ALMA MATER STUDIORUM

UNIVERSITA' DI BOLOGNA

SCUOLA DI SCIENZE

Corso di laurea in Analisi e gestione dell'ambiente – Climate-KIC

Double Dyke System - Natural engineering solutions

Tesi di laurea in Idrologia

Relatore: Marco Antonellini

Correlatore: Jim van Belzen

Controrelatore: Beatrice Maria Sole Giambastiani

Presentata da:

Andrea Natali

Anno Accademico 2019/2020

First of all, I want to thank NIOZ and the people who helped me during the internship. Jim van Belzen, supervisor and friend, who introduced me to the world of research and programming, who followed and taught me all the time, and who gave me the opportunity to grow and write this thesis. Tim Dubbeldyke, who allowed me to use his knowledge and material to write my thesis. I would like to thank all the trainees and PhDs I met during the internship, who became true friends from colleagues.

I thank my supervisor, Marco Antonellini, for his patience and trust in me and for helping me to complete my studies.

I would like to thank my family, for their psychological, financial, and lifelong support. Thank you for having always been there and for having suffered my complaints and ramblings.

I thank my friends and colleagues of LUMO, thanks to whom I always grew up and put myself on the line. Thank you for having always been there and for pulling me out of the darkest moments.

Last but not least, I would like to thank my friends and all the people who have helped me during these years and who have supported me throughout my studies. Thank you.

Voglio ringraziare innanzitutto NIOZ e le persone che mi hanno aiutato durante il tirocinio. Jim van Belzen, supervisore e amico, che mi ha introdotto al mondo della ricerca e della programmazione, che mi ha seguito ed insegnato per tutto il tempo, e che mi ha dato la possibilità di crescere e di scrivere questa tesi. Tim Dubbeldyke, che mi ha permesso di utilizzare le sue conoscenze ed il suo materiale per poter la stesura della tesi. Ringrazio tutti i tirocinanti e PhD che ho incontrato durante il tirocinio, che da colleghi sono diventati veri amici.

Ringrazio il mio relatore, Marco Antonellini, per la pazienza e la fiducia riposta in me e per avermi aiutato nel completare i miei studi.

Ringrazio la mia famiglia, per l’appoggio psicologico, economico, e di una vita. Grazie per esserci stati sempre e per aver subito le mie lamentele e le mie sfuriate.

Ringrazio i miei amici e colleghi di LUMO, grazie ai quali sono cresciuto e mi sono messo in gioco in tutti i frangenti. Grazie per esserci sempre stati, e per avermi tirato fuori dai momenti più bui.

Infine, non per importanza, ringrazio i miei amici e tutte le persone che mi hanno aiutato durante questi anni e che mi hanno accompagnato per tutto il mio percorso di studi. Grazie.

ABSTRACT

According to various studies, the effects of climate change will be a danger to ecosystems and the population, especially in coastal areas, increasing the risk of floods. Authorities are taking action to prevent future disasters using traditional engineering solutions. These solutions can have high environmental and economic costs, fixing the coastline, increasing the salinization of aquifers, and can be subject to failure mechanisms.

For this reason, studies were made to use natural engineering solutions for coastal protection, instead of traditional solutions, to achieve the UN SDGs. Coastal ecosystems have the natural ability to repair and restore themselves, increasing soil elevation, and attenuating waves. One of these solutions is the Double Dyke System, consisting of creating a salt marsh between the first dyke and a second inland. The goal is to protect the coasts and to restore ecosystems.

The purpose of this study is to compare the costs of natural engineering solutions with traditional ones. It is assumed that these solutions may be more effective and less expensive in the long run. For this evaluation, a suitability analysis of the polders in the Dutch Zeeland region to assess the costs and benefits under different SLR scenarios was made. A saline intrusion model was also created to analyze the effects of a salt marsh on the aquifers. From the analyzes conducted, the implementation of the DDS turns out to be the cheapest coastal defense system in all SLR scenarios. The presence of a salt marsh could also have a positive impact on the prevention of saline intrusion in the various scenarios considered.

The DDS could have a positive economic and environmental impact in the long term, reducing the investment costs for coastal defense and bringing important benefits for the protection of man and nature.

Despite the results, more studies are needed on the efficiency of this defense system and on the economic evaluation of non-marketable ecosystem services.

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1. Introduction

1.1. Global Trends

The global trend shows an increasing of the anthropogenic activity in coastal areas (Bouma et al., 2014), with a global average density of people living in coastal areas of 405 to 534 people/km^2 by 2060 (Van Coppenolle, 2018), creating direct and indirect effects on the ecosystems. Moreover, according to various studies (Bouma et al., 2014; Gracia et al., 2017; Temmerman et al., 2013; Van Coppenolle, 2018), the increasing of storminess, the land subsidence and the sea-level rise are leading to an increasing of the coastal flood risk. Globally, some studies show that at least 40 million of people and US$ 3 billion of assets are already located in flood-prone areas and are expected to become 150 million of people and US$35 billion by 2070 (Temmerman et al., 2013; Nicholls et al., 2007). Thus, the use and the implementation of coastal protection solutions is needed to counter the effects that climate change can have on coastal areas and on the economy.

1.2. Coastal defense

Coastal engineering structures were used as part of the flood risk mitigation solution, such as the building of sea walls, dykes and embankments. The use of these structures provided a stable environment, giving an economic stability at first, but some studies have proved that those solutions had leaded to an economic and ecosystem drawback, as the erosion of tidal habitats, hence compromising the natural adaptive capacity of the shoreline and the spreading of toxic algal bloom (Gracia et al., 2017; Temmerman et al., 2013). Furthermore, the loss of the ecosystem functions, the loss of biodiversity and coastal vegetation in coastal and estuarine ecosystem can lead to biological invasion, worsening of the water quality and a decreased in coastal protection from flooding and storm events (Barbier et al., 2011). Moreover, their maintenance and the adjustment of them to cope with the sea-level rise have a cost: for instance, it has been estimated that the Dutch Delta Programme for the adjustment of the flood defense system will require an investment up to €1.6 billion per year in 2050, while the potential cost of a single dyke failure range between €30-50 billion (Temmerman et al., 2013; Kabat et al., 2009).

1.2.1. Conventional Engineering

The most commonly used method of coastal defense is by adding to the height of the dyke (Figure 1). However, this is an expensive method of strengthening dykes and sometimes the structural base of the dyke makes this impossible. This method of strengthening is most commonly applied in urban or industrial areas when the area behind the dyke is unavailable because there are buildings and other infrastructure.

Figure 1 - This figure demonstrates the way dyke heightening is implemented to protect the coast. (Galvan, et al., Dike Heightening, 2018)

Another method of strengthening is creating a so called ‘unbreachable dyke’ (Figure 2). This method focuses on extending the base of the dyke to make sure a dyke collapse is impossible. It makes sure that even in extreme conditions waves could wash over the dyke without the dyke collapsing allowing the land behind to flood minimally. Just like increasing the height of existing dykes this is method of strengthening is costly.

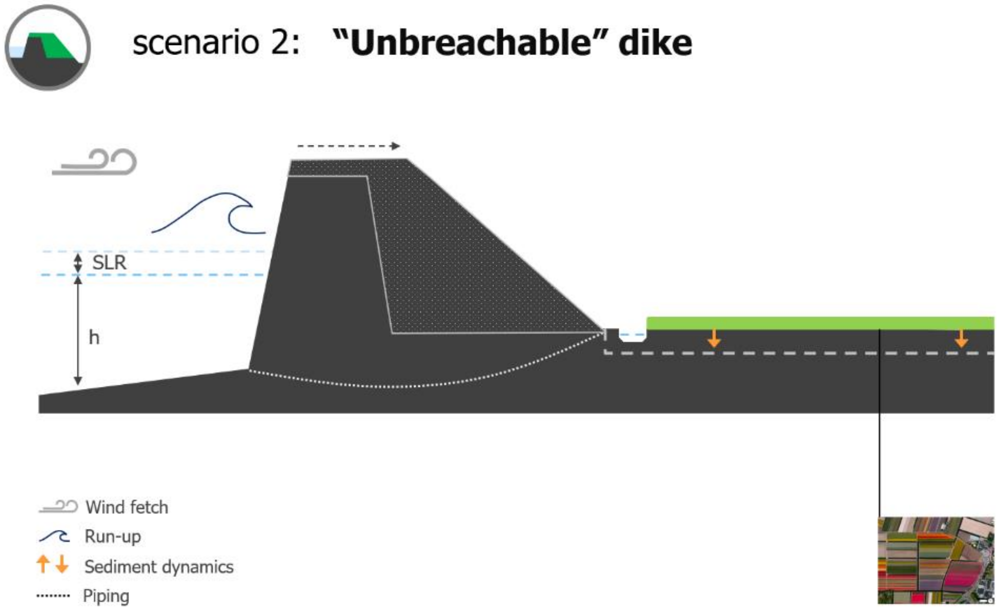


Figure 2 - The unbreachable dyke is another way of strengthening. An increase in height is not specifically necessary, even when waves overtop the dyke in extreme conditions the structural integrity of the dyke is not in danger (Galvan, et al., Unbreachable Dike, 2018).

Although the use of engineering solutions is widely known and trusted as a form of coastal protection, they can lead to several problems such as the fixing of the coastline in the position of the time of construction. Even though initially beneficial, it can be problematic because coastlines are naturally dynamic landforms which respond to factors such as sea-level rising and waves. They can also be subjected to failure mechanisms as shown in Figure 3.

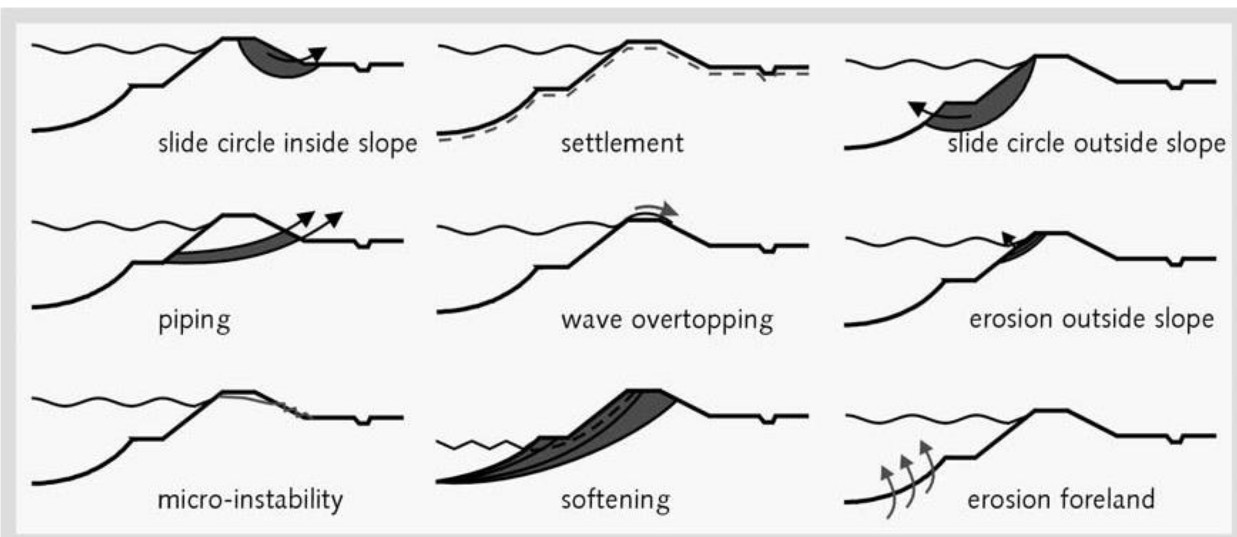


Figure 3 - Failure mechanism of a dyke (Technical Advisory Committee for Flood Defences., 1999)

In order to manage it, there is a constant need for maintenance and adaptation of the dykes. In contrast to this solution, wetlands are capable of undergoing with SLR by increasing sediment accumulation, besides having less disadvantages (Linham, 2010).

Affected variable	Conventional coastal engineering	Ecosystem-based coastal defence
Natural habitat	Degredation or destruction	Conservation and restoration
Sediment accumulation (after SLR)	Disturbed or stopped by embankments, groins, dams, and so on	Sustained (if enough sediment is available)
Land subsidence	Exacerbated by wetland reclamation, soil drainage, groundwater and gas extraction	Counter balanced by sediment trapping, but continues behind ecosystems
Storm surge propagation through an estuary or delta	Wetland reclamation reduces water storage and friction, enhancing inland storm surges	Wetland restoration enlarges water storage and friction, lowering inland storm surges
Long-term sustainability	Low: regular maintenance is needed at high costs	High: ecosystems are self-maintaining (if enough sediment is available)
Cost-benefit appraisal	Moderate to high	Mostly high due to added benefits
Water quality of estuary, delta and coastal sea	May degrade by organic matter accumulation and toxic algal growth in closed-off estuaries	Improved and sustained by nutrient and contaminant cycling in restored wetlands
Fisheries and aquaculture production	Reduced: less habitat for young fish, shellfishand crustaceans due to wetland reclamation	Improved: more habitat for younf fish, shellfish and crustaceans due to wetland and reef restoration
Human recreation potential	Negative perception of artificial landscape	Positive perception of natural landscape
Required space	Moderate	High, therfore, not applicable for cities at the coast
Difficulty of creating the defence structure	Moderate	Relatively high due to natural dynamics and variablity
Existing implementation and experience	Substantial, but many failures in the past	Limited so far. More research is urgently needed
Social and political acceptance	Widely accepted	So far, only accepted in certain areas (Europe and US)
Health hazards (other than flooding)	None	Wetlands with stagnant water may facilitate breeding of mosquitos that could spread disease

Figure 4 - Limitations and potentials of conventional and ecosystem-based engineering *(Temmerman et al., 2013)*

1.2.2. Nature-Based solution

Given the current global challenges like the land use impact, climate change and biodiversity loss, international policies at multiple scale such as the United Nations Conventions on Biological Diversity (CBD) Strategic Plan, the UN Agenda 2030 and the European Biodiversity Strategy are endeavoring to combat those challenges to enhance resilience (Haase et al., 2018; de la Vega-Leinert et al., 2018). There is, as a matter of fact, a great interest in the restoration and in the conservation of coastal habitats for nature-based defenses and coastal protection (Narayan et al., 2016; Temmerman et al., 2013). The Netherlands is a key example, where the

DELTA committee called for removing existing structures to restore natural estuary and tidal regimes while protecting from flooding and storm surge (Kabat et al., 2009).

Recent studies have given attention to the flood prevention capacity of coastal and estuarine ecosystem such as tidal marshes and mangroves as an ecological engineering solution to tackle climate change, given its more sustainable and cost-effective than conventional engineering (Temmerman et al., 2013; Boerema et al., 2016). Ecosystems have, indeed, the natural capacity to self-repair and recovery, providing significant advantages against coastal erosion, such as reducing storm waves and storm surge. The ability of various species common in intertidal areas, such as mussel beds or vegetation, is to trap and stabilize sediment increasing the soil elevation and, subsequently, attenuating waves. Thanks to the soil elevation, they are also able to keep up with the sea-level rise (Koch et al., 2009; Gracia et al., 2017; Temmerman et al., 2013; Borsje et al., 2011). Throughout this thesis we will focus on marsh ecosystems, as studies have shown that they are capable of attenuating up to 97% of incoming wave energy depending on the width of the marsh, accumulating sediments and reducing storm surge duration and height (Barbier et al., 2011). Impacts on conventional protection structures are thereby lowered and maintenance costs are reduced (Temmerman et al., 2013). Furthermore, water quality is improved, fishery is maintained and new areas for tourism, recreation and research are created (Barbier et al., 2011).Moreover, the oxidation of peat soils and therefore subsidence is reduced, and carbon sequestration is enhanced (Hoogland et al., 2012).

In order to develop nature-based solutions through the use of marshes, two possible methods have been proposed: the managed realignment solution and the creation of a double dyke system (DDS).

Managed realignment solutions consist in setting back the line of actively maintained defenses to a new line, inland of the original, while the primary dyke will be demolished. This should promote the creation of intertidal habitats between the old dyke and the new one, allowing those areas to get daily tidal inundation and creating a spontaneous ecological development of the ecosystem. The intertidal habitat can lead to some benefits such as the soil formation and the reduction of erosion rates, thus attenuating waves and flooding risk (Figure 5) (Linham, 2010).

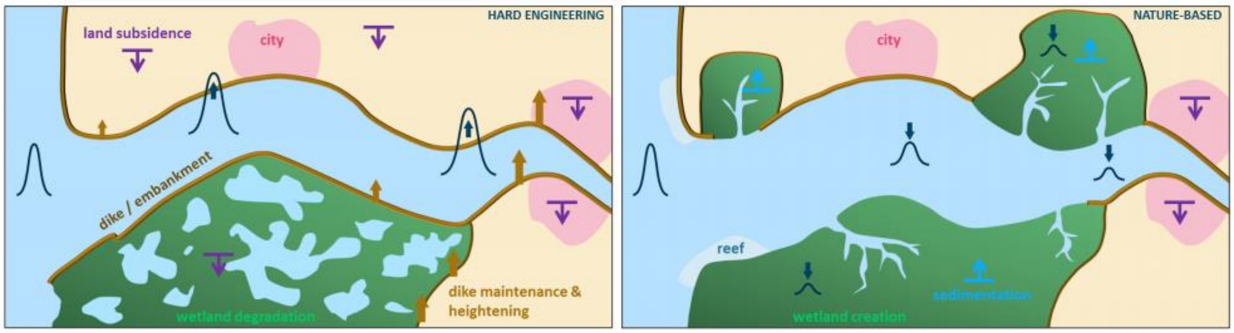


Figure 5 - Traditional engineering coastal protection structures versus the managed realignment solution. Blue arrows indicate an increase or decrease in intensity of storm wave, storm surge and sea level. (Van Coppenolle, 2018)

The Double Dyke system, on the other hand, involves in the creation of an ecosystem between the first dyke and a second one inland. The primary dyke would then not be demolished, except in some areas to create breaches, controlled or not, and would not even need the classic maintenance of conventional engineering solutions (Figure 6a). The need to elevate it or strengthen it to counteract future sea level rising is lessened by the use of the secondary dyke (Figure 6b). The latter would allow the protection of the internal areas even if the waves overtopped the primary dyke. The secondary dyke would be built specifically to leave space for the development of the ecosystem, or secondary dykes already present in the landscape could be used for this purpose. The purpose of the DDS is not only about coastal protection and restoring ecosystems, but also creating long-term protection by increasing the elevation of the land in suitable polders with the aim of closing the breach in the primary dyke and returning it to the agriculture. That would increase the elevation of the coastal areas of Zeeland, acting against the sea-level rise in the farther future.

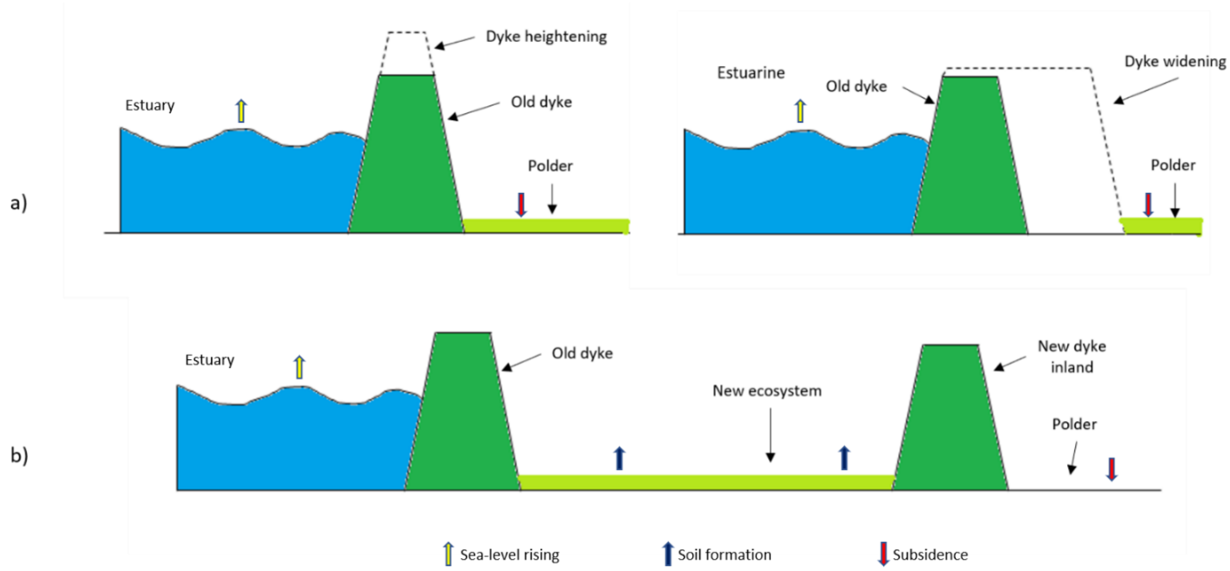


Figure 6- The use of double dyke system (b) could prevent the future maintenance of primary dykes (a).

The use of a double dyke system would be cheaper than the managed realignment, as the use of primary dykes would maintain a primary protection, reducing the height of the secondary one, thereby reducing the costs of constructing the secondary dyke and felling the primary one.

1.2.2.1. Salt marsh development

Marshes are generally defined as land covered with halophytic vegetation that is regularly flooded by the tide and drained by creeks (Allen, 2000).The feedbacks between the hydrological and geomorphological processes determine the growth of a marsh platform that creeps up to MHWL. The main factors controlling surface elevation are sediment regime, tidal regime, SLR and vegetation (Allen, 2000).The sediment pool must be large enough to allow for vertical growth of SLR or greater to prevent the salt marsh from drowning, not allowing vegetation to grow. Salt marshes are found mainly in sheltered areas, where reduced wave energy allows sediments to settle and pioneer plants to settle (Friess, 2012). In addition, vegetation reduces the speed of the waves and consequently traps sediments. Fresh sediment deposits are rich in nutrients that accelerate the growth of vegetation (Friess, 2012; Van Groet, 2013). Depending on time, space and shape, a tidal marsh can be divided into three main parts related to its elevation: mud flat, low marsh, high marsh (Van Groet, 2013). With sufficient sediment-supply, low marshes rise quickly to the level of MHW. Subsequently, the sedimentation rate decreases, and the marsh tends to an equilibrium with the rising MHW (Temmermann et al., 2003)

At a constant growth stage with sea level, the vertical growth rate is assumed to be equal to the SLR rate (Temmermann et al., 2003).Although sedimentation rate and SLR are the major drivers in marshes development, the change in surface elevation is further affected by subsurface processes. These processes can be both natural and anthropogenic, for example self-compacting, depending on the thickness of the deposits, the decomposition of organic matter, the deep subsidence and the use of the fresh water reserves present in the subsoil (Temmermann et al., 2004). The feedbacks between all the natural processes that form a tidal marsh are illustrated in Figure 7.

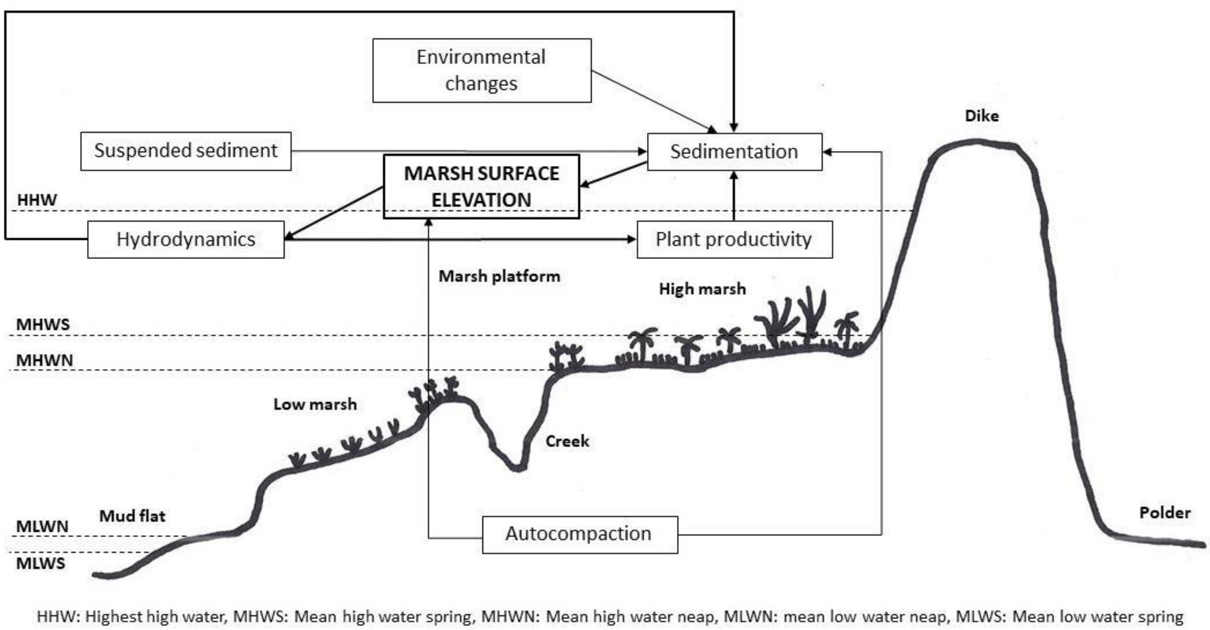


Figure 7 - Feedbacks influencing the marsh surface elevation. A tidal marsh accretes to a level high in the tidal frame (*(Allen, 2000; Van Groet, 2013)*

1.2.2.2. DDS pilot

A pilot project, which aims to study this system, started in 2017 in the province of Groningen, The Netherlands. An existing seaward dyke between Eemshaven and Delfzijl needed to be strengthened, but instead the province Groningen and the waterboard “Noorderzijlvest” implemented a double-dyke system as part of a more integrative approach to ensure coastal protection (Figure 8) (Provincie Groningen., 2018)

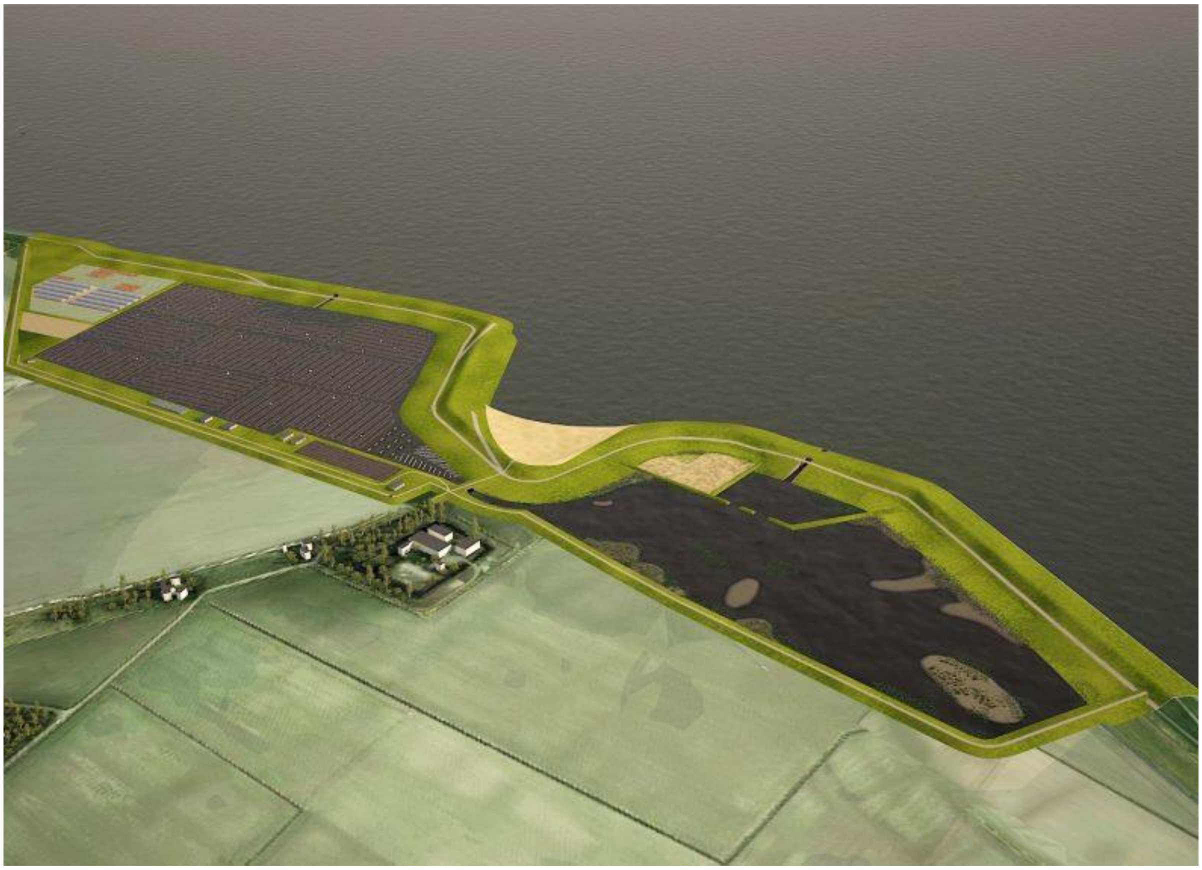


Figure 8 - The double-dyke between Eemshaven and Delfzijl in the Eems-Dollard region. The system is divided into two compartments. The right compartment is for nature conservation. The left compartment serves for new forms of agri- and aquaculture

1.2.2.3. Ecosystem services

The use of ecosystem-based solutions (NBS) can lead to several benefits compared with conventional engineering, providing services to the society. Such Ecosystem Services (ESs) may include, in addition to sediment accumulation and coastal protection, natural habits, water quality improvement, fisheries production, recreational uses and blue carbon storage, so that in the long-term they could be more cost-effective than conventional defenses (Temmerman et al., 2013; Boerema et al., 2016; Bouma et al., 2014; Craft et al., 2009; Pendleton et al., 2012). According to the Millennium Ecosystem assessment (2005) ecosystem services are defined as "the benefits that people get from ecosystems", similar to the definition given by The Common

International Classification of Ecosystem Services (CICES), which defines them as "the contributions that ecosystems make to human well-being" (Haines-Young, 2018). The ESs can be categorized in four main categories (Mitsch et al., 2015):

- Provisioning services: those are the products obtained from ecosystems such as food, fresh water and genetic resources.
- Regulating services: they include air quality regulation, the climate regulation, the water purification, disease and pest regulation, pollination and natural hazard regulation.
- Cultural services: those are the benefits that people gain from ecosystem related to spiritual enrichment, recreation, tourism, education and cultural heritage.
- Supporting services: all the basic ecosystem processes of nutrient cycling and primary productivity that may lead to the other three services listed above.

As some studies as shown there are few gaps for what concerning the assessing of the values of the ecosystem services (Boerema et al., 2016; Koch et al., 2009; Barbier et al., 2011). In general, only services that are already quantified are included in the evaluation, as many services are still non-marketed, such as recreational activities or the provisioning and regulating services. Moreover, given the difficulty in predict whether and when the climax stage will be reached and the gaps regarding the functional characteristics of coastal habitat that provide services, the evaluation processes are still critical. Furthermore, sufficient evidence suggest that some services are not uniform across estuarine and in the coastal seascape. The development of intertidal areas depends on environmental and hydrologic parameters along the estuary, such as salinity or the suspended sediment concentration (SSC), as they both can vary depending on the position along the estuary. These two parameters can influence both the composition of sediments, such as the amount of organic matter present in the soil, and the development of biotic structures.

Economically using ecosystem-based engineering offers new innovative opportunities. Tidal areas can be used to store freshwater which can be used during dry summers to water crops. Tidal areas can also be used for aquaculture. Aquaculture is quickly progressing to becoming one of the primary forms of food production (Helmstetter, 2019) although it will not yield the same income as that of crops. However when ecosystem services returned from salt marshes are expressed in monetary values there is an immense difference in annual benefit (Boerema, Geerts, Oosterlee, Temmerman, & Meire, 2016), as shown in the graph in Figure 9. Possible land uses that can create benefits are aquaculture, recreation, and freshwater storage. Electricity can be generated by installing a turbine at the inlet, or by u. The retention of salt marshes for future generations, carbon sequestration and the filtering effects by oysters (if there is aquaculture) are other possible ESs create by ecosystems (King & Lester, 1996).

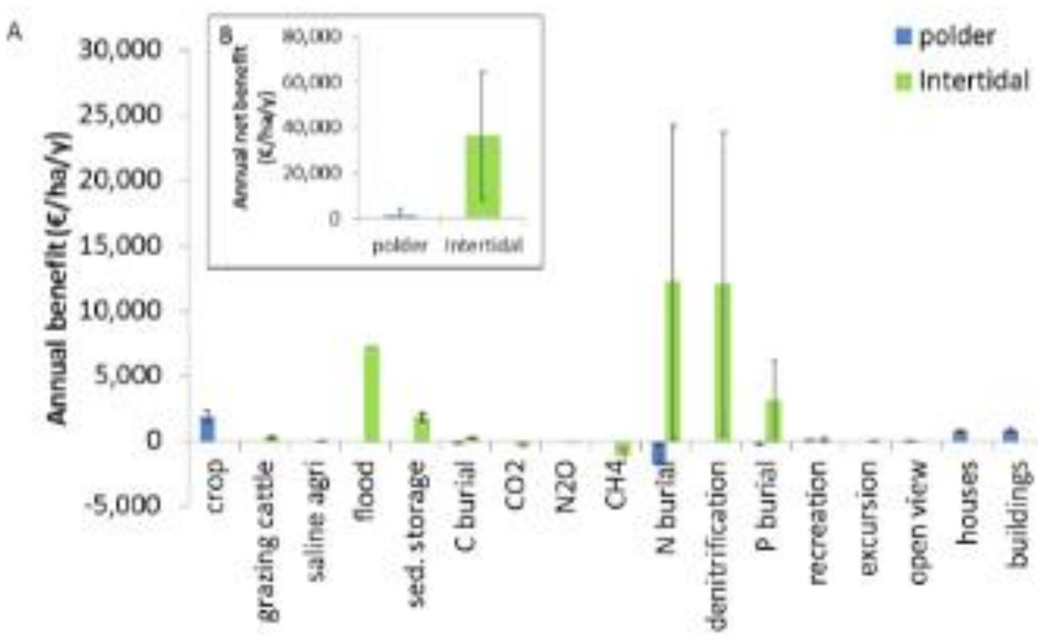


Figure 9 - Ecosystem services in polders compared to intertidal zones. (Boerema, Geerts, Oosterlee, Temmerman, & Meire, 2016)

As a consequence of the heightening and vegetation development, interaction with other animal species establishes. Namely, the vegetation on the marshes provides shelter and food sources for insects, crustaceans and breeding birds, shaping unique areas with high ecological value. Positive feedback mechanisms exist between vegetation, sedimentation and ecology. The vegetation influences the interaction between morphology and hydrodynamics. silt trapping and vegetation development heighten the area. As vegetation densifies, the flow velocity decreases, causing more sedimentation, and thus heightening of the surface. More vegetation species can develop on higher marshes as the conditions are less stressful, leading again to more animal species. Whether the pioneer vegetation can develop, depends on their tolerance on flooding frequency and salinity.

The ecosystem that is built up is not taken into account when making a cost-benefit analysis because natural systems/effects are often hard to quantify and translate to monetary values. Thus the gain of tidal habitats is an added benefit to ecosystem-based engineering.

1.3. Dutch situation

The Netherlands is one of the countries with the highest flooding risk in the EU according to the World Risk Report 2016 (Garschangen, 2016), with more than 9 million people living in coastal areas (Kabat et al., 2009). After the big flooding in 1953, Dutch authorities acted to prevent future disasters: as a consequence, 3200 km of primary dykes and 14000 km of secondary dykes have been built with the aim to reduce the flooding risk. Nevertheless, the country features an elevation varying between 0 to 7 m below the mean sea-level depending on the area (Ritzema et al., 2018) continuing up with a rate up to 4 mm/year, depending on the location in the country (Coastal flood risk The Netherlands, 2018). The Netherlands has been subjected to a sea-level rise of roughly 0.7-0.8 mm per year (Ritzema et al., 2018). Moreover, the predicted sea-level rise, considering the influence of climate change, range from 0.65-1.3 m by the year 2100 up to 2-4 m by the year 2200 (Ritzema et al., 2018; Delta Committee, 2008). With the increase in sea-level rising and land subsidence, economic and natural effects could affect the livability of the area. The subsidence of the land across the sea shore will lead to a greater intrusion of salinity in the area, creating problems with the agricultural use of polders and a poorer quality of water, while the sea-level rising leads to an increasingly frequent maintenance of the primary dykes, increasing their costs. The risk of flooding is, indeed, closely related to the impact of land subsidence on the height of existing seawalls and dykes. As some studies have shown (University of California - Berkeley, 2018; Wung et al., 2012), depending on how fast seas rise, the areas at risk of inundation could be twice than what had been estimated from sea level rise only, if the land subsidence is considered.

Figure 10 shows how sea-level rise, subsidence and different water management over time are one of the biggest challenges of the Netherlands.

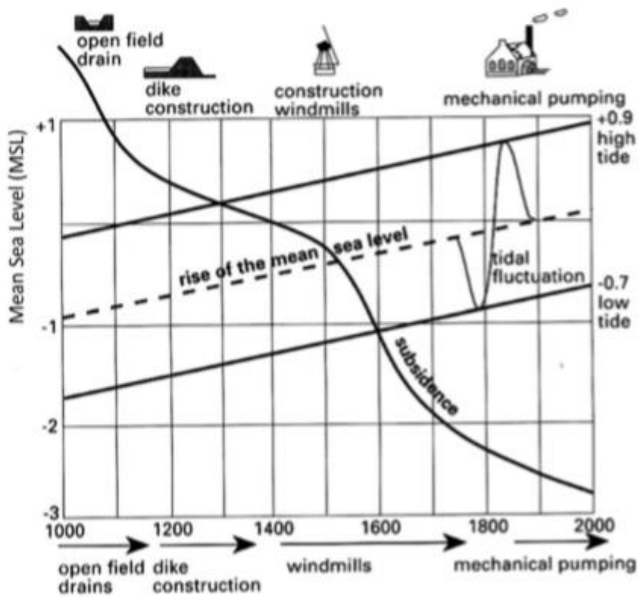


Figure 10 - Subsidence, in combination with sea-level rise, challenge the water management in time (Ritzema et al., 2018)

1.3.1. Zeeland

This research concentrates on the province of Zeeland, located in the South-Western part of the Netherlands. The climate in Zeeland is temperate, with cool summers and mild winters. Winds predominantly blow from south-west and the annual average precipitation is 900 mm (De Vriend et al., 2011).

After the North Sea Flood in 1953, the Dutch government decided to construct the so-called Delta Works to reduce the length of vulnerable Dutch coastline. Contrary to the initial plan, which implied the construction of a closed dyke at the outlet of the Eastern Scheldt, storm surge gates were installed that could be closed during storms. The Western Scheldt was kept open because it forms an important shipping lane (Goemans et al., 1987).

Zeeland's scenery is typical for the western part of the Netherlands: drained peat meadows, fen-meadows, dykes and ditches form the landscape. The fertile soils are mainly used for agriculture, nature conservation or residence and recreation. A major problem in Zeeland is the subsidence of polders as a result of artificial drainage of peat soils to keep them suitable for agriculture (Cuenca et al., 2008). Large parts of Zeeland are below sea level (Figure 11) (Kirby et al., 2019), which involves a high risk for the 380.000 people living in close vicinity with the sea (Centraal Bureau voor de Statistiek., 2018).

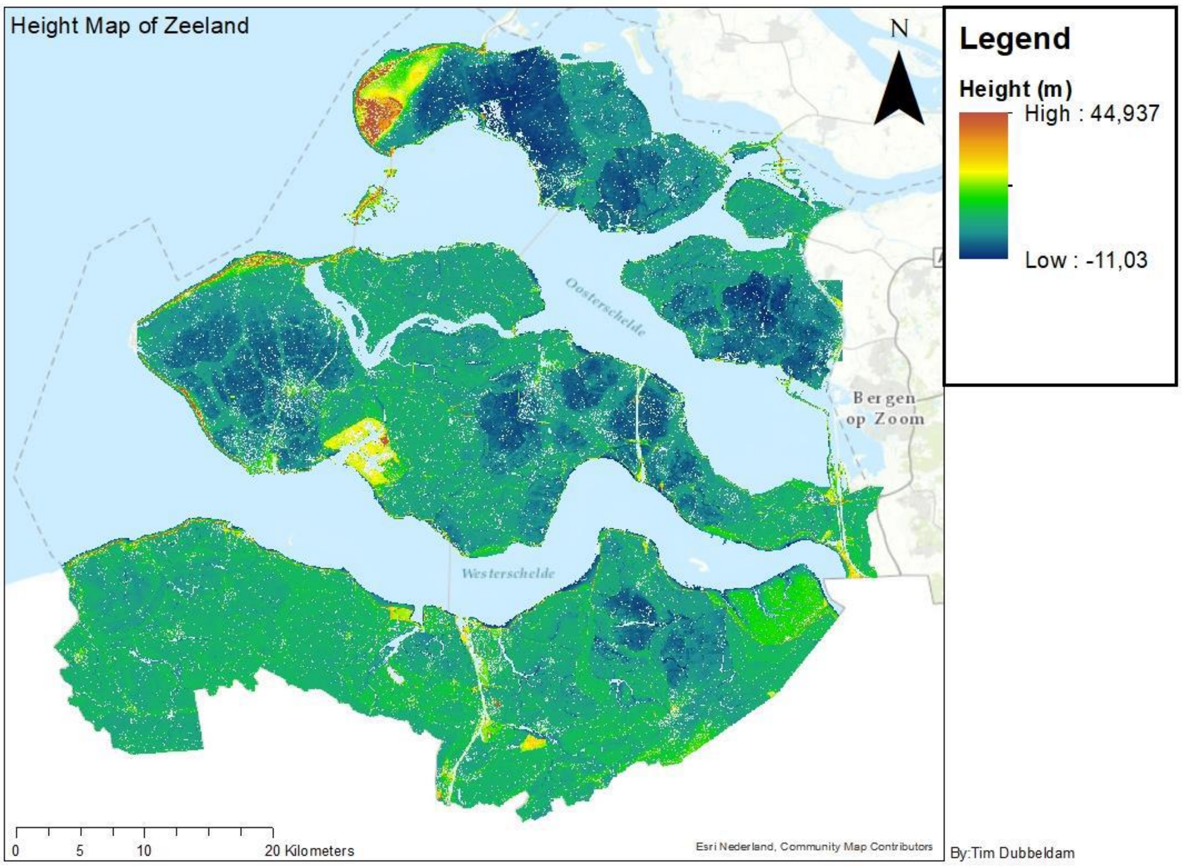


Figure 11 - Maps of the height of Zeeland (made by Tim Dubbeldyke) (Actueel Hoogtebestand Nederland, n.d.)

As a result of the subsidence and the stress on the available fresh groundwater resources due to tourism and agriculture, Zeeland has been largely salinized as shown in Figure 12. The available freshwater can be found dune areas and more elevated areas (Joost R Delsman et al, 2018)

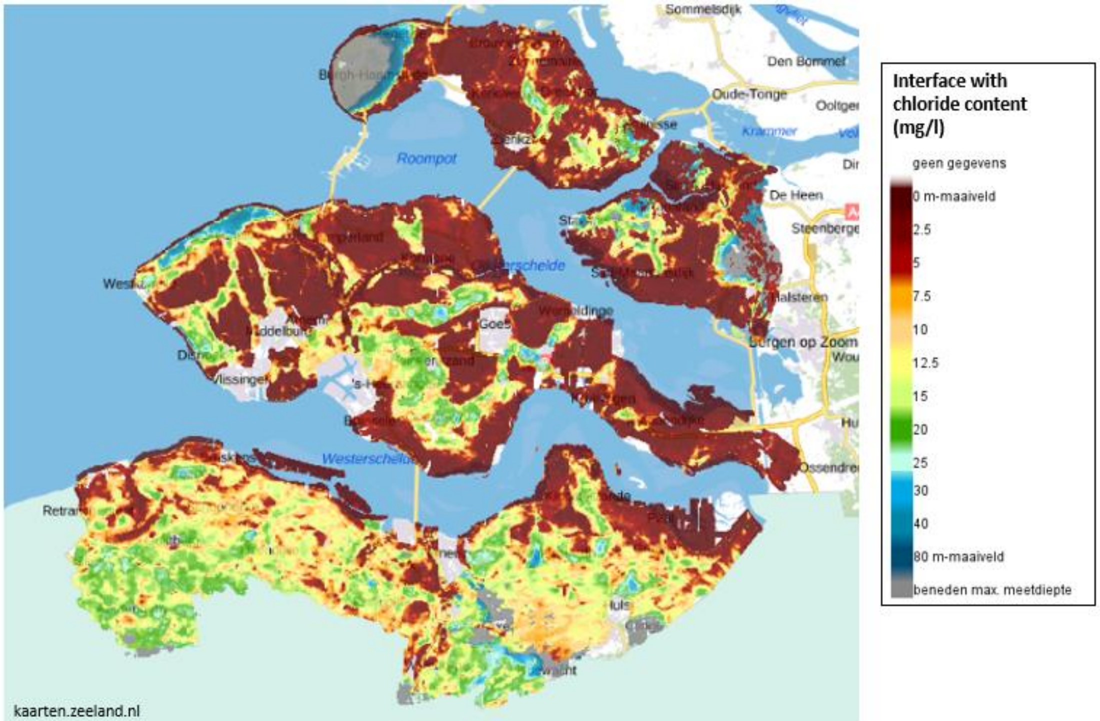


Figure 12 - Chloride content interface in Zeeland (Joost R Delsman et al, 2018)

1.4. NIOZ

The Royal NIOZ, an NWO Institute, is the Dutch national institute for fundamental and applied marine sciences and It is one of the world leading institutes in oceanographic research. It consists of four different departments: Estuarine & Delta Systems, Coastal Systems, Ocean Systems and Marine Microbiology & Biogeochemistry. This research is part of the Estuarine and Delta Systems department (EDS).

The aim of the EDS is to understand complex interaction between organisms and their environment in estuaries and delta systems in the context of natural and anthropogenic changes. The department is involved in the project “Zeeland 2121” funding by WWF, which aims to study and understand the development of tidal marshes, the costs of these solutions and the benefits they can lead to the population, in order to implement ecosystem-based solutions for coastal defense in the Zeeland province. This research will focus on the optimization of this solution and to the benefits it can lead.

2. Research questions

To understand the impact of the implementation of the Double Dyke System as a nature-based solution for coastal defense in Zeeland, a main question was asked:

- Which are the costs and benefits of this system?

To being able to answer this main question, a comparison between traditional coastal defense and the DDS in needed, and a better understanding of the ecosystem services generated by it is needed to assess the benefits created. To find this information, sub-questions were made:

- Which are the most suitable polders for implementing the DDS?
- What is the effect of a salt marsh on the saltwater intrusion on the aquifer?

2.1. Aim

The aim of the research is to create a realistic view of the implementation of the double dyke system in Zeeland and the related effects that a nature-based solution can create compared to traditional coastal defense.

3. Method

The purpose of this research is to provide insight into the implementation of nature-based coastal defenses in Zeeland by comparing the costs and benefits with those of traditional coastal defenses. To do this, a study of the suitability of the polders for the project was carried out and a study of the ecosystem services created by the Double Dyke system has been made.

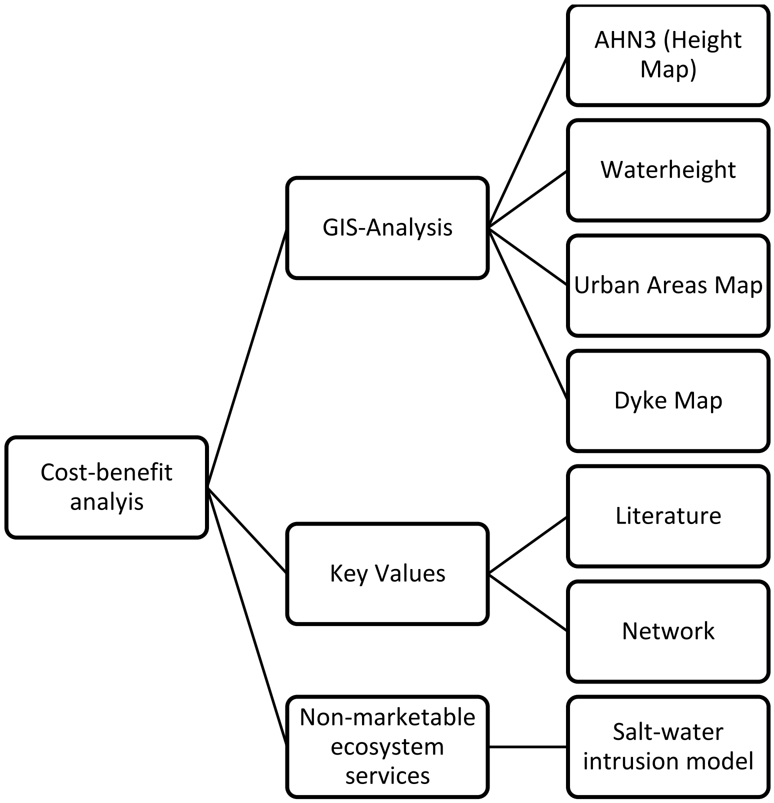


Figure 13 - Model representation of the study

In Figure 13 an overview of the model used to produce a cost-benefit analysis is shown. The GIS-Analysis, Key Values and Pilot Project form the input on which the cost-benefit analysis will be based. The GIS-analysis uses multiple sources as input, AHN3 is used to extract all height related values. Water height is needed to decide the land-use of areas and maps with the dykes and urban areas are used as a spatial aspect in the model. The key values in the model have been gathered from literature research and by using personal contacts.

The used data were collected from multiple sources: Rijkswaterstaat (RWS) gave information about the water-level at multiple locations, while the Waterboard Scheldestromen provided information about the locations of all dykes in Zeeland and the key values about recent projects the waterboard executed. Other key values were found in literature and an anonymous source provided key values about the costs of building and heightening dykes. The AHN3 (Actueel Hoogtebestand Nederland, n.d.) was consulted for information about the ground height and dyke height. The information gathered are the most accurate and latest available. Recent changes may not feature in this information.

Pre-conditions:

- In urban/industrial areas dyke heightening will be carried out due to space limitations.
- The only land use benefits that will be considered for the plan of concept are the following: agriculture loss, aquaculture, energy, recreation, freshwater storage, carbon sequestration.
- Only three designs of coastal protection will be considered: dyke heightening, dyke widening, nature-based coastal engineering.
- In the dune areas of Zeeland, the coast is already sufficiently protected and will not be considered.
- Heights will be determined by using the readily available data for GIS systems, in this case the ahn3.
- Mapping will be done using ArcGIS 10.6 software.
- Non-marketable ecosystem services were assessed only in a qualitative way using a salt-water intrusion model.

3.1. Polders Suitability in Zeeland & Cost-Benefit Analysis

In order to have a clear view of the polders suitable for the implementation of the Double Dyke system and for a comparison of the costs and benefits between the different coastal defense techniques, a GIS study has been carried out.

3.1.1. Scenarios

Sea-level rise

Multiple climate scenarios in which different levels of sea level rise occur are used to accurately represent the future of coastal defense systems in Zeeland and the related costs and benefits.

- First scenario: this is used as the control situation. In this scenario, a sea level rise of 0 m is assumed to represent the effects on the costs and benefits of implementing coastal defenses at present. Unless human behaviour changes, this scenario will most likely not be present in the future.
- Second scenario: A sea level rise of 0.5 m is assumed to represent a scenario in which the goals set in the Paris Agreement are met. Achieving these goals will most likely slow the speed of climate change and result in a minimal amount of sea level rise. According to the IPCC, the most likely SLR will be between 26 cm and 60 cm if global greenhouse gas emissions peak between 2010-2020 and significantly decrease after (IPCC, 2018).
- Third scenario: 'business as usual'. To simulate this scenario a sea-level rise of 1 m is assumed. This means global emissions continue as they are at this moment and goals in the Paris Agreement are not accomplished.
- Fourth scenario: extreme situation. To define the costs and benefits in this scenario a sea-level rise of 1,5 m is used. This is an estimation of the sea-level rise if the problems caused by climate change are ignored and are made worse.

In addition to the of sea-level rise scenarios, different designs of coastal defence have been used.

- Design 1 (S1): traditional method of coastal defence. This scenario uses dyke heightening as a coastal defence method along the entire coastline.
- Design 2 (S2): traditional method of coastal defence. In this scenario, the widening of the dykes is used where possible and the use of dyke heightening in the areas where the latter is not possible. It is a little more up to date method of coastal defence.
- Design 3 (S3): nature-based coastal defence approaches (Figure 14).
    - S3a: implementation of a double dyke system 200 m land inwards from the current primary dyke. This implies the "building" of a secondary dyke inland.

- S3b: implementation of a double dyke system 1000 m land inwards from the current primary dyke. A secondary dyke is 'built'. This leads to a significantly larger tidal area.
- S3c: implementation of a double dyke system using the historical context of the landscape. In this scenario there is no need to build a new dyke, using dykes inland that have already been constructed in the past. The costs of this approach may be minimized.

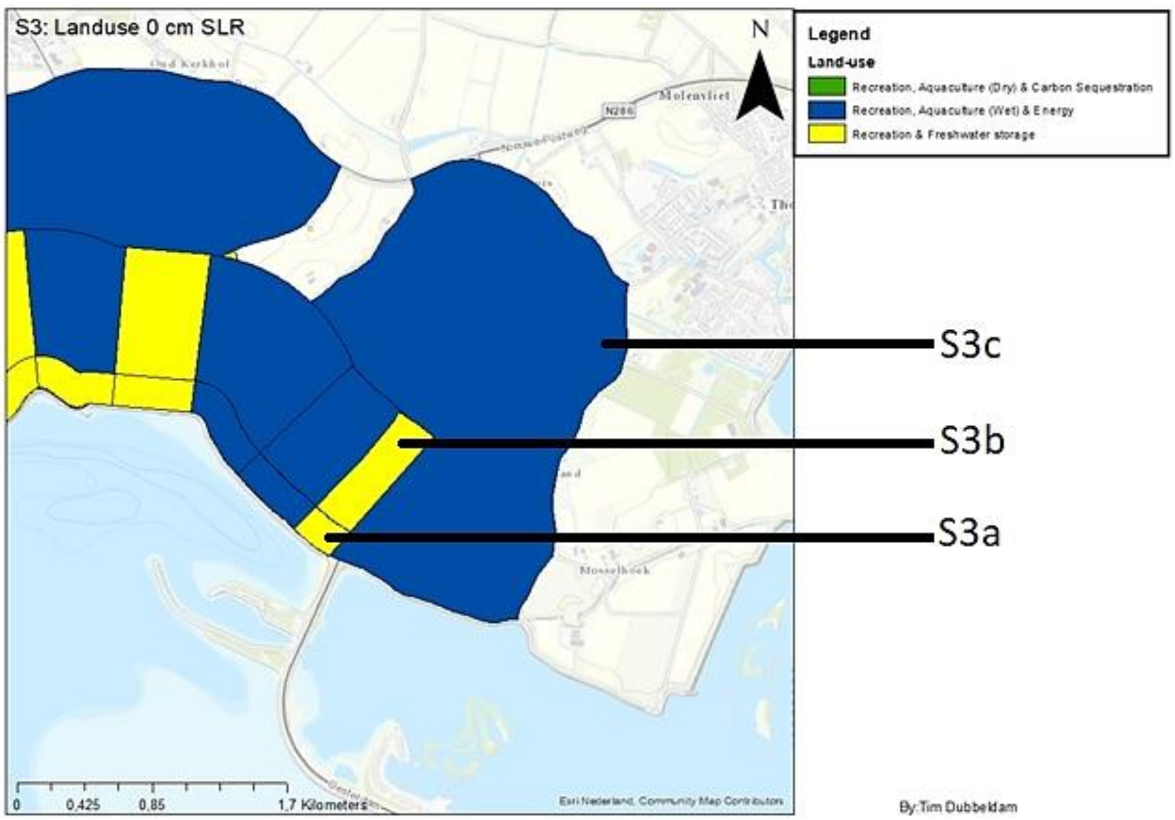


Figure 14 - Graphical representation of design S3 in the GIS analysis (made by Tim Dubbeldyke).

3.1.2. GIS development

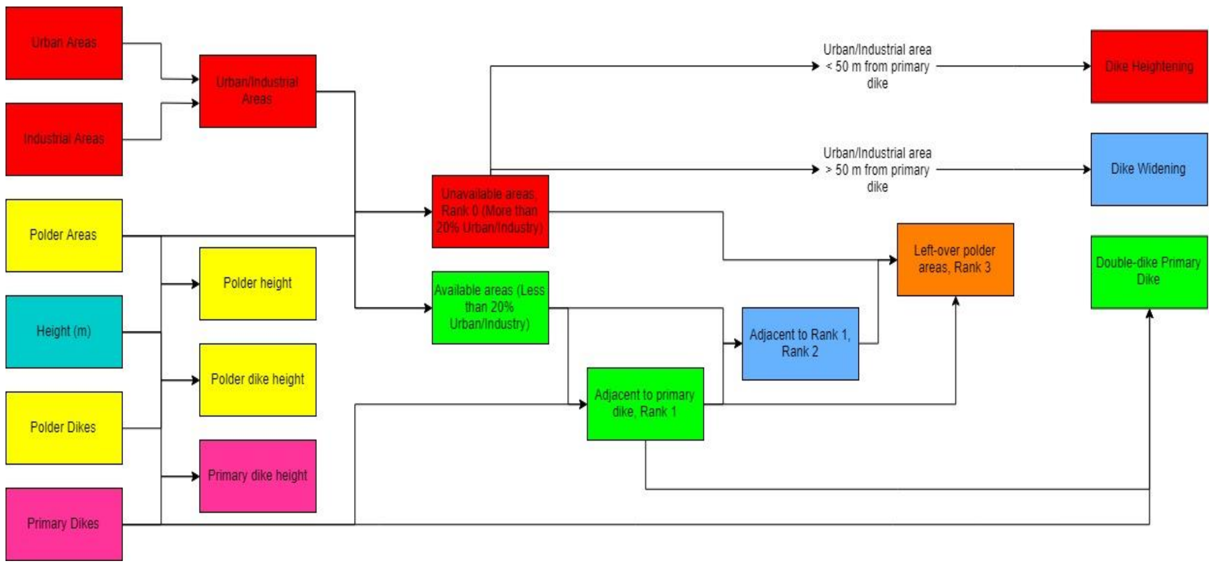


Figure 15 - Sub models used in the GIS analysis.

To accurately determine where dyke maintenance is needed, the primary and secondary dyke were segmented. Therefore, in the S1 and S2 desings, the dykes are first transformed into a long line and then divided into segments of 10m. Dividing it into 10m segments gives an accurate representation of the change in dyke height. Larger segments would mean less accuracy. Smaller segments (e.g. 5m) would make model processing very slow, as there are about 300km of primary dykes in Zeeland (Figure 16).

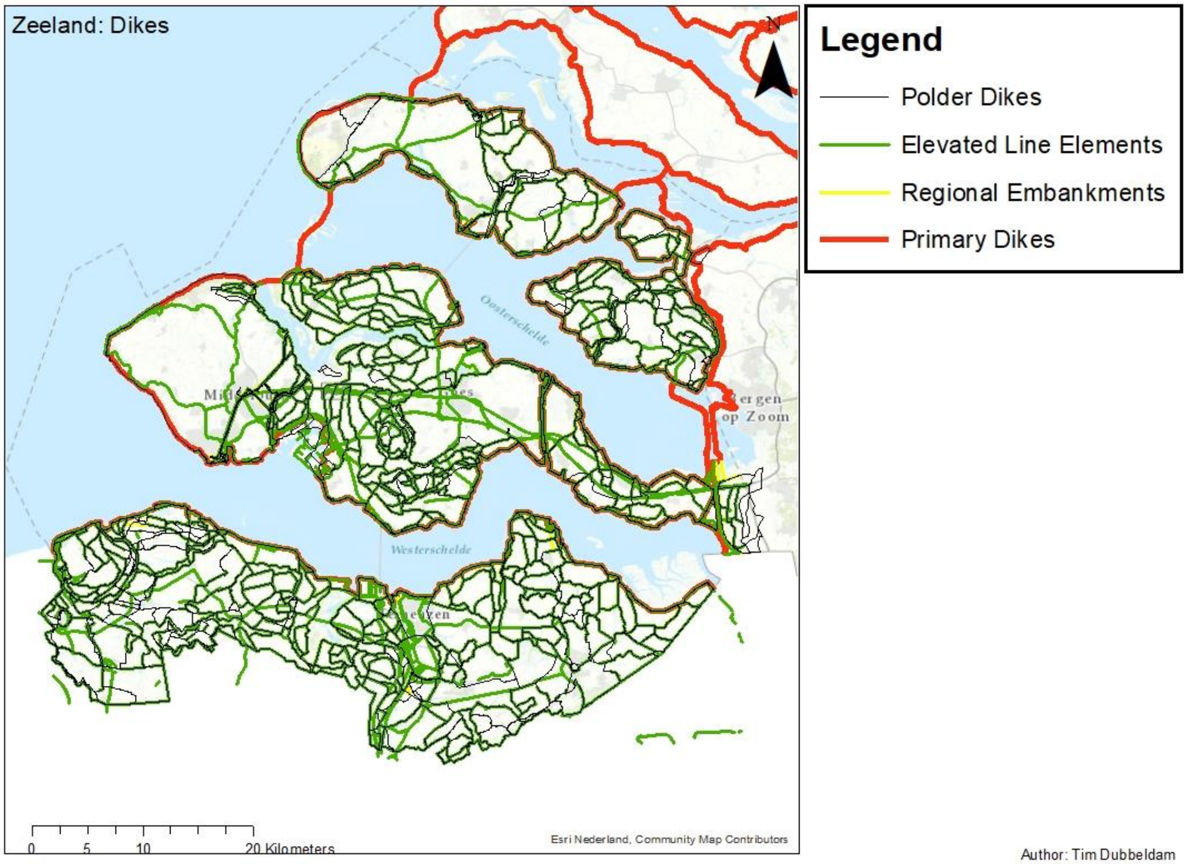


Figure 16 - Dyke classification in Zeeland (made by Tim Dubbeldyke)

For S3a and S3b the primary dyke was instead divided into larger segments. For these scenarios, a segment length of 500m was used, which is the largest possible size as the segments would not have been equally divided in the case of larger size.

"Dyke Height"

The lines of dykes are not always located at the maximum height of the dyke. This means that an area around the dyke line must be considered to decide what the maximum height of the dyke is. The typical angle of slope of a dyke is 1:3 (Technical Advisory Committee for Flood Defences., 1999) (Figure 17).

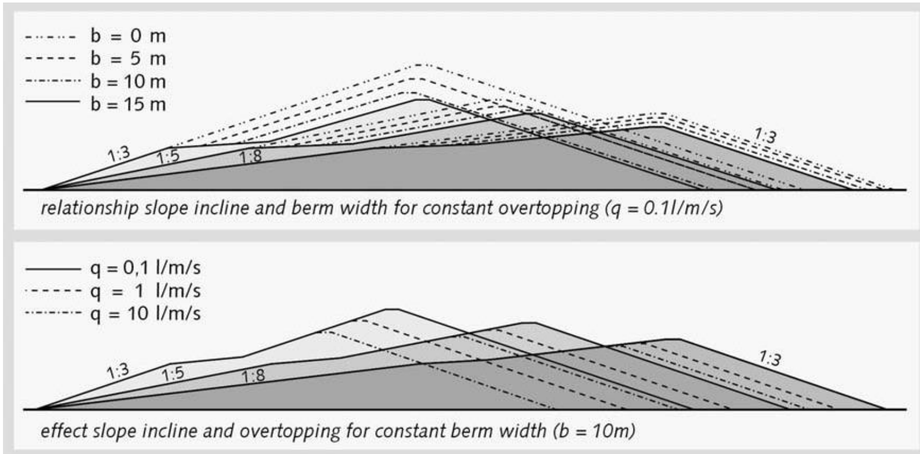


Figure 17 - Reduction crown height due to gentler outside slope and outside berm (Technical Advisory Committee for Flood Defences., 1999)

This means that for a dyke that is 10 m high the width of the dyke is at least 60 m. After creating profile graphs in 10 different primary dyke areas the maximum height found was never more than 25 m from the location where line was in the maps. To enhance the precision of the analysis a buffer of 30 m to both sides of the primary dyke was considered. For all secondary dykes a smaller buffer area 20 m was used because these dykes are considerably lower in height meaning they are also less wide.

Primary dyke buffer: 30 m

Secondary dyke buffer: 20 m

Coastal defence method:

- Urban/Industry within 50 m of primary dyke -> Dyke heightening in polder
- Urban/Industry within 50 m – 200 m of primary dyke -> Dyke widening in polder
- Urban/Industry >200 m of primary dyke -> Double dyke system in polder

According to this classification, some polders with urban/industrial areas <200m from the primary dyke may still be suitable for the DDS. To increase the number of suitable polders, the total area of the urban/industrial area is compared with the area of the polder. If the total urban/industrial area is greater than 20% of the total polder area, the whole polder is considered unsuitable. If it is less than 20% of the total polder area, the polder is suitable for a double dyke system and dykes will need to be implemented around the urban/industrial area.

If this margin were raised to 30%, more areas would be suitable but the costs of building new dykes to protect urban areas would result in an overall loss, creating an overall negative impact.

“Polder Height”

In order to decide on the most suitable land use of each polder it is necessary to know the digital elevation model of the various polders. Using the AHN3 data, the height is added for each area of the polder. For each polder, the average height over the entire polder will be used.

“Manual Editing”

Some suitable polders contain urban/industrial areas. It is not possible to use a tool or model to create a corridor to ensure access to the urban/industrial areas. Other infrastructure like highways or train tracks were also not to be interfered with. Therefore, manual editing needed to be done. Some polders were also too big in size, as a reference value all polders were checked to have the secondary dyke within 2000 m of the dyke because the tidal area would otherwise be too large. If polders were indeed a larger a fault margin of 500 m was used, for example if the secondary dyke was at 2050m from the primary dyke new dykes were not implemented. If a polder was bigger or did have critical infrastructure within its new dykes were drawn using the current landscape elements. This means that new dykes often were by roads, ditches & tree lines.

“Emergence”

The emergence percentage is a key factor in deciding which land-use is suitable for double-dyke systems. To decide the emergence percentage, water height data from Rijkswaterstaat over 2018 were used. This dataset provides the water depth every 10 minutes over a whole year. By calculating the percentage over a year of each frequency at each water depth the submergence/emergence percentage can be calculated.

Land-use for all the suitable areas was based on the height of the area. The height was linked with the emergence percentage of the same height. The emergence percentage was then joined to a table containing land-use emergence percentages (Rijkswaterstaat, sd). The emergence percentage per land-use was calculated during the pilot project as can be seen in Figure 18.

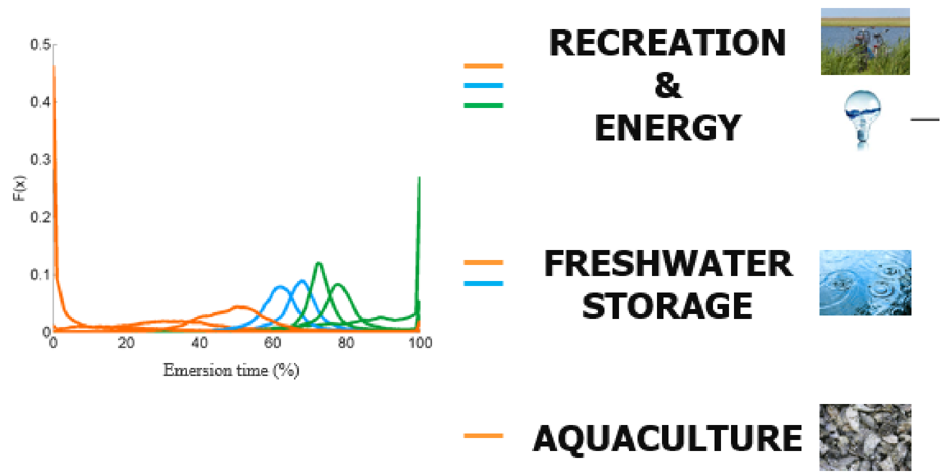


Figure 18 - The optimal emersion time per group of land-uses (Galvan, Zeeland 2070: Wealth from safety)

3.1.3. CBA

The cost-benefit analysis was done through the use of valuable ecosystem services, such as aquaculture and the production of energy, and the costs for the management and the changes of the dykes. The designs used are the same used in the suitability analysis (3.1.1).

Research into costs in similar projects proved difficult as most project leaders did not want to share information about the costs because of the project sensitivity to the public. This meant seeking other ways of finding information about the costs and benefits. A person that wishes to remain anonymous provided the following information about the costs. To calculate the benefits made from some ESs, values from a first pilot project (Galvan, Zeeland 2070: Wealth from safety) were taken.

This analysis was done by other trainees during the Zeeland 2121 project.

3.1.3.1. Formula's Cost-Benefit Analysis:

Abbreviations:

A = Annuity Factor

CH = Current Height

DH = Design Height

DL = Dyke Length

I = Increase factor

SLR = Sea-level rise

T = Time horizon

Costs

Costs are separated differently according to the scenario:

Western Scheldt: Urban/Industrial (<50m distance to primary dyke)

Western Scheldt: Urban/Industrial (>50m <200m distance to primary dyke)

Western Scheldt: Rural (>200m distance to primary dyke)

Eastern Scheldt: Urban/Industrial (<50m distance to primary dyke)

Eastern Scheldt: Urban/Industrial (>50m <200m distance to primary dyke)

Eastern Scheldt: Rural (>200m distance to primary dyke)

Because the Eastern Scheldt has a storm-surge barrier values for Eastern and Western Scheldt are split. For the designs in which there is no storm-surge barrier +2 is calculated to the Eastern Scheldt dykes.

Splitting the costs:

Dyke heightening costs are separated only between Urban/Industrial and Rural because there are different costs for heightening the dyke in rural vs. urban/industrial situations.

Dyke widening costs are separated only between Urban/Industrial (<50m distance to primary dyke) and Urban/Industrial (>50m <200m distance to primary dyke) because in cases where urban/industrial area is <50m from primary dyke, dyke heightening needs to be implemented.

Double Dyke systems have all costs separated.

Design 1 (S1): Dyke Heightening

Initial investment costs:

To calculate the Δ design height with storm-surge barrier:

$$\Delta\, DH\ (m)\ =\ SLR\ \times\ I$$

For Δ design height without storm-surge barrier:

$$\Delta\, DH\ (m) =\ SLR\ \times\ I + 2$$

To calculate the Unit cost (10^6 € km^{-1} length):

$$Unit\ cost\ (10^6\ €\ km^{-1}\ length)\ =\ Unit\ cost\ (10^6\ €\ m^{-1}\ height\ km^{-1}\ length)\ \times \Delta DH$$

To calculate Total Cost (10^6 €):

$$Total\ Cost = Unit\ Cost\ (10^6\ €\ km^{-1}\ length)\ \times DL$$

In which:

SLR	= Variable
Increase Factor	= 1.55 m
Dyke Length	= Variable
Unit cost rural	= 8 x 10^6 €
Unit cost Urban/Industrial	= 19 x 10^6 €

Total costs investments:

$$Total\ cost\ with\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ with\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

$$Total\ cost\ without\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ without\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

<u>Accumulated maintenance costs:</u>

To calculate Total Cost (10^6 €):

$$Total\ Cost = DL\ \times Unit\ Cost\ (10^6\ €\ km^{-1}\ yr^{-1})\ \times T\ \times A$$

In which:

T	= 100
A	= 31
Unit cost 10^6 € km^{-1} yr^{-1}	= 0.1
ΔDL	= Variable

Total costs maintenance:

$$Total\ cost\ with\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ with\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

$$Total\ cost\ without\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ without\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

Design 2 (S2): Dyke Widening

If urban/industrial is within 50 m of primary dyke, dyke heightening is implemented. The methods used to calculate dyke heightening are shown on the previous page. Below, methods explicitly used to calculate the costs for S2.

<u>Initial investment costs:</u>

To calculate the Δ design height with storm-surge barrier:

$$\Delta\ DH\ (m)\ =\ SLR$$

For Δ design height without storm-surge barrier:

$$\Delta\, DH\ (m) = \ SLR + 2$$

To calculate the Unit cost (10^6 € km^{-1} length):

$$Unit\ cost\ (10^6\ €\ km^{-1}\ length)\ =\ Unit\ cost\ (10^6\ €\ m^{-1}\ height\ km^{-1}\ length)\ \times \Delta DH$$

To calculate Total Cost (10^6 €):

$$Total\ Cost = \Delta\ \mathrm{DH}\ \times Unit\ Cost\ (10^6\ €\ m^{-1}\ height\ km^{-1}\ length)\ \times DL$$

In which:

SLR	= Variable
Increase Factor	= 1.55 m
Dyke Length	= Variable
Unit cost rural	= 5 x 10^6 €

Total costs investments (Add costs of areas where S1 needed to be implemented, S1 + S2):

$$Total\ cost\ with\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ with\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

$$Total\ cost\ without\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ without\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

Accumulated maintenance costs:

To calculate Total Cost (10^6 €):

$$Total\ Cost = DL\ \times Unit\ Cost\ (10^6\ €\ km^{-1}\ yr^{-1})\ \times T\ \times A$$

In which:

T	= 100
A	= 31

Unit cost 10^6 € km^{-1} yr^{-1}	= 0.0003
DL	= Variable

Total costs maintenance (Add costs of areas where S1 needed to be implemented, S1 + S2):

$$Total\ cost\ with\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ with\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

$$Total\ cost\ without\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ without\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

Design 3 A, B & C (S3A/S3B/S3C): Buffer 200m/Buffer 1000m/Using Context of Landscape)

If urban/industrial is within 50 m of primary dyke, dyke heightening is implemented, if urban/industrial area is between 50 m and 200 m of primary dyke, dyke widening is implemented. For these methods, formulas are shown in the designs above. Below, methods explicitly used to calculate the costs for S3A and S3B are shown. The only factors that change the costs between S3A, S3B, S3C is the total length of the dykes and the starting height of new dykes.

Initial investment costs:

To calculate the Δ design height with storm-surge barrier:

$$\Delta\, DH\ (m) = DH - CH$$

For design height without storm-surge barrier:

$$\Delta\, DH\ (m) = DH - CH$$

The unit cost (10^6 € km^{-1} length) for double dyke systems is a key value that corresponds to the Δ design height

To calculate Total Cost (10^6 €):

$$Total\ Cost = Unit\ Cost\ (10^6\ €\ km^{-1}\ length)\ \times DL$$

In which:

Dyke Length	= Variable
Unit cost double dyke	= Variable (corresponds to key values)
Design height	= Variable (on the following page)

Total costs investments (Add costs of areas where S1 or S2 needed to be implemented, S1+S2+S3a/b/c):

$$Total\ cost\ with\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ with\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

$$Total\ cost\ without\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ without\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

<u>Accumulated maintenance costs:</u>

To calculate Total Cost (10^6 €):

$$Total\ Cost = DL\ \times Unit\ Cost\ (10^6\ €\ km^{-1}\ yr^{-1})\ \times T\ \times A$$

In which:

T	= 100
A	= 31
Unit cost 10^6 € km^{-1} yr^{-1}	= 0.0035
DL	= Variable

Total costs maintenance (Add costs of areas where S1 or S2 needed to be implemented, S1+S2+S3a/b/c):

$$Total\ cost\ with\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ with\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

$$Total\ cost\ without\ storm\ surge\ barrier = Westernscheldt\ total\ cost\ urban, industrial, rural + Easternscheldt\ without\ storm\ surge\ barrier\ total\ cost\ urban, industrial, rural$$

Design 3: Design height

The design height is calculated using the following values and formulas, it is calculated for each scenario of sea-level rise and storm-surge barrier/non storm-surge barrier. The design height is needed to calculate the investment costs of scenario 3.

Abbreviations:

DH = Dyke Height

DWL = Design water level

ID = Increase design height

IF = Increase factor of design height

LS = Land subsidence

S = Seiches

SLR = Sea-level rise

WH = Wave Height

WR = Wave run-up

WW = Wind wave

Key values:

	Non storm-surge barrier (m)	Storm-surge barrier (m)
Dyke Height (DH)	10	8
Design water level (DWL)	5,4	5,4
Land subsidence (LS)	0,1	0,1
Seiches (S)	0,15	0,15

Sea-level rise	0.0 m / 0.5 m / 1.0 m / 2.0 m	0.0 m / 0.5 m / 1.0 m / 2.0 m
Increase factor of design height	1.55	1.0
Wind wave (200 m)	0.13	0.13
Wind wave (1000 m)	0.28	0.28

Table 1 - Key values used to calculate the design height of dykes in design 3.

To calculate the wave run-up:

$$Wave\ run\ up\ secondary\ dike = DH - DWL - LS - S$$

To calculate wave run up second dyke (200 m):

$$Wave\ run\ up\ second\ dike\ (200m) = Wave\ height\ (200m) \times 8 \times 0.202$$

To calculate wave run up second dyke (1000 m):

$$Wave\ run\ up\ second\ dike\ (1000m) = Wave\ height\ (1000m) \times 8 \times 0.202$$

To calculate wave height:

$$WH = \frac{WR}{8 * 0.2020}$$

To calculate wave height secondary dyke (200 m):

$$WH\ secondary\ dike = \frac{WH}{2 + WW\ (200\ m)}$$

To calculate wave height secondary dyke (1000m):

$$WH\ secondary\ dike = \frac{WH}{2 + WW\ (1000\ m)}$$

To calculate increase design height:

$$Increase\ design\ height = SLR\ \times IF$$

Total height for with and without storm-surge barrier:

Design 3A (200 m buffer):

$$Height\ second\ grass\ dike\ (200\ m) = DWL + WR\ (200m) + LS + S + ID$$

Design 3B (1000 m buffer):

$$Height\ second\ grass\ dike\ (1000\ m) = DWL + WR\ (1000m) + LS + S + ID$$

Design 3C (Using context of landscape):

$$Height\ second\ grass\ dike = \frac{Total\ Height\ 200m + Total\ Height\ 1000m}{2}$$

Design 3: Wealth

The following method is used to calculate accumulated benefits from aquaculture (wet/dry). For carbon sequestration the same calculation is used but the units are in tons instead of kg's.

A book by B. G. Miller in 2017 defines the sequestratoin rate of CO_2 in different environments. In Table 2 the result of his research has been defined. Interestingly the sequestration rate of carbon dioxide in wetlands has a higher minimum value than all other biomes. However this sequestration rate is less effective if there are regular disturbances in the soil such as the disturbances of aquaculture.

Biome	**Sequestration Rate (Metric Tons/Acre/Year)**	**Sequestration Rate (Metric Tons/Hectares/Year)**
Cropland	0.2 – 0.6	0.08 – 0.24
Forest	0.05 – 3.9	0.02 – 1.56
Grassland	0.12 – 1.0	0.05 – 0.4
Swamp/floodplain/wetland	2.23 – 3.71	0.89 – 1.49

Table 2: Sequestration rates of Carbon dioxide for various biomes. (Miller, 2017) Note: 1 acre = 0.40 hectares

A recent research done into carbon sequestration as an ecosystem service in the Mediterranean area that the carbon credit market is on the rise. In 2013 the price of one-ton CO_2 was €4,36 on the European Trade Scheme. However, at this time the European Commission's estimate was that the social cost of carbon was around €19/ton$_{CO2}$. In the Netherlands specifically the price per credit was €25/ ton$_{CO2}$ (Canu, et al., 2015). These values are needed to calculate the profit from carbon sequestration in Double Dyke systems.

Freshwater storage is also calculated in the same way (with m^3) but the yield changes according to the level of SLR using values from (Galvan, Zeeland 2070: Wealth from safety)

$$Biophysical\ assessment = yield\ (kg\ ha^{-1}\ yr^{-1}) \times area\ (ha)$$

$$Benefits\ (10^6\ €) = \frac{yield\ (kg\ ha^{-1}\ yr^{-1}) \times Market\ price\ (€\ kg^{-1}) \times\ area\ (ha)}{1000000}$$

$$Total\ accumulated\ benefits = Benefits\ \times Annuity\ Factor$$

Energy production is calculated in the same way but just like freshwater storage, the yield depends on the area. To calculate the yield the following formula is used.

$$Yield\ Energy\ (GWh\ y^{-1}) = \frac{Area\ (km^2)}{0{,}08} - 50.164$$

Recreation benefits are calculated differently because there is no market price involved. This is calculated by executing the following formula:

$$Recreation\ benefits\ (10^6\ €) = \frac{yield\ (€ha^{-1}\ \ yr^{-1})\ \times\ area\ (ha)}{1000000} \times annuity\ factor$$

Accumulated agricultural loss

This is only calculated for design 3. The agricultural loss represents the loss of land because the area that was agriculture will be used as tidal range. To calculate the accumulated agricultural loss the following values are used.

Crop	**Percentage** (%)
Potatoes	21
Sugar beets	11
Wheat	20
Maize	20
Vegetables	12
Others	16

Table 3 - Percentage distribution used to calculate area of crop

.

		Values	Units
Agriculture loss	Potatoes	2023	€ ha^{-1} yr^{-1}
	Sugar beets	792	€ ha^{-1} yr^{-1}
	Wheat	440	€ ha^{-1} yr^{-1}
	Maize	824	€ ha^{-1} yr^{-1}
	Vegetables	2455	€ ha^{-1} yr^{-1}
	Others	1306.8	€ ha^{-1} yr^{-1}

Table 4 - Economic values of agricultural production (Galvan, Zeeland 2070: Wealth from safety)

Other factors that are used are the following:

Annuity factor: 31

First the area needs to be calculated this is done using the following formula:

$$Area\ (ha) = \frac{Total\ area\ (ha) \times percentage\ of\ crop}{100}$$

Once the area is calculated the costs of (no) soil salinization needs to be calculated. For no soil salinization the following method is used:

$$No\ soil\ salinizatoin\ costs\ (10^6\ €\ yr^{-1}) = \frac{Area\ (ha) \times Productivity}{1000000}$$

In case soil salinization does occur, the following formula is used:

$$Soil\ salinization\ costs\ (10^6\ €\ yr^{-1}) = \frac{No\ soil\ salinization\ cost\ (10^6\ €\ yr^{-1})}{2}$$

For soil salinization costs, a loss equal to half the costs of no soil salinization was assumed. According to various studies, the loss of productivity is linked to the type and tolerance of the crop and to the salinity of the soil (Figure 19), making the values variable (Duan, 2016).

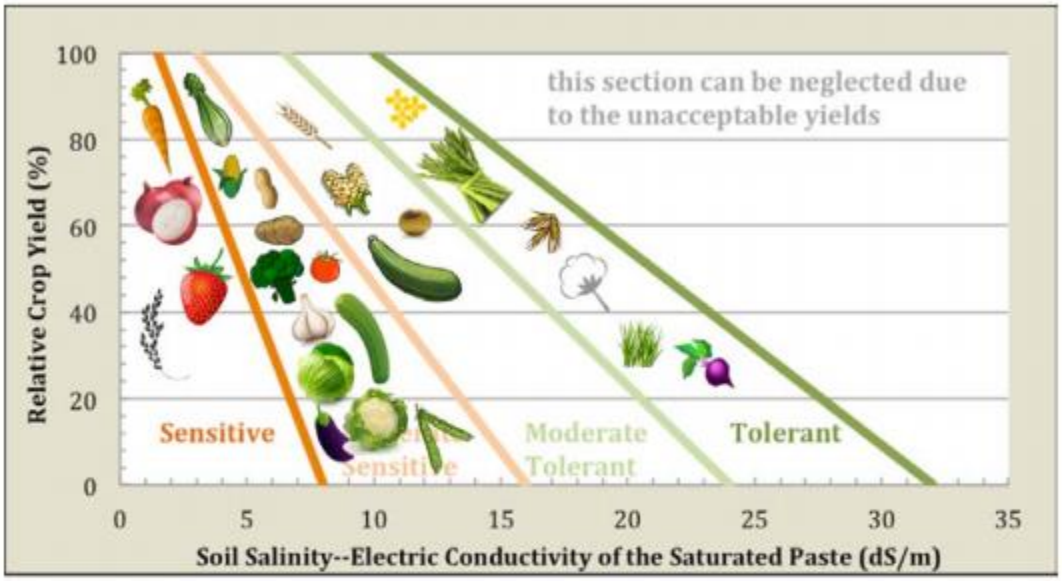


Figure 19 - Classification of most common agricultural productions according (Duan, 2016)

To calculate the accumulated costs the cost calculated in the formulas above need to be multiplied by the annuity factor (31).

Loss due to relocation in design 3

To calculate the loss due to coastal defence adaptation the following calculations are used. Only agricultural ground, grasslands and houses are taken into account.

$$Relocation\ cost\ (10^{6}\ €\ ) = number\ of\ houses\ or\ area\ (ha) \times unit\ price\ (€)$$

The cost-benefit analysis total

Using all of the formulas on the previous pages the total cost or benefit of a scenario in different sea-level rise scenarios can be calculated. This is method used to determine the overall balance of each scenario. For scenario 1 (dyke heightening) and scenario 2 (dyke widening) agricultural loss, relocation costs and benefits were not applicable.

$$
\begin{aligned}
&Total\ balance\ of\ coastal\ defence\ method\ per\ SLR\ scenario \\
&\qquad = Investments\ costs - Accumulated\ maintenance\ costs \\
&\qquad - Accumulated\ agricultural\ loss - Relocation\ costs \\
&\qquad + Accumulated\ wealth
\end{aligned}
$$

3.2. Salt-water intrusion model

In order to understand the effects of the creation of a salt marsh, in front of the primary dyke and inside the polder (DDS), a simple analytical model has been created. The aim is to understand the impact of the saltwater intrusion on the aquifer and on the agriculture.

3.2.1. Area of study

Within the Zeeland province, it was chosen to use the Kl. Eendragt polder as a reference polder. Located on the Westersheldte, this polder has an area of 269136 m^2 and a length of 800m. The average elevation of the soil is 1.40 m SLM with a subsidence rate of 1.86 mm/y. The subsidence rate was calculated for a research inside the project “Zeeland 2121”.

The choice is due to the low salinization of the underlying aquifer in order to understand both the positive and the negative effects on the freshwater availability created by the presence of tidal vegetation.

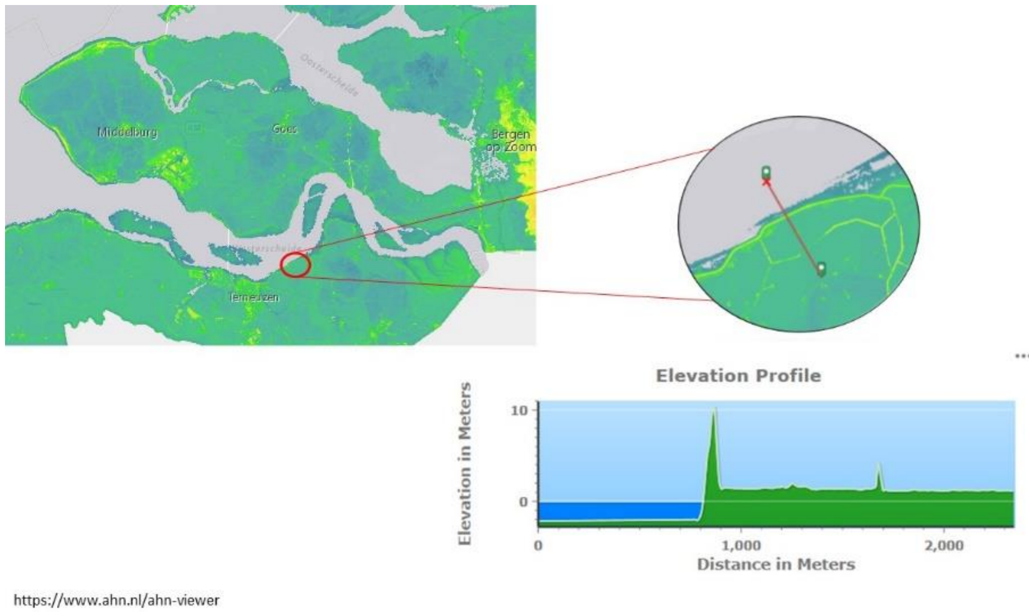


Figure 20 - Kl. Eendragt polder and the DEM used to create the salt water intrusion model ((Actueel Hoogtebestand Nederland, n.d.)

3.2.2. Scenarios

The model has been created to simulate saline intrusion in three different scenarios with the aim of compare three cases:

S1 – BAU: business as usual. This scenario is used to understand the behavior of the salinity intrusion if nothing is made.

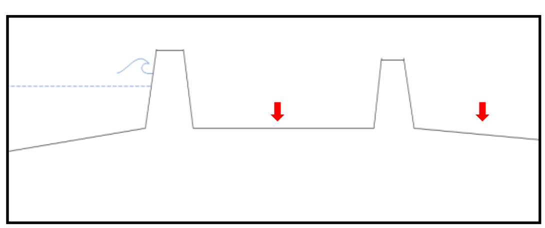


Figure 21 - S1 scenario: business as usual. The red arrows show the subsidence.

S2 – Salt marsh along the coastline: the aim of this scenario is to understand the effect on the aquifer due to the presence of a salt marsh in front of the primary dyke.

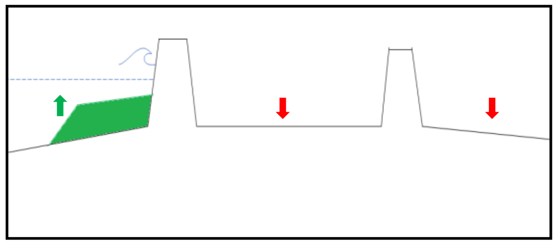


Figure 22 – S2 scenario: salt marsh in front of the dyke. The red arrows show the subsidence, the green arrow is the creation of a salt marsh.

S3 – Double Dyke System: this scenario is used to understand the impact of the DDS during its development and once the primary dyke is closed.

a: Open Double dyke system without marsh (0y)

b. Double dyke system with marsh (30y)

c: Closed Double dyke system (30y)

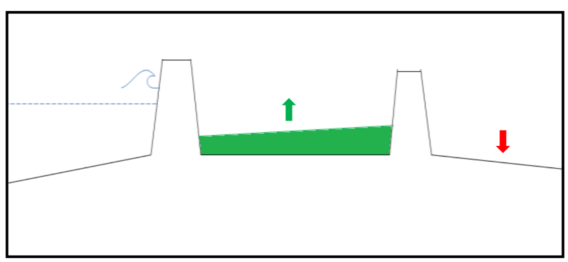


Figure 23 – S3 scenario: DDS. The red arrows show the subsidence, the green arrow is the creation of a salt marsh.

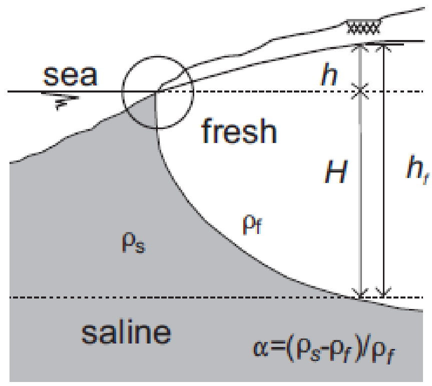
3.2.3. Model Development

In the following we will analyze the main equations, the data and the assumptions used to develop the model.

3.2.3.1. *Equations*

To develop the model, a homogeneous aquifer was assumed, where the hydrodynamic dispersion and the flows in every direction are negligible. The model is based on the Badon Hijben (1889)- Herzberg (1901) principle to describe the location of the interface between salt and fresh water:

$$h = \frac{\rho_s - \rho_f}{\rho_f} H \qquad h = \alpha H$$



The Boekelman & Grakist (1973) principle was also used to simulate freshwater lens evolution in a steady state situation (the time dependent factor F(t) is assumed equal to 1, t ► ∞):

$$H(x,t) = F(t)\sqrt{\frac{f(0.25B^2 - x^2)}{k(1+\alpha)\alpha}}$$

The use of this equation has been used to simulate the salt intrusion in presence of channels when the elevation of the soil is less than the MSL in scenarios 2 and 3.

For the S3-b scenario, the following formula was also used to estimate the creation times of the new aquifer after that the breach in the primary dyke is closed:

$$\tau(days) = \frac{\pi n_e B}{8}\sqrt{\frac{(1+\alpha)}{kf\alpha}}$$

3.2.3.2. Parameters

- Time Horizon: 30y were assumed for the complete development of the marsh in S3, while in S1 and S2 the steady state is assessed.
- Subsidence rate: as the subsidence of the polder, related to the elevation of it after the embankment, is 1,86 mm/y (Bonatz, 2020) and the prediction for the sea level rise rates in the Netherlands are equal to 2-3 mm/y (Ritzema et al., 2018), we assumed the rate equal to the sum of the two rates.
- Sea level: the mean high-water level used is MHW=240,7 cm NAP, misurated in Overloop van Hansweert in the period between December 2019 and January 2020.
- Salinity: for the density of salt water and fresh water, the STD values from the literature were used (ρ_s=1035 kg/m^3, ρ_f=1000 kg/m^3). To simulate the presence of a salt marsh developed in front of the primary dyke, a density of 1012 kg/m^3 was used (M. Van de Broek et al., 2016).
- Water table: the water table was calculated according to the digital elevation model: a 0.5m rooting zone was assumed and kept constant by a pumping system. If the elevation is less than the MWL, the water table created by a freshwater lens between two irrigation channels was used. In addition, the waterproofing of the dykes was assumed on both sides of it.
- Salt Marsh: the representation of the salt marsh is divided in two main parts: High marsh and low marsh. The first is assumed as high as the MHW, while the latter is represented as half of the high marsh.
- Precipitation: the precipitation rate used is 900 mm/y as average for Zeeland (Zeeland Climate, 2019).

For the development of the model assumptions were made:

- The channel depth was assumed equal to 0.6m
- The aquifer is homogeneous with a conductivity of 10 m/day.
- The dyke is impermeable on both side of it.
- There are no flows from inland. The natural recharge due to precipitations.

4. Results

In this section the main results about the Double Dyke system were showed and explained starting from the polder suitability and the cost-benefit results to the effects on the aquifer due to the development of the DDS.

4.1. Polders suitability

As shown in Figure 24, not all the polders are suitable for the implementation of a double dyke system, due to the presence of urbanized and industrial areas. The most suitable polders, ranked as 1, are adjacent to primary dykes and present in the innermost areas of the estuary, towards the border with Belgium, as the land use is mostly agricultural land. The ranked 2 polders could be suitable for the use of the DDS but, given their distance from the primary dyke, they are excluded due to the higher cost of building a connecting channel, if it is not already present. The third rank are polders with a low ratio between urban/industrial and agricultural area but given the location or size of the polder they are not totally suitable for the creation of a DDS.

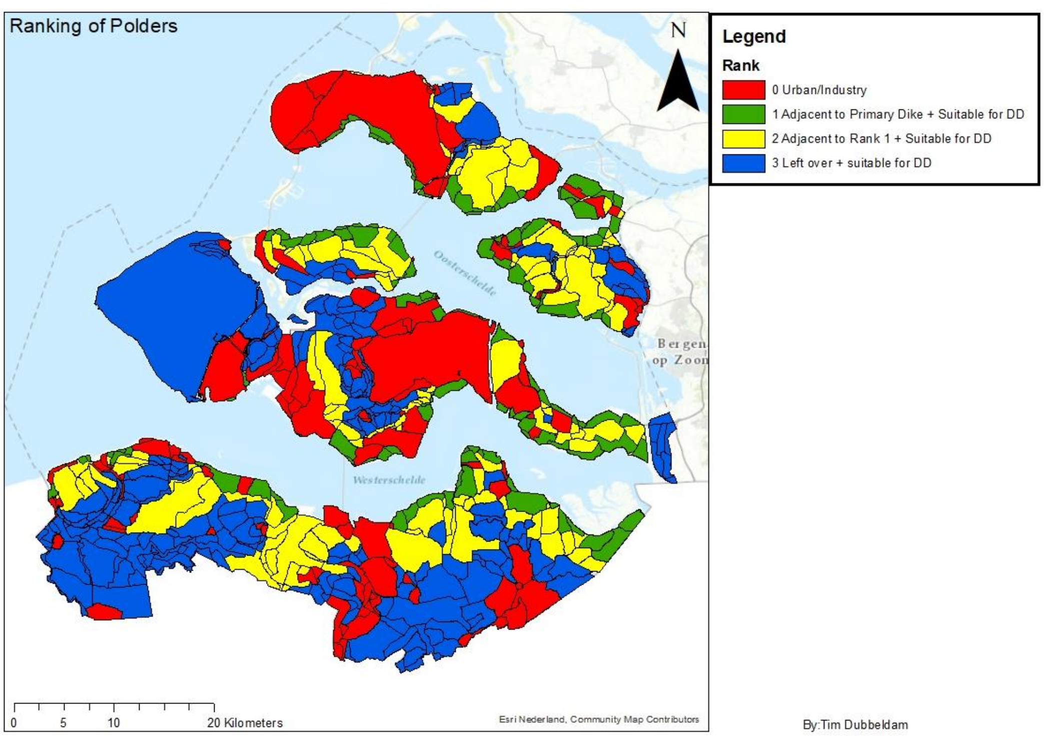


Figure 24 - Ranking of Polders based on the DDS suitability

The land-use of the rank 1 polders was analyzed through the use of the sea-level rise scenarios.

- Land-use 0 cm SLR

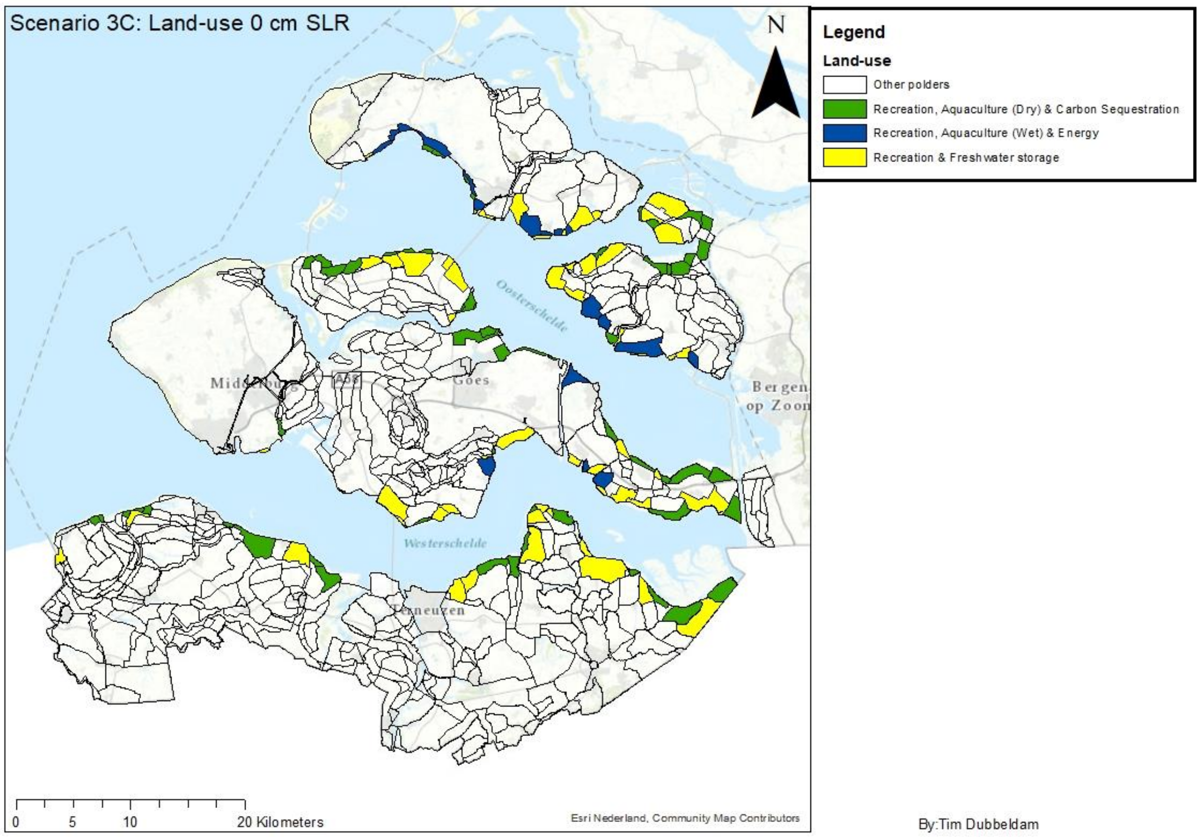


Figure 25 - Design S3C: polders land-use at 0cm SLR scenario

- Land-use 50 cm

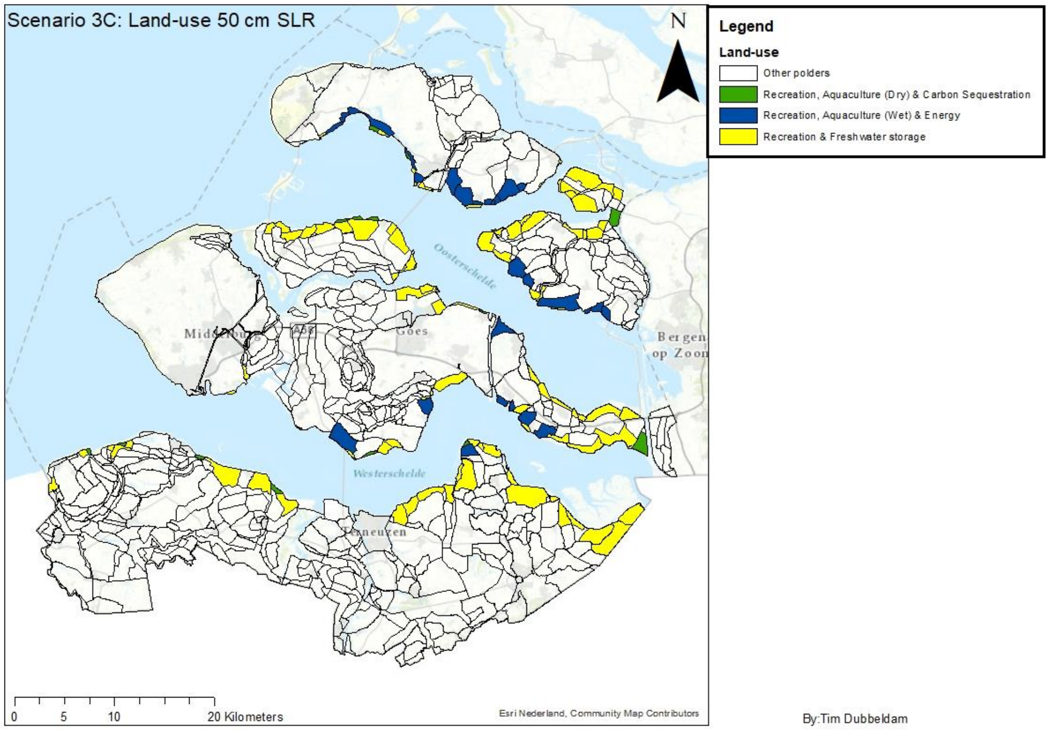


Figure 26 - Design S3C: polders land-use at 50cm SLR scenario

- Land-use 100 cm SLR

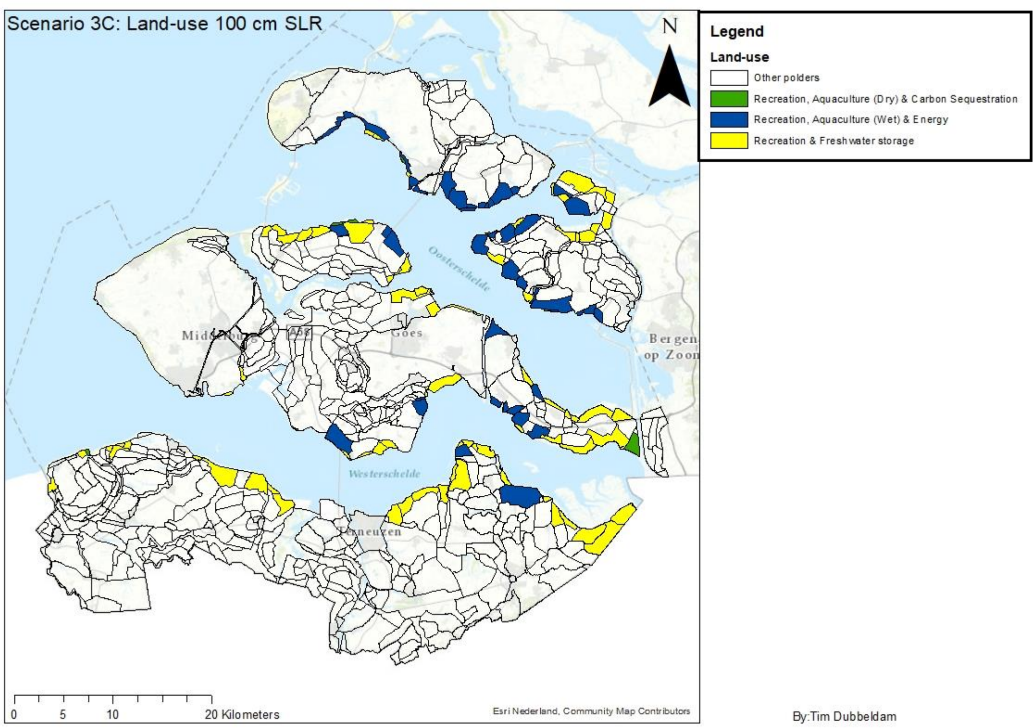


Figure 27 - Design S3C: polders land-use at 1m SLR scenario

- Land-use 150 cm SLR

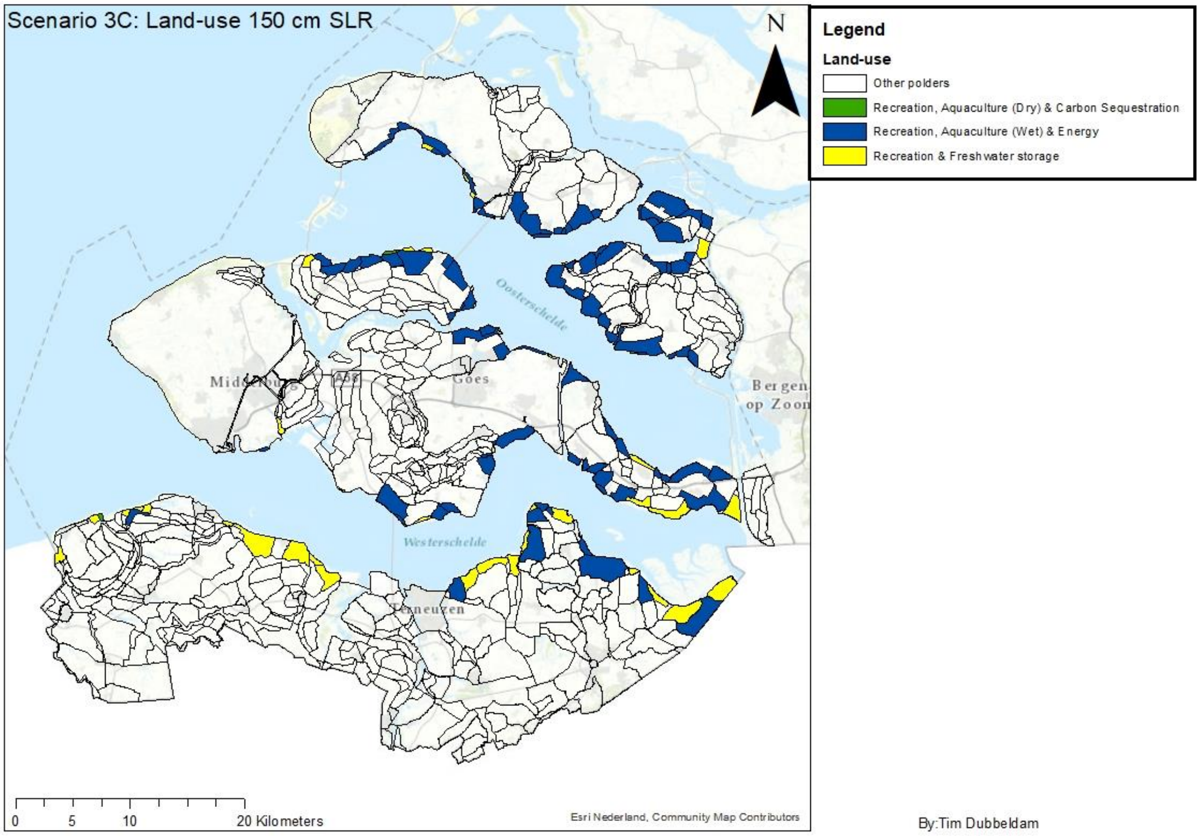


Figure 28 - Design S3C: polders land-use at 1.5m SLR scenario

4.2. CBA

In this section the results of the cost-benefit analysis, made thanks to the results of the GIS analysis, are displayed. For each SLR scenario, a comparison between traditional methods of coastal defence and ecosystem based coastal engineering has been shown.

In Table 5 a complete overview of all different methods of coastal defence has been made. All the cells which have been marked filled with a red colour are negative overall balances. The total balance is calculated over a 100-year period.

The cheapest design is S3c if a sea level rise of 1.5m will occur, reaching the breakeven point as shown in Figure 29. The most expensive scenario, on the other hand, is a sea level rise (SLR) of 1.5m without a storm surge barrier in the S1 design, using a traditional coastal defense method by raising the current primary dyke. Even with a storm surge barrier this would still be the most expensive method of coastal defense. The most realistic sea level rise according to the IPCC is approximately of 50 cm by the year 2100 (IPCC, 2018). In this scenario, S3c would be the cheapest method of defense. The most consistent of all SLR scenarios is the S3a double dyke system, although it always results in a negative balance. In any case, the least expensive and most constant design is S3c.

		SLR	SLR	SLR	SLR	
		0	0,5	1	1,5	
		Balance				Units
Adaptation measure	Oosterschelde storm-surge barrier					
Dyke heightening (S1)	Yes	**-99948**	**-102279**	**-104610**	**-106941**	x 10^6 €
	No	**-103254**	**-106035**	**-108817**	**-111598**	x 10^6 €
Unbreachable dyke (S2)	Yes	**-19088**	**-20462**	**-21836**	**-23210**	x 10^6 €
	No	**-23388**	**-25773**	**-28158**	**-30544**	x 10^6 €
Double dyke system						
200 m (S3a)	Yes	**-20601**	**-24682**	**-26479**	**-25458**	x 10^6 €
	No	**-21085**	**-25446**	**-27325**	**-26585**	x 10^6 €
1000 m (S3b)	Yes	**-16947**	**-28055**	**-18509**	**-6123**	x 10^6 €
	No	**-18766**	**-30606**	**-21142**	**-9487**	x 10^6 €
Secondary Dykes (S3c)	Yes	**-5176**	**-13715**	**-9711**	**1009**	x 10^6 €
	No	**-5933**	**-14555**	**-10803**	**-166**	x 10^6 €

Table 5 - An overview of all the different methods of coastal defense in different climate scenarios

In Table 5 graphically displays the cost-benefit analysis of all the different coastal defense methods considered. In all cases S3c seems to be the most convenient implementation method even if in case SLR does not occur. It is also interesting to note that S3b and S3c are both less effective at 0.5m SLR but are more effective at higher SLR levels. In the pattern observed in Figure 29 is looked at in more detail.

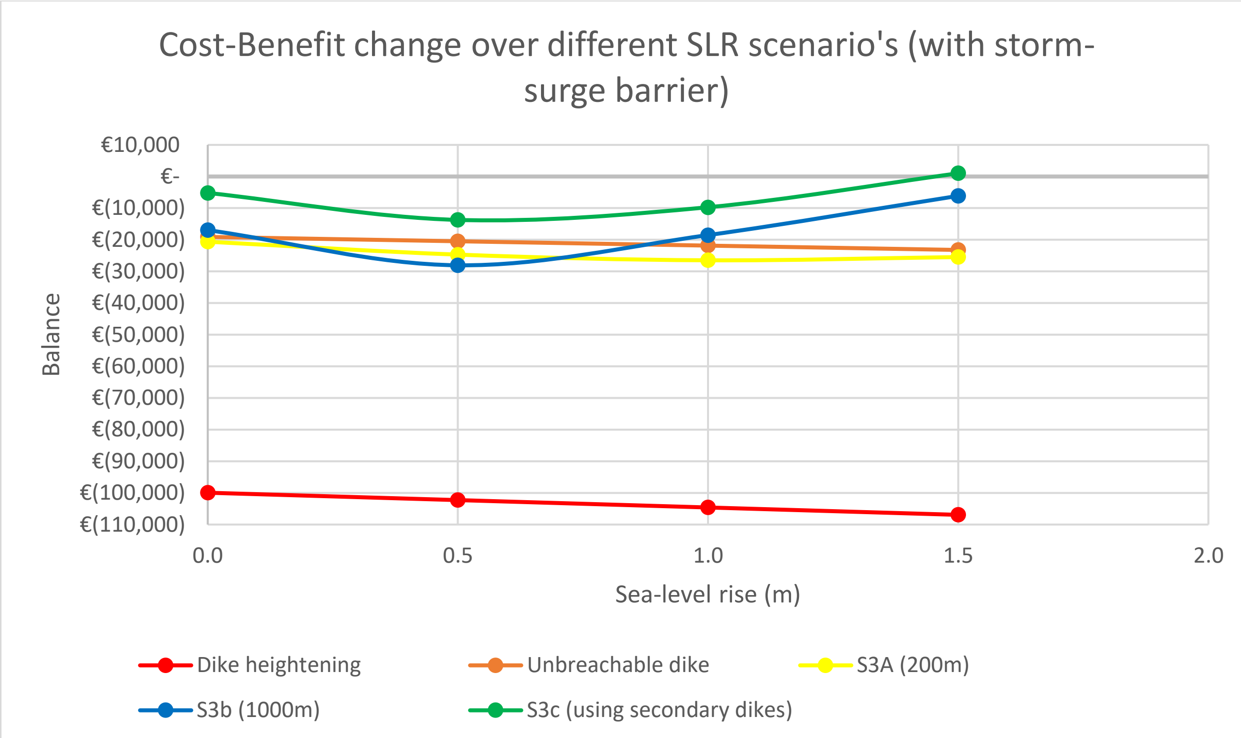


Figure 29 - A graph showing the change in costs over different levels of sea-levels of rise using different coastal defense methods.

In Table 6 a comparison between design S3b and S3c is shown. This table shows that in S3b the costs are all a lot more than those of S3c. This table shows that in S3b the costs and benefits are all much greater than those of S3c but due to the investment costs which are almost double those in S3c, the overall balance is usually about double the latter at parity by SLR. Table 6 also shows the change in benefits (richness) on different sea level rises which has a low value at 50cm SLR, while it increases if an SLR of 1.0m or 1.5m occurs.

				COSTS				BENEFIT	BALANCE	UNITS
SLR (m)	Adaptation measure		Oosterschelde storm-surge barrier	Investment costs	Maintenance costs	Agriculture loss	Relocation Loss	Wealth		
0	S3b	1000 m	Yes	19897	35475	525	3463	42414	-16947	x 106 €
			No	21192	35475	1050	3463	42414	-18766	x 106 €
0	S3c		Yes	8149	23109	419	1484	27986	-5176	x 106 €
			No	8488	23109	838	1484	27986	-5933	x 106 €
0.5	S3b	1000 m	Yes	22559	35475	525	3463	33966	-28055	x 106 €
			No	24584	35475	1050	3463	33966	-30606	x 106 €
0.5	S3c		Yes	9464	23109	419	1484	20760	-13715	x 106 €
			No	9885	23109	838	1484	20760	-14555	x 106 €
1	S3b	1000 m	Yes	24642	35475	525	3463	45596	-18509	x 106 €
			No	26750	35475	1050	3463	45596	-21142	x 106 €
1	S3c		Yes	10748	23109	419	1484	26049	-9711	x 106 €
			No	11421	23109	838	1484	26049	-10803	x 106 €
1.5	S3b	1000 m	Yes	27303	35475	525	3463	60643	-6123	x 106 €
			No	30142	35475	1050	3463	60643	-9487	x 106 €
1.5	S3c		Yes	11948	23109	419	1484	37970	1009	x 106 €
			No	12705	23109	838	1484	37970	-166	x 106 €

Table 6 - Comparison between scenario S3b and S3c

In Table 7 an example of the benefits yielded from S3b at 0.0 m, 0.5 m and 1.0 m is shown. At 0.0 m, implementation of S3b without SLR the most profitable use is aquaculture (dry) because it has a high market price (7€ per kg). Considering at 0,0 SLR is the most suitable for freshwater storage and dry aquaculture these would also be expected to have the highest accumulated benefits. In design S3b – 0.5 m there is a shift towards more aquaculture (wet) but most areas are now most suitable for freshwater storage which is reflected in the 32.5% of the total accumulated benefits. If a SLR of 1.0 m occurs the dominant land-use shifts towards more aquaculture (wet) and energy production. These two land-uses have a better market price vs. yield ratio which is reflected in the total accumulated wealth. This also explains why at 0.5 m the total accumulated benefits for S3a, S3b and S3c is lower than in the other levels of SLR.

S3b - 0.0 m	x 10^6 €	%	S3b - 0.5 m	x 10^6 €	%	S3b - 1.0 m	x 10^6 €	%
Aquaculture (Wet)	6113	14,4	Aquaculture (Wet)	10635	31,3	Aquaculture (Wet)	19076	41,8
Aquaculture (Dry)	22350	52,7	Aquaculture (Dry)	2085	6,1	Aquaculture (Dry)	1030	2,3
Freshwater storage	7576	17,9	Freshwater storage	11049	32,5	Freshwater storage	8128	17,8
Energy	4723	11,1	Energy	8561	25,2	Energy	15726	34,5
Carbon Sequestration	17	0,0	Carbon Sequestration	2	0,0	Carbon Sequestration	1	0,0
Recreation	1635	3,6	Recreation	1635	3,6	Recreation	1635	3,6
Total	42414	100,0	Total	33966	100,0	Total	45596	100,0

Table 7 - The benefits of S3b before and after 0.5 m SLR

4.3. Saltwater intrusion model

In this section the results from the salinity intrusion model are explained, to understand and evaluate the effects of the presence of a salt marsh nearby a dyke to the bellowed aquifer.

- Scenario S1:

  The scenario S1 shows how the salinity intrusion simulated by the model behaves similar to the one represented by Figure 31 from Freshem site (FRESHEM Zeeland, n.d.), created by previous studies on the saltwater intrusion in Zeeland (Joost R Delsman et al, 2018). In both the images, it can be seen how the saline interface (in Figure 31 represented as a gradient) has a very similar behavior reaching depths of about 25m and going up after the second dyke, about 1km from the shore. It demonstrates that the assumptions made can represents the reality.

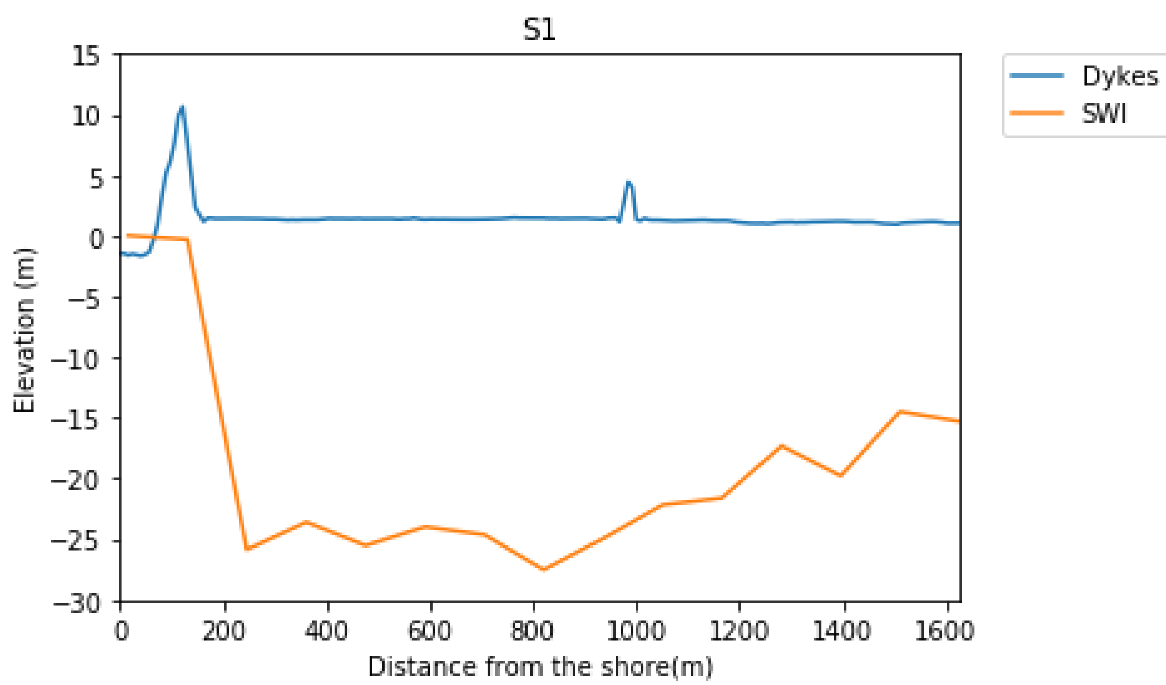


Figure 30 - SWI Scenario 1 results: business as usual

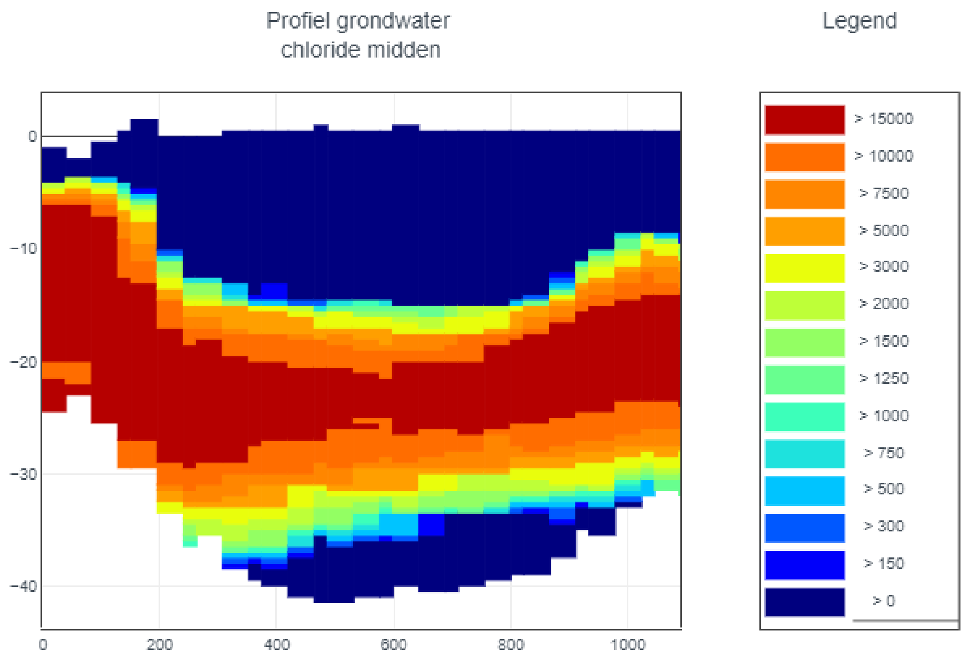


Figure 31 - Saltwater intrusion representation of Kl. Eendragt polder (FRESHEM Zeeland, n.d.)

- Scenario S2

  The scenario S2 shows how the presence of a salt marsh along the coastline can change the behavior of the saline interface compared to S1. Given the difference in salinity between seawater (30 ppt) and marsh salinity (>20 ppt) (M. Van de Broek et al., 2016), a "buffer" area of brackish water is created between salt and fresh water inland. This interface goes down to the basement and can be in the long time a form of protection against the salt intrusion into the aquifer, besides the benefits due to the presence of the ecosystem. This buffer area would increase the freshwater aquifer quality and increase the size of it.

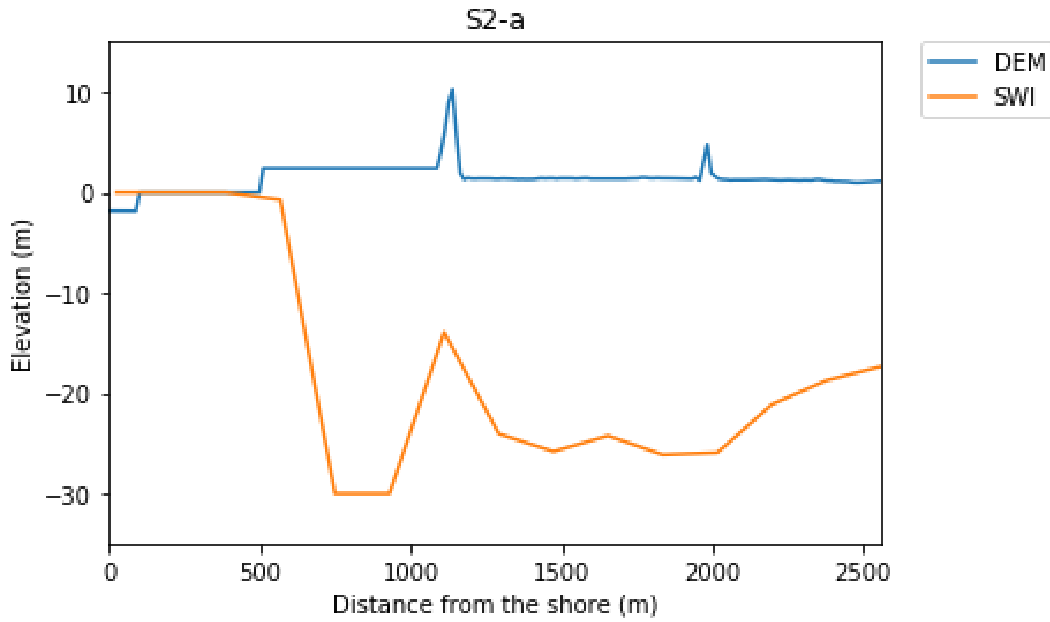


Figure 32 - SWI Scenario 2 results: presence of a salt marsh in front of the primary dyke

- Scenario S3

  As represented in the scenario S3a and S3b, the implementation of the Double Dyke system would lead to an increase in salt intrusion due to the salt water to entering the polder. Even if the aquifer under the polder would be almost completely salinized in the short term (Figure 33), and then create a buffer similar to the S2 scenario, the aquifer present in the inland polder could present improvements in quality and size, thus improving its condition.

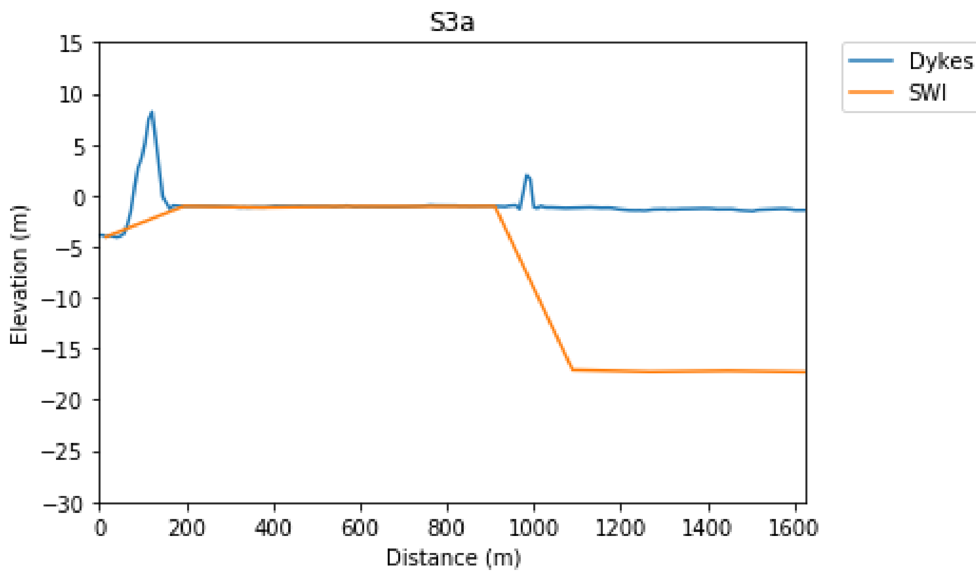


Figure 33 - Saltwater intrusion Scenario 3a results: open DDS with no marsh

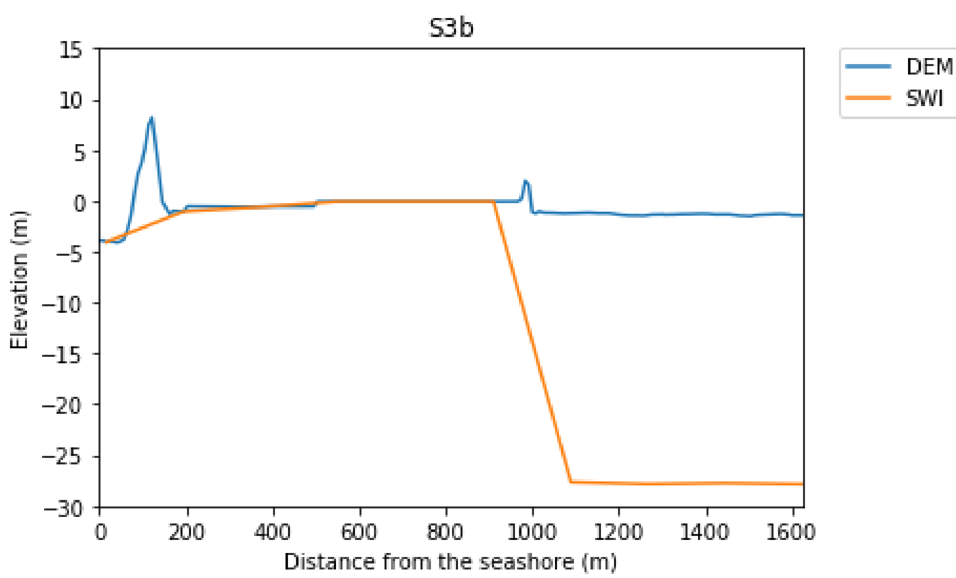


Figure 34 – Saltwater intrusion Scenario 3b results: open DDS

According to the simulation made in the scenario S3c, once the marsh has been developed, estimated between 30 and 50 years, and the breach in the primary dyke has been closed, the aquifer would take about 11 years to completely restore itself, increasing its capacity and raising the ground.

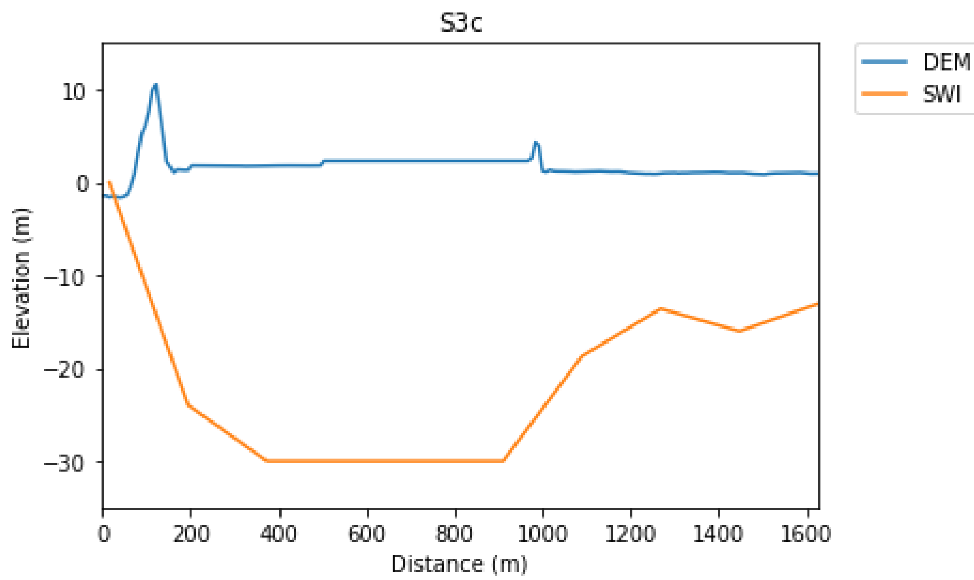


Figure 35 – Saltwater intrusion Scenario 3c results: closed DDS

With the improvement and increase of the aquifer capacity as an effect of the presence of a salt marsh in the S2, S3b and S3c scenarios, it is presumed that the benefits calculated during the CBA (Paragraph 4.2) will undergo positive changes. The decrease in saline intrusion can in fact not only improve freshwater storage, but also increase and improve the quality of agricultural production, as demonstrated by some studies conducted by the FAO (Rohades et al., 1992).

5. Discussion

Throughout this chapter, the results will be discussed. The strengths and weaknesses of the Double Dyke system found during the various analyzes will be shown. The problems of the analyzes conducted and the effects that this system can create will then be analyzed, modifying the results obtained from the cost-benefit analysis.

According to the CBA analysis, it appears that the implementation of a DDS is less expensive than normal coastal defense solutions, thanks to the lower investment cost and benefits that an ecosystem can create. The use of this solution can in fact bring economic benefits from energy production and aquaculture, but also environmental benefits such as the sequestration of carbon dioxide, the protection of biodiversity and the increase of freshwater storage, positively affecting the intrusion. saline. The latter, in fact, can create advantages both in agriculture and in the civil and social sphere. During this project, however, various assumptions were made, including land use and the effects of creating an ecosystem.

One of the main points of discussion is the duration of land use. This depends on various factors, such as sedimentation rate, sediment stability and previous land use, which can influence the level of it. Furthermore, the presence of vegetation can further vary these factors, and can be influenced by them. To have a better evaluation of the effects caused by the presence of a salt marsh, it is important to study the development and sedimentation factors of this ecosystem (Koch et al., 2009; Gracia et al., 2017; Temmerman et al., 2013).

Another important point of discussion regarding the DDS is the land use combined with safety. Energy and wet aquaculture have in common that they conflict with security. In areas where energy and wet aquaculture is practiced, the ground height must be low enough to allow more water into the DDS (Galvan, Zeeland 2070: Wealth from safety). However, the goal of this system is protection from storm surges and waves. This means that more elaborate spatial planning rules must be used.

The production of energy using the DDS is a land use that is still very uncertain and full of problems. The profits were assumed like the production of a tidal power turbine plant, but the costs of implementing such plant were not assessed. Furthermore, this structure could have ecological impacts that have not been considered, such as the change in the sedimentation rate due to turbines (Smith, Bugden, & Wu, 2012). Moreover, energy production is one of the benefits that allow the return on investment thanks to the high economic value of renewable energy. This could lead to misinterpretation of the results, making DDS the most economical solution thanks to energy production. More studies are indeed recommended. However, the use of alternative forms of energy, such as the implementation of an energy production system through a compressed air chamber, could have positive impacts if also used as an infrastructure in the breach to counteract the erosion in the breach. However, this system was not considered due to the few studies present.

An important discussion point for the implementation of the DDS is the type of primary dyke present. Not all dykes are suitable for holding water on both sides. A dyke that is hydraulically head on both sides, if not designed for that purpose, could fail.

The capacity of the polder must also be considered. With the increase in the elevation of the soil, there would be a decrease in storage, risking an overtopping of the secondary dyke. More engineering studies are required to overcome these problems.

Due to the large amount of ecosystem services present, and the difficulty in quantifying and therefore evaluating non-marketable services, it was not possible to include many services within the cost-benefit analysis (Boerema et al., 2016; Mitsch et al., 2015). Only those that can be easily monetized were considered, such as CO_2 sequestration, food production (aquaculture) and freshwater storage. The use and proper evaluation of all the ecosystem services involved could in fact increase the benefits produced by natural solutions.

In the case of the effects on the aquifer and the freshwater storage, many assumptions have been made. More studies are needed including new factors, such as the spatial position of the polder, inland water flows, the stratification of geological horizons and a greater study of the effect of dykes on saline intrusion. There is also a need for real data and estimates given from in situ sampling due to the lack of scientific literature on the subject.

Another concern is the social acceptability of implementing large-scale nature-based coastal engineering. Over time, similar projects have been the subject of much negative criticism. These projects were often very local and small-scale, so large-scale implementation would require extreme precision and precaution. The use of information on possible benefits on land use and freshwater storage could be a way to involve the agricultural sector. Various studies and policies have shown how stakeholders and decision-making bodies are trying to find the best solutions for the conservation and rehabilitation of water reserves in scenarios of uncertainty (Affeltranger, 1999; Poff et al., 2016). Furthermore, the use of bottom up methods and approaches can help stakeholders in including citizens in decisions (Vinke-de Kruijf et al., 2010). A study of the population's thinking about DDS is recommended to understand the best methods of communication.

Nature-based engineering not only has the advantage of being a less expensive alternative to conventional coastal engineering methods in areas with a low population density, it also increases the ecological value that is not taken into account in the cost-benefits analysis, due to the conservation of the biodiversity and the ecosystem services non-marketable not considered. The creation of new ecosystems, in fact, is a unique opportunity to expand or preserve tidal habitats for future generations according to SGDs 13, 14 and 15 of the UN "Agenda 2030" (Figure 36).

Figure 36 - Sustainable development goals from the UN Agenda 2030

6. Conclusion

This research aimed to provide information on the possibilities of implementing ecosystem-based coastal engineering in Zeeland and its environmental effects. By comparing the research with traditional coastal defense methods and an abstract version of coastal defense based on creating an ecosystem, the feasibility was tested. Four different sea level rise scenarios were used to account for the costs and benefits of sea level rise.

Due to the high investment and maintenance costs, almost 4 times higher than other methods, the raising of dykes is the most expensive method of defense in any context considered. In the case of urban and industrial areas, this method may be unavoidable, while natural solutions are recommended where applicable.

The enlargement of the dyke, on the other hand, turns out to be cheaper than the raising of it and turns out to be the cheapest method among the engineering method of coastal defense. It turns out to be very expensive in the case of the presence of the storm barrier, but less cost than the removal of the latter.

To test the feasibility of nature-based solutions, specifically double dyke systems, the implementation of a secondary dyke at 200m and 1000m from the coast over a period of 100 years was evaluated. The 200m buffer showed net loss in every SLR scenario. However, this loss was minimized by the generation of ecosystem services generated by the presence of an ecosystem, but their evaluation was not sufficient to significantly modify the costs or benefits. Due to a difficult evaluation of some ecosystem services, even the 1000m buffer showed high investment costs, minimized by the generation of benefits. This meant that when land-use freshwater storage was dominant, the benefits were not close enough to offset the higher investment costs. However, dry aquaculture, wet aquaculture and energy production all showed significant benefits per year, which allowed the accumulation of benefits to increase faster than the increase in costs. Hence, the lowest balance was recorded for a higher sea level rise.

In most cases the creation of a double dyke system using the context of the current and historical landscape of the area proved to be the most effective method of coastal defense. The benefits increase as sea level rises making it extremely adaptable to the future the world is heading towards reaching the breakeven point in the extreme SLR scenario. In addition, investment costs are minimized thanks to the use of pre-existing dykes.

Finally, a saline intrusion prediction model was created to evaluate the hydrological effects. It turned out that the presence of a salt marsh and an ecosystem as a form of coastal protection can bring long-term benefits for the preservation of water quality and agriculture. The elevation of the soil and the slightly difference in salinity concentration between seawater and the salt marsh water, can increase and protect the nearby aquifer, improving the quality of the freshwater and of the agricultural production.

These natural solutions can in fact lead to a series of benefits that cannot be evaluated economically, such as non-marketable ecosystem services, thus reducing the costs for their implementation.

7. Recommendations

A more in-depth assessment of land use over the 100-year period is recommended. As noted in the discussion, the development dynamics of the salt marsh may not be constant, making it suitable or unsuitable for certain types of land use over time.

A cost-benefit analysis with multiple factors is also recommended. The assessment of non-marketable ecosystem services could indeed increase the benefits created by nature-based solutions. This assessment could help the population and decision-making bodies in choosing the most suitable solution to fight climate change. An analysis of recreational and educational ecosystem services could also help in understanding how to better communicate the benefits of these solutions. The costs of building and removing roads and the costs of implementing energy production systems should be taken into account in a future calculation. The purchase price of the land needed to build a double dyke area needs to be further investigated. The purchase price of the properties alone does not consider how much the demolition of these houses will cost.

A more accurate study of the effects of ecosystems on the quality of aquifers is recommended, with the aim of better understanding the hydrological dynamics present in the case of a future implementation of the DDS in various areas. A more in-depth study of the dynamics presents between salt water and ecosystems outside the double dyke system is also recommended.

Using the research that has been done, it is recommended that double dyke systems be implemented in the near future. Even without sea level rise, it is already a more profitable way to use the land than it is currently used and effective in the fight against climate change.

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