety requirements anymore. An exception to this is the case in which the first step of an adaptation option (or whole adaptation pathway) is sufficient to adapt the sea defence to 2 meters of sea level rise. An example of this is for example the case in which a berm width increase to 50 meters is sufficient, in this case a berm width increase to 75 meters is not included.

Not every pathway in Appendix G is required to mitigate the effects of 2 meters of sea level rise, all considered pathways in this evaluation are shown underneath in Table L.9.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
1	2	1	Crest + 1,95 m		
2	2	1	Foreshore to -3,08 m		
3	2,5	1	Foreshore to -1,18 m		
3.2	2,5	2	Foreshore to -3,08 m	Foreshore to -1,18 m	
7	3,2	1	Berm 50 m		
10	3,85	1	Slope angle		

Table L.9 adaptive pathways which adapt sea defence base design variant 3 to 2 meters of sea level rise

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. The scores of the different paths for these criteria are indicated in Table L.10 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
1	2	1	1952	7658	0	12
2	2	1	5219	41783	662	1
3	2,5	1	6022	48218	702,8	-
3.2	2,5	2	6022	48218	702,8	-
7	3,2	1	3776	11802	27	7
10	3,85	1	3188	23363	45	4

Table L.10 Values of the various adaptation pathways for the four selection criteria

Environmental cost indicator

Increasing the crest level (1) has the lowest ECI-value of all adaptation options, while foreshore adaptation (2, 3) has the highest ECI-value. Slope angle adaptation (10) and berm adaptation (7) have an equally high ECI-value, due to the movement of Xbloc during the construction process of slope angle and berm width adaptation, which imposes high ECI-values. Increasing the crest level is the preferred adaptation option.

Direct construction costs

The situation for direct construction costs can be compared to that in which the ECI-values were regarded. Increasing the crest level (1) has the lowest direct construction costs of all adaptation options, while slope angle adaptation (10) has the highest (due to the expenses made for extra Xbloc units on the longer outer slope). Increasing the crest level is the preferred adaptation option. Foreshore adaptation (2, 3) is the most expensive adaptation option.

Shift in toe location

Increasing the crest level (1) is the only adaptation option which does not shift the outer toe of the sea defence into the North Sea. The toe shifts due to berm adaptation and slope angle adaptation are very comparable, while foreshore adaptation imposes a shift of over 660 meters.

Flexibility and adaptability

Since crest level adaption (1) can be combined with every other adaptation option and it has a low tipping point, a lot of adaptation pathways can still be formed after implementing this a first adaptation step. Even though berm adaptation (7) has a high tipping point (3,2 meters of sea level rise), still a few pathways can be formed effectively after application of this adaptation option, which provides flexibility.

Foreshore adaptation (2, 3) cannot be combined with other pathways and does therefore rule out further (efficient) adaptation of the Delta21 sea defence.

Conclusion

An increase in crest level (1) is the preferred first adaptation step for base sea defence variant 3 for 2 meters of sea level rise.

Foreshore adaptation is the least efficient adaptation method, due to the substantially higher ECI-value and Direct construction costs as well as the large imposed shift in outer toe location. On top of that, foreshore adaptation rules out the (efficient) use of the other adaptation options in a combination.

Pathway evaluation for 3 meters of sea level rise

Not every pathway in Appendix G is required to mitigate the effects of 3 meters of sea level rise, all considered pathways in this evaluation are shown underneath in Table L.11.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
5	3	1	Crest + 3,90 m		
5.2	3	2	Crest + 1,95 m	Crest + 3,90 m	
7	3,2	1	Berm 50 m		
10	3,85	1	Slope angle		

Table L.11 adaptive pathways which adapt sea defence base design variant 3 to 3 meters of sea level rise

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. The scores of the different paths for these criteria are indicated in Table L.12 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
5	3	1	3081	11346	0	4
5.2	3	2	3963	15490	0	4
7	3,2	1	3776	11802	27	7
10	3,85	1	3188	23363	45	4

Table L.12 Values of the various adaptation pathways for the four selection criteria

Environmental cost indicator

The ECI-values for crest level increase (5) and slope angle adaptation (10) are more or less equal when the first is performed in a single 3,90 meter increase (5). Once crest level increase is performed in more than a single step (5.2), the required increase in berm width (7) has a lower ECI-value (comparing pathway 5.2 with 7). The adaptation of slope angle (10) has a low ECI-value and gives a high tipping point in single step, therefore it can be said that this is the preferred adaptation methods according to this evaluation criterium.

Direct construction costs

The direct construction costs for increasing the crest height in a single step (5) are lower than that of a berm width increase (7), although it does not differ much. When the crest level is increased in two steps (5.2), the costs for crest level increase is more expensive than berm width increase (pathways 5.2 and 7). A change in slope angle (10) is the most expensive of all these methods as all Xbloc have to be relocated and new Xblocs and a lot of sand has to be placed. It can be said that crest level increase in one step (5) is the preferred adaptational method for 3 meters of sea level rise for base design variant 3 when looking at the direct construction costs.

Shift in toe location

Both berm width increase and slope angle adaptation impose a shift of outer toe location into the North Sea. Therefore crest level increase is preferred according to this criterium, as the Natura2000 area in front of the Delta21 sea defence is not touched.

Flexibility and adaptability

The use of berm adaptation (7) occurs in a lot of efficient combinations in the adaptive pathway scheme for design variant 3, therefore this adaptational measure also gives a lot of flexibility in the selection of adaptational measures in the future.

Conclusion

When adapting to 3 meters of sea level rise, a crest level increase with 3,90 meters in one step compared to the base design is the most efficient method. Both the ECI-value and direct construction costs are the lowest when this is performed in a single adaptation step of 3,90 meters. However once the sea defence is adapted in two steps because of flexibility, a berm width increase in one step is more efficient when looking at ECI-value and the amount of possible adaptive pathways after an increase of berm width to 50 meters. The shift in toe location by 27 meters means that during early planning phase at least 27 meters of space should be reserved as a buffer between the sea defence and the Natura2000 area.

For 3 meters of sea level rise, a berm width increase by 27 meters is the preferred pathway for base design variant 3.

Pathway evaluation for 4 meters of sea level rise

Not every pathway in Appendix G is required to mitigate the effects of 4 meters of sea level rise, all considered pathways in this evaluation are shown underneath in Table L.13.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3
12	4	1	Crest + 5,85 m		
12.2	4	2	Crest + 1,95 m	Crest + 5,85 m	
12.3	4	2	Crest + 3,90 m	Crest + 5,85 m	
12.4	4	3	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m
16	4,35	2	Crest + 1,95 m	Berm 50 m	
19	4,55	1	Berm 75 m		
19.2	4,55	2	Berm 50 m	Berm 75 m	
22	4,9	2	Slope angle	Berm 50 m	

Table L.13 adaptive pathways which adapt sea defence base design variant 3 to 4 meters of sea level rise

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. The scores of the different paths for these criteria are indicated in Table L.14 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
12	4	1	4269	15162	0	1
12.2	4	2	5151	19330	0	1
12.3	4	2	5151	19330	0	1
12.4	4	3	6032	23451	0	1
16	4,35	2	5428	18460	27	2
19	4,55	1	7290	18593	53	2
19.2	4,55	2	7570	23947	53	2
22	4,9	2	7058	35488	72	1

Table L.14 Values of the various adaptation pathways for the four selection criteria

Environmental cost indicator

The ECI-value is the lowest for crest level increase in one or two steps (pathways 12, 12.2 and 12.3), followed by a combination of crest level increase and berm width increase (16) or a crest level increase in 3 steps (12.4). A large berm width increase (19, 19.2) has a higher ECI-value, after which a combination of slope angle adaptation and berm width increase (22) has the highest ECI-value.

Because of the inner slope reinforcement of design variant 3, every crest level increase requires the removal and re-appliance of the asphalt protection layer on the inner slope which increases the ECI-value when the crest level is increased in multiple steps. Berm width increase and slope angle adaptation require the removal and re-appliance of Xbloc, which poses an even higher ECI-value.

Direct construction costs

The direct construction costs follow the ECI-value, however the direct construction costs for a combination of berm width increase and crest level increase (16) are higher than those for a single large increase in berm width (19). When the berm width is increased in 2 steps however, this is more expensive (comparing pathways 19 and 19.2 to 16).

Shift in toe location

The increase in berm width shifts the location of the inner toe to the Natura2000 area in in the North Sea. For a berm width increase to 50 meters this is 27 meters and for a berm width increase to 75 meters this is 52 meters. Slope angle adaptation shifts the toe with 45 meters.

Flexibility and adaptability

A crest level increase with 5,85 meters is too high to be adapted further effectively in a combination with an adaptation option other than another crest level increase in the future. A combination of a small crest level increase and a berm width increase (16) however can be adapted further in a combination with other adaptation options, the same goes for a large increase in berm width.

A crest level increase with 5,85 meters can be performed in multiple steps of variable size, which adds flexibility since the pathways are not restricted in step size.

Conclusion

The preferred pathway to adapt base design variant 3 to 4 meters of sea level rise is an increase in crest level with 5,85 meters when performed in 1 or 2 adaptation steps. However when increasing the crest level in 3 steps this is no longer efficient, then it is preferred to adapt the crest level in combination with berm width increase. This does however mean that 27 meters of empty space should be reserved in front of the sea defence for adaptation in the future.

Pathway evaluation for 5 meters of sea level rise

Not every pathway in Appendix G mitigates the effects of 5 meters of sea level rise, all considered pathways in this evaluation are shown underneath in Table L.15.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	Adaptation step 1	Adaptation step 2	Adaptation step 3	Adaptation step 4
23	5	1	Crest + 7,80 m			
23.2	5	2	Crest + 1,95 m	Crest + 7,80 m		
23.3	5	2	Crest + 3,90 m	Crest + 7,80 m		
23.4	5	2	Crest + 5,85 m	Crest + 7,80 m		
23.5	5	3	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m	
23.6	5	3	Crest + 1,95 m	Crest + 3,90 m	Crest + 7,80 m	
23.7	5	3	Crest + 1,95 m	Crest + 5,85 m	Crest + 7,80 m	
23.8	5	4	Crest + 1,95 m	Crest + 3,90 m	Crest + 5,85 m	Crest + 7,80 m
24	5	2	Crest + 3,90 m	Berm 50 m		
24.2	5	3	Crest + 1,95 m	Crest + 3,90 m	Berm 50 m	
25	5	2	Crest + 1,95 m	Berm 75 m		
25.2	5	3	Crest + 1,95 m	Berm 50 m	Berm 75 m	
27	5	2	Slope angle	Crest + 1,95 m		
28	5	2	Slope angle	Berm 75 m		
28.2	5	3	Slope angle	Berm 50 m	Berm 75 m	

Table L.15 adaptive pathways which adapt sea defence base design variant 3 to 5 meters of sea level rise

In order to create a comparison between the various adaptation pathways, the evaluation criteria as elaborated upon in Section 8.2 are used. The scores of the different paths for these criteria are indicated in Table L.16 below.

Pathway number	Tipping point [mSLR]	Number of adaptation steps	ECI – value [€]	Direct construction costs [€]	Shift in toe location [m]	Possible pathways after implementation
23	5	1	5515	19107	0	-
23.2	5	2	6398	23298	0	-
23.3	5	2	6398	23298	0	-
23.4	5	2	6398	23298	0	-
23.5	5	3	7279	27427	0	-
23.6	5	3	7279	27427	0	-
23.7	5	3	7279	27427	0	-
23.8	5	4	8159	31541	0	-
24	5	2	6857	23148	27	-
24.2	5	3	7039	26292	27	-
25	5	2	9242	26251	53	-
25.2	5	3	9522	31605	53	-
27	5	2	5499	32582	45	-
28	5	2	10660	42580	98	-
28.2	5	3	10940	47933	98	-

Table L.16 Values of the various adaptation pathways for the four selection criteria

Environmental cost indicator

A combination of slope adaptation and a single step of crest level increase (27) has a lower ECI-value than a crest level increase of 7.80 meters (23). When performed in more than two steps, the combination of crest level increase and berm width increase (24.2) has a lower ECI-value than crest level increase (23.5 – 23.8). This is due to the same reasoning as for design variant 2 (Section 8.6.2).

The use of slope angle adaptation in combination with a berm width increase (28) has the largest ECI-value, which is more than a factor 2 higher than that of a crest level increase. When looking at the environmental cost indicator, a combination of slope angle adaptation and crest level increase (27) is the best adaptation option for base design variant 3.

Direct construction costs

The direct construction costs are the lowest for crest level increase (23). However when the adaptation is performed in 3 or 4 steps (23.5 – 23.8) it is less expensive to perform a combination of berm width adaptation and crest level adaptation (24, 25).

The implementation of slope angle adaptation (27, 28) is at least a factor 1.5 more expensive, which makes this the least preferred adaptation method.

Shift in toe location

The maximum shift in toe location is 98 meters for a combination of slope angle adaptation and berm width increase (28). The outer toe does not move under the influence of crest level increase.

Flexibility and adaptability

It is more efficient when looking at ECI-value and direct construction costs to perform a combination of crest level increase and berm width increase, compared to only using crest level increase. Therefore a combination of these two adaptation methods is preferred when looking at the adaptability.

Conclusion

When performed in only one step of 7,80 meters or 2 smaller steps (23 – 23.4), an increase in crest level with 7,80 meters is preferred. However with the possibility that 5 meters of sea level rise might not occur during the lifetime of the sea defence, it is preferred to adapt the sea defence in multiple steps. Therefore a combination of crest level increase with 3,90 meters and a berm width increase of 27 meters (24.2) is the adaptation pathway of choice for design variant 3.