An Eco-efficiency analysis of conventional and living dikes

Comparing the long term economic- and environmental impact of a conventional dike construction method, and a 'Living dike' on Schiermonnikoog, the Netherlands.

Master Thesis

University of Twente

Department of Water Engineering and Management

Author: N. Snoeijink BSc.

Date: August 2024

Supervised by:

dr. ir. B.W (Bas) Borsje — Head of committee UT

dr. ir. P.W.J.M. (Pim) Willemsen — Daily supervisor UT

prof. dr. ir. M. (Markus) Berger — Daily supervisor UT

Acknowledgements

Though it has not been written in the most typical process, I would like to express my sincere gratitude to everyone who contributed to the completion of this master thesis. Throughout my research journey, I learned valuable lessons about Nature-based solutions in flood protection, and life cycle assessments (LCA). Additionally, this process allowed me to discover more about myself.

I would like to thank the following people who have helped me undertake this research:

First and foremost, I extend my heartfelt appreciation to Jos van Zuylen and Sweco. Their generous provision of data and support significantly enhanced the quality of my research. Their expertise and willingness to assist were instrumental in overcoming challenges when shaping the research.

I would also like to acknowledge my dedicated supervisors. Their patience, guidance, and encouragement sustained me throughout this process. Their insightful feedback and constructive discussions helped strengthen and refine my work.

Lastly, to everyone who played a role, directly or indirectly, in this journey — thank you. Your impact is acknowledged beyond these pages.

Abstract

This thesis presents a comprehensive eco-efficiency analysis comparing conventional dikes and living dikes, with a specific focus on their economic and environmental impacts over a long-term period of 50 to 200 years.

The research employs Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies to quantify the environmental and economic impacts, respectively. These methodologies provide a detailed evaluation of the total costs and benefits associated with each dike type over a 50-year design period. The study aims to determine if the inclusion of ecosystem services (ES) such as, carbon sequestration, biodiversity enhancement and other benefits for society significantly changes the overall cost-benefit outcome of the dike construction methods.

By including a case study on the reinforcement of an existing dike at Schiermonnikoog, a Dutch island in the Wadden sea, the study evaluates the conventional dike construction method, characterized by a sand core and impermeable clay outer layer, against a nature-based alternative that integrates salt marshes in flood protection.

The findings reveal that conventional dikes, although effective in providing immediate flood protection and relatively low direct costs, come with significantly more environmental disruptions due to the reliance on large quantities of construction materials. Living dikes, on the other hand, offer substantial ecological benefits, including improved water quality, habitat creation, and increased resilience to sea level rise (SLR). The presence of salt marshes in living dikes reduces wave energy, thus decreasing the hydraulic load on the dike, which can extend the dike's functional lifespan. However, ensuring stable salt marsh requires costly maintenance.

An essential aspect of the analysis involved assessing the resilience of salt marshes to SLR at the case study location. Research indicates that while salt marshes can adapt to gradual SLR, rapid increases could exceed their growth capacity, leading to higher reinforcement costs or failure of the flood defence. The study also examines the impact of material use and sustainability on economic and environmental outcomes, highlighting the importance of using sustainable construction materials.

The results from the LCA and LCC assessments underscore that living dikes provide significant environmental benefits and decreased long-term costs when ES are included in the comparison. Conventional dikes, despite lower direct costs, exhibit higher long-term environmental costs, especially under high SLR scenarios. This research shows that integrating salt marshes into flood defence strategies not only enhances ecological sustainability but also provide economic advantages over time.

The conclusion drawn from this study is that living dikes are a viable and sustainable alternative to conventional dikes, offering a more sustainable approach to flood protection that aligns with broader ecological and economic goals in relatively high hydraulic boundary conditions. This however is a scenario that also results in the highest uncertainty of salt marsh survival. Using locally acquired materials results in higher direct costs but is the favoured approach for most hydraulic boundary conditions, as the implementation of ES result very low environmental costs compared to regular construction materials.

The findings highlight the need for more comprehensive and detailed valuation techniques for ES to better reflect the true value of Nature-based solutions. Additionally, pilot projects at various locations with suitable conditions are recommended to gather more data and refine implementation strategies for living dikes.

Overall, this thesis provides valuable insights for policymakers, engineers, and environmental planners seeking to implement Nature-based solutions for coastal protection in muddy coasts, emphasizing the importance of considering long-term impacts and integrating ES into flood defence planning.

Content

1. Introduction

Flood risk management and adaptation to sea level rise (SLR) are essential to the Netherlands' existence as nearly 60% of the country is prone to large scale coastal and river flooding (of which 26% below mean sea level) (Haasnoot et al., 2020). Therefore, the Dutch have a longstanding history of preventing flooding through traditional water management i.e., deploying conventional strategies and solutions (e.g., dikes) in which its natural environment has been altered to enable societal needs. Such dikes protect those living in areas below sea-level, but consequently alter the natural dynamics of the water system. Subsequently reducing the systems' resilience and therefore requiring regular reinforcements (Demmers et al., 2022). Additionally, the expected future climate change is theorised to result in more SLR, which in turn further intensifies the need for such reinforcements. These regular reinforcements are not only costly, but also demand a considerable amount of space, which can result in high societal costs with regard to nature, infrastructure and housing (Springer - Rouwette, 2019).

To combat these negative effects a recent trend in water management focuses on Nature-based solutions, a collection of approaches that harness the power of nature to boost natural ecosystems, biodiversity and human well-being to address major societal issues (Kwakernaak & Lenselink, 2015; Nature-Based Solutions Initiative, 2022). In the context of water management, Nature-based solutions are used to ensure a more resilient water system, reducing the need for additional regular reinforcement investments, whilst enabling additional societal, environmental, and economic benefits (Witteveen+Bos, 2022). Additional benefits are e.g. carbon and nitrogen sequestration, water purification, air quality improvement and increasing biodiversity (Millennium Ecosystem Assessment Program, 2005; Russi et al., 2013).

An example of such a Nature-based solution is a 'living dike'. A living dike aims to reduce hydraulic conditions at the dike-toe by including a salt marsh on the foreland in its design. This design relies on the wave dampening effect of a shallow and vegetated foreshore. Due to the dynamics of a salt marsh, sediment is trapped on the marsh. This natural phenomenon allows the marsh to rise vertically in the right conditions, which could make the dike resilient against SLR (Best et al., 2018).

Although the aforementioned benefits indicate that this could be a positive alternative to conventional dike construction, they are not applied in practice often. As Nature-based solutions are making use of nature in the respective area, regulations regarding construction are tighter vs. its conventional counterpart (Rijksoverheid, 2021). This is especially true for Natura 2000 area's, which is the case around the Waddenzee and many other areas near the coast. Consultants from Sweco experience that these regulations result in longer lasting and more difficult decision-making processes for dike reinforcement projects.

Besides these legal hardships, Nature-based solutions also come with risks (Best et al., 2018). Salt marshes, which can function as part of Nature-based solutions, grow or erode in length depending on inundation-depth and -frequency, and suspended sediment concentrations (Best et al., 2018; Kirwan et al., 2010; Temmerman et al., 2003). Additionally, vegetation is fluctuating due to seasonality and consequently has the risk of drowning. More importantly, rapid SLR or high waves can harm the salt marsh, negating the reduced wave attenuation and aforementioned other positive effects (Best et al., 2018; Schuerch et al., 2014; van Dobben et al., 2022).

When comparing conventional and Nature-based solutions in flood protection, additional benefits and risks of Nature-based solutions should be considered beyond the initial investment and subsequent reinforcement costs, as this would give insight in the feasibility of Nature-based solutions in flood protection (Millennium Ecosystem Assessment Program, 2005; Roode et al., 2019; Russi et al., 2013; Stroming, 2012). This research attempts to give insight in a larger range of benefits and risks that come with Nature-based solution, to allow better decision making for such projects in the future.

This research therefore integrates ecosystem services (ES), such as biodiversity and carbon sequestration, into the comparison of alternative dike construction methods over the entire lifetime of the dike, to see whether this inclusion changes the cost-benefit result of these alternatives.

On Schiermonnikoog (Island in the Dutch Wadden Sea area) Nature-based solutions are taken into consideration for planned future reinforcements of an already existing dike. This research applies an extended cost benefit analysis (as aforementioned) to this area as a case study, as there is limited research to the effects of these benefits in a real-life applied scenario.

2. Problem formulation

Nature-based solutions are identified as a potential solution for more a resilient flood protection system. The interest in such solutions comes from a combination of factors, increasing levels of SLR requiring dike reinforcements, limited space, and high costs. These factors are a result from the paradigm in Dutch flood protection design. Nature-based solutions are seen as an opportunity that could mitigate multiple of these aforementioned factors in synergy (West Coast Environmental Law, 2018; Witteveen+Bos, 2022). By performing a literature review and conversations with consultants from Sweco (Zuylen, personal communication, 2022), three major reasons were found for limited implementation of Nature-based solutions in flood protection thus far; Nature-based solutions have (1) the stigma of having higher initial investment costs, (2) carry a certain degree of uncertainty with them due to their dynamics (which is undesired in flood protection), and (3) require a long period of planning and decision making due to construction oftentimes taking place in nature areas with tight(er) regulations (Haasnoot et al., 2020; Rijksoverheid, 2021; Vuik et al., 2019).

Though these challenges tend to be discussed in deliberations on relevant water management options and alternatives, additional benefits of Nature-based vs. conventional solutions are often neglected. Such benefits are not only economic, but also environmental and cultural. These benefits could make Nature-based solutions a viable option for flood protection (Hanna et al., 2018; Millennium Ecosystem Assessment Program, 2005). Although some research has been performed on these benefits and how to compare them on a monetary level, no clear guidelines have been established (Van der Wilde & Newell, 2021; Zhang et al., 2010).

To get a better understanding of the feasibility of Nature-based solutions as flood protection, both disadvantages and advantages need to be compared. These (dis)advantages need to be quantified to allow for honest comparison. This chapter will examine literature, and research gaps, on the functioning of Nature-based solutions, its benefits and disadvantages, how and whether these (dis)advantages can best be quantified.

2.1. Literature review

Over the past decades dikes have been constructed and reinforced throughout the Netherlands (i.e. respective country of interest) following the same construction method. This standardization of construction is a result from major upscaling of dike construction after the big floods of 1953. Upscaling of dike construction led to relatively inexpensive sand extraction in large quantities. Such inexpensive sand is well suited as big water-retaining mass as long as it is covered with a sufficiently impermeable and erosion resistant layer (Dijkwerkers, 2018).

According to the Dutch legal assessment protocol for dike design (WBI2017), the predicted water level and wave conditions form the hydraulic boundary conditions that a dike should be able to withstand (Rijksoverheid, 2017). In order to withstand these hydraulic conditions, a dike design roughly consists of 2 layers; the water retaining core from sand and an outer layer to protect the sand core that can easily erode. The outer layer is often made of clay and makes the dike impermeable. Protection against erosion often consists of grass, concrete, or basalt if the hydraulic load is high.

When a dike is designed, the design period is customarily 50 years. This means that it is designed to be sufficiently safe for the next 50 years. To realize this lifespan, future hydraulic boundary conditions due to SLR and expected settlement of the dike itself are also taken in to account (Warmink, 2018). These and other relevant aspects for the required dike height are shown in Figure 1.

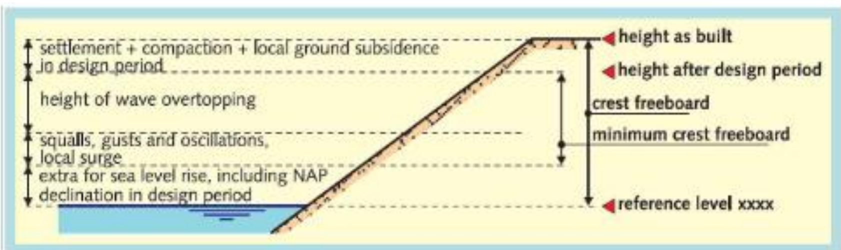

Figure 1: Dike height design aspects according to WBI 2017 (Warmink, 2018)

The following sub-chapters answer a series of questions that together give insight in the current standing of literature and topics of interest that need to be included to answer the research questions in this report. Specifically, it explains the potential Nature-based solutions for flood protections and their additional benefits vs. conventional solutions, whether such additional benefits can be quantified and lastly, the risks and limitations of these vs. conventional solutions.

2.1.1. What are potential Nature-based solutions for flood protection, how do they work, and what benefits do they have compared to conventional dikes?

Nature-based solutions leverage nature and the power of healthy ecosystems to protect people, infrastructure and biodiversity. A term that can be applied to many fields of more resilient solutions for problems in society that for example occur due to climate change. This can vary from e.g. heat mitigation in urban areas by increasing surface greenery and vegetation, to stormwater parks to decrease urban floodings due to intense rainfall.

In general, when Nature-based solutions cover the field of hydraulic engineering, such solutions are also called Building with Nature: a "new philosophy in hydraulic engineering that utilizes the forces of nature, thereby strengthening nature, economy and society." (EcoShape, 2024). To note, these terms are often considered synonyms and used interchangeably. Examples of Building with Nature are constructing or using oyster reefs, mangroves and salt marshes.

Building with Nature solutions do not follow the existing paradigm of dike construction and attempt to make use of natural systems and/or processes to reach a certain goal. Nature based Solutions either give room for water to reduce water levels or try to slow it down in order to decrease wave height. Both of these approaches result in lower hydraulic conditions on the primary flood protection.

Depending on the coast or environment where a water safety project is required, Nature based Solutions can offer a tailored approach for those conditions. For sandy coasts, one could think of the 'Sand Motor' near The Hague where one large sand suppletion that spreads sediment along the coast by naturally occurring currents could replace the many smaller nourishment in order to protect the coastline(Rijkswaterstaat, 2023). For muddy coasts, which for example are found around the Wadden sea, other approaches such as growing salt marshes or developing double-levee systems are more applicable. These measures make use of tidal areas in order to create a stable shoreline and attenuate waves (EcoShape, 2023). Figure 2 shows a schematization of what such an approach looks like. This figure also depicts one of the biggest benefits that Building with Nature solutions are known for (vs. conventional solutions): improved ecosystems.

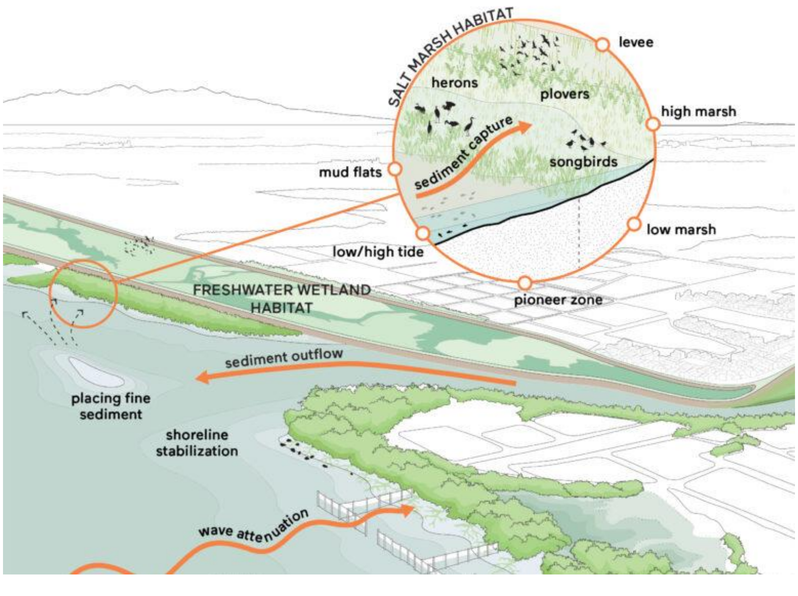

Figure 2: Nature based Solutions for a muddy coast schematized (EcoShape, 2024)

As of 2023, multiple Nature-based solutions pilot projects have been, or are being, executed along the Dutch coast, many of which entail the establishment or integration of salt marshes as integral components of flood protection measures. This combination of salt marsh ecosystems with flood defences is commonly referred to as a 'living dike'.

One such pilot is the 'Brede Groene Dijk', which involves the incorporation of both salt marshes and locally sourced soil to construct a resilient flood protection system. By combining natural elements such as salt marshes with engineered solutions, the 'Brede Groene Dijk' pilot aims to create a robust and sustainable defence against flooding events.

Having explained different Nature-based and Building with Nature solutions, the next sub-sections will explain the functioning of Nature-based solutions as flood protection and highlight the benefits of such solutions vs. the aforementioned conventional solutions.

2.1.1.1. Functioning of Nature based Solution as flood protection

Nature-based solutions use a variety of natural processes to improve the functionality of flood protection. The location and type of environment determine what processes can be used. This section will highlight two examples, that of a sandy ('Sand Motor') and muddy coast (Living dike).

The 'Sand Motor' for example, located near The Hague in the Netherlands, is an innovative coastal management project designed to address shoreline erosion and maintain a dynamic coastal environment. This intervention involves depositing a large volume of sand and allowing natural processes such as wind, waves, and currents to distribute this sand along the Dutch coast over time. This is contrary to the conventional approach of depositing sand suppletion's along the Dutch coast.

A Living dike, that can be applied in muddy coasts, considers the wave dampening capacities of the dynamically stable foreland of the dike, the salt marsh. A salt marsh has wave attenuating capacities due to its high bed roughness, vegetation, and elevated bed level (Maza et al., 2022; Vuik et al., 2019). the vegetation on living dikes plays a crucial role in attenuating wave energy. The stems, leaves, and root systems of plants help break up and absorb the force of incoming waves, reducing their erosive potential. This natural dissipation of wave energy helps to protect the dike structure and prevent erosion along the waterline.

Waves approaching the dike decrease in wave height and flow velocities, which allows suspended sediment in the water to deposit at the marsh as shown in Figure 3. Over time, in theory, this can result in a vertical accretion of the salt marsh. A higher bed level will attenuate waves more effectively and results in a positive reinforcement loop until a dynamic equilibrium is reached.

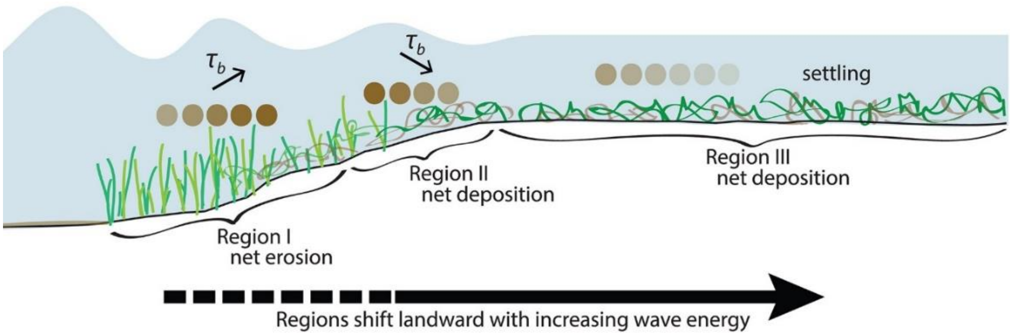

Figure 3: Schematization of sediment deposition process on a salt marsh (Lacy et al., 2020)

The reduction in wave height achieved through the implementation of Living dikes also corresponds to a decrease in the hydraulic pressures exerted on the dike structure. Consequently, there is potential to optimize the dimensions of the dikes, allowing for a reduction in their size. This optimization can be achieved by leveraging existing salt marshes or by constructing new ones.

By integrating salt marshes into flood protection strategies, significant economic and environmental savings can be realized, particularly in terms of mitigating the need for dike reinforcement (Vuik et al., 2019). This approach not only offers a cost-effective alternative to conventional flood defense measures but also yields ecological benefits by preserving or restoring natural habitats and promoting biodiversity.

2.1.1.2. *Benefits of Nature-based solutions*

This section will highlight the economic, environmental, and cultural benefits of Nature-based vs. conventional solutions. As aforementioned, suspended sediment accumulates on the salt marsh. Using this material can reduce the amount of construction materials that need to be brought in from elsewhere. The 'Brede Groene Dijk'-project where they have ripened mud locally, has shown that that local sediment can be used as construction material. Using local sediment as construction material can reduce the amount of transportation and mining that would normally be required.

Besides the contribution to flood protection and its construction, the ecosystem that is established or preserved also has many benefits to society and nature. These are so called ES. ES are usually divided into 4 categories: provisioning, regulating, cultural, and supporting. Provisioning services are services that provide goods such as food and raw materials. Regulating services are services that keep things in balance such as water purification, carbon sequestration or for example flood protection. Cultural services provide cultural or recreational experiences. Lastly, supporting services make it possible for the ecosystem to keep providing services.

ES related to coastal water wetland ecosystems mostly concern carbon sequestration, production of food, production of peat, pollution control, flood control, and recreational (Millennium Ecosystem Assessment Program, 2005).

ES that are linked to Building with nature in the Netherlands are for e.g. CO2 sequestration and biodiversity. In areas of the world where people are more dependent on nature, these communities also benefit from improved biodiversity and flourishing ecosystems (Millennium Ecosystem Assessment Program, 2005). For example, protection as stimulation of mangrove forest can reduce coastal erosion, but also improve fishing conditions for local fishermen.

2.1.2. Can additional benefits of Nature-based solutions be quantified?

Although some aspects of the life cycle costs of Nature-based solutions can be quantified in economic costs (e.g., construction costs, maintenance, materials) and compared to conventional dikes, this does not cover all costs and certainly not all benefits. An Eco-efficiency analysis combines environmental and economic costs and benefits and is ideal to create a full understanding of life cycles of systems. It does so by combining a Life Cycle Assessment (LCA) with a Life Cycle Costing (LCC) (Y. van der Meer, 2019).

ES provide benefits that create value to society (Baveye, 2017; Boerema et al., 2017; Hanna et al., 2018; Sagoff, 2011). This value should therefore also be considered when comparing alternatives. Accounting for ES in LCAs has been applied in research, reviews have been made for strategies as well (Van der Wilde & Newell, 2021; Visentin et al., 2020).

One way to account for ES, is to link the functions of an ecosystem to the benefits it supplies. These benefits can then be expressed in a value. This relation is depicted in Figure 4.

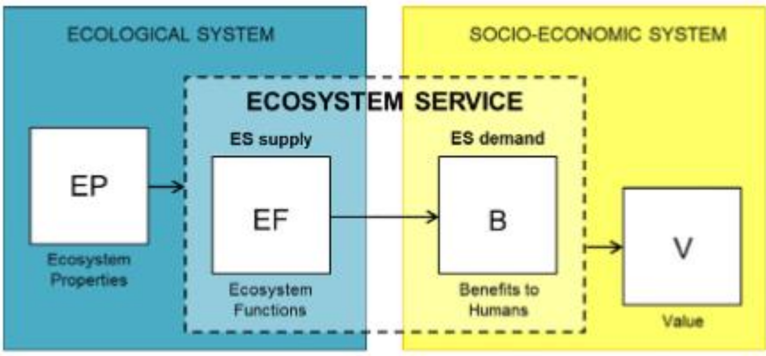

Figure 4: Ecosystem services to value (Boerema et al., 2017)

Some ES can be quantified through environmental costs (e.g., reduction in material emissions, reduction of transport emissions, and CO_2 accretion). Environmental costs are at times described as the costs of ‘clean up later’ and can therefore add to the value of a solution if considered as a (reduced) expense (Ekins & Zenghelis, 2021).

Although it is acknowledged that ES vary geographically, studies however often assume geographic uniformity and spatial consistency in impact calculations (Van der Wilde & Newell, 2021). This results in a certain degree of uncertainty in their quantification.

There is currently an open-ended debate on how to put a price tag on biodiversity. Some approaches consist of pricing certain species, price per hectare of habitat, or by determining a ‘mean willingness-to-pay for biodiversity’ (Nijkamp et al., 2008). Using these tools however only leads to estimates.

2.1.3. What are the risks and limitations of Nature-based solutions as flood protection?

As mentioned in previous paragraphs, ‘sustainable’ also relates to the maintainability of a product in the future. Risks result from the inherent uncertainty in nature. For every dike reinforcement project, risk is mitigated (to a certain extent) through accounting for a range of potential future water levels and wave heights.

In case of Nature-based solutions for coastal protection this aspect brings about more uncertainties, as the material properties are not always fully consistent, and biophysical processes that are used cannot be fully controlled. The growth of a salt marsh depends on the frequency and depth of inundation, the sediment availability, and vegetation at the marsh (Best et al., 2018; Kirwan et al., 2010; Temmerman et al., 2003). This leads to uncertainty in marsh development and vegetation growth, which in return influences the effectivity of the dike itself. Such uncertainty is mitigated to a much larger extent in conventional solutions for coastal protection, as fluctuations in material properties and biophysical processes are largely negated.

In good conditions, sediment is deposited during calm conditions and the salt marsh rises in elevation, consequently decreasing the inundation depth and frequency, which in turn decreases the growth rate. With rising sea levels, this creates a dynamic equilibrium where the salt marsh keeps up with SLR (Allen & Rae, 1988; Kirwan et al., 2010). However, when SLR exceeds the growing capacity of the salt marsh, the inundation depth increases and the marsh drowns (Fagherazzi et al., 2013; Kirwan et al., 2010; Mariotti & Fagherazzi, 2010; Mudd et al., 2013). Values of SLR that a marsh can withstand however greatly depends on other local conditions as suspended sediment and vegetation (D’Alpaos et al., 2011; Mariotti & Fagherazzi, 2010).

Lower concentrations of suspended sediment will limit the growth of the salt marsh. By using five numerical models, critical values for SLR were found for a range of suspended sediment concentrations. with suspended sediment concentrations of 1-10 mg/L critical SLR rates are just a few millimeters. When suspended sediment concentrations are 30-100 mg/L the critical rate can be as high as several centimeters (Fagherazzi et al., 2013; Kirwan et al., 2010).

To further increase complexity, vegetation is additionally of much importance to trap the abovementioned sediment. Vegetation slows down flow velocities at the marsh, which allows the suspended sediment to settle (Baaij et al., 2021). At the same time, vegetation is also prone to flooding and vulnerable when being submerged for too long. These factors lead to a system which is more prone to imbalance vs. conventional solutions.

For existing salt marshes, historic behaviour can be used as reference for the future. In case a salt marsh is constructed, the salt marsh and its wave attenuating will develop over time, leading to uncertainty. In case of a drowning or eroding salt marsh, the wave attenuating function might be lower than anticipated due to higher inundation depth and lower vegetation density, negating the desired positive effects. This can mitigated with more maintenance.

These three main aspects; Hydraulic conditions, sediment concentrations, and vegetation growth all have their own deeper levels of complexity: e.g. wind conditions, nutrients in the soil, seasonality etc. Although these aspects are not taken into account in this research, the complexity and combination of different factors makes it challenging to predict the behaviour of (in this case) a salt marsh with certainty.

As the rate of SLR is expected to increase, the resilience of a salt marsh against a change in these three main factors of influence should be investigated.

2.2. Research gaps

Long term-effectiveness and life-cycle costs of living dikes have been investigated by Vuik et al., (2019). They concluded that salt marsh construction is cheaper than dike heightening in certain circumstances. However, a full comparison between hard structures and living dikes regarding biodiversity and the economic value of ES is needed in order to perform a fully integrated cost-benefit analysis (Vuik et al., 2019).

Accounting for the economic value of ES however appears to be difficult. Van der Wilde & Newell (2021) have looked into 91 studies that integrate ES into LCA's. They have categorized these studies based on the kind of ecosystem service and its methodology of implementation. Of the 91 studies, 52 suggest a purely biophysical, 12 a purely monetary, 6 a mixed method. Many of these only focused on one single ES or a few. The most used ES is CO_2 sequestration. As most papers that integrate ES in a LCA do this on a purely biophysical basis.

Benefits that have no direct monetary value to society such as biodiversity, are challenging to quantify. However, biodiversity is required for a healthy/functioning ecosystem that provides services and therefor does have value (Kirwan et al., 2010).

To get insight in the feasibility of Nature-based solutions as flood protection, it is important to understand what benefits such alternatives can offer compared to conventional construction methods (Zhang et al., 2010). Existing methods however often lack the ability to consider all ES as they are expressed in different units. Also considering these services partially may lead to misleading results. Overcoming these challenges regarding the integration of LCA and ES would add a lot to the current state of the art (Zhang et al., 2010). Besides the integration of benefits into the valuation, it is also important to understand what the limits of such systems are, as a higher degree of uncertainty applies to Nature-based solutions as flood protection (Vuik et al., 2019).

3. Objective and scope

Based on the literature review and problem formulation, it can be concluded that there is a lack of understanding on the feasibility of Nature-based solutions compared to conventional construction methods. This research addresses that lack of understanding in the context of dike reinforcement, as it is expected that much reinforcement is required in the coming decades and a range of alternative construction methods exist. In order to set up this research in an effective and useful manner, the objective and scope are determined in this section.

3.1. Objective

Climate change and resulting SLR will require dike reinforcements in the future. Because flood protection is regulated by law, dikes have an allowed failure probability (Rijksoverheid, 2017). While many dikes have been constructed according to a similar method in the past, the allowed failure probability can be reached in a variety of ways.

The extensive muddy coasts in the Netherlands, unlike the more actively managed sandy coasts, present a unique set of challenges and knowledge gaps. Unlike sandy coasts that have been actively maintained, these areas have been subject of much less alterations for flood safety projects, consequently leading to a lack of detailed understanding on optimal dike reinforcement and construction for such areas. Therefore, this research focuses specifically on the muddy coasts, aiming to fill the aforementioned knowledge gaps and provide insights that are directly applicable to these regions. This thesis seeks to develop a strategy for dike construction assessment that accounts for the unique environmental and hydrodynamic conditions of these areas. In doing so, aiming to enhance both the reliability and effectiveness of flood protection measures for the respective areas.

Two schools of thought for dike construction are considered in this research; Conventional dikes with a sand core and impermeable clay outer layer, and living dikes with a salt marsh on the foreland of the dike that dampens the waves before the dike toe is reached. To assess a preferred solution, costs and benefits should be compared over a longer period of time.

Costs and benefits are a combination of economic- and environmental impact. Most of the costs occur during the construction and maintenance life-phases of a dike. The benefit of a dike is safety against hydraulic conditions and avoided costs of flooding. In order to compare design alternatives, these costs and benefits have been calculated in the work field in the past. Methods that have been established for this follow similar principles, may it be under different names.

Some costs and benefits of living dikes can be calculated according to the same methods as for conventional dike construction. Similar aspects are for example construction- and maintenance costs, and the design should also comply with the same safety regulations. Values for these costs and benefits differ between conventional dikes and living dikes. For a living dike in ideal circumstances; construction costs and maintenance costs go down due to local acquisition of materials and reduced wave height. In less ideal circumstances, more maintenance is required or even additional reinforcement is required. Although this is not a standard procedure, small optimizations to existing models can be made to include this by e.g. decreasing the costs of transportation.

Besides the costs and benefits that can be quantified similarly to conventional dikes, current calculation methods do not consider the benefits of the salt marsh that is established or maintained with a living dike. These benefits are the aforementioned ES (e.g., Biodiversity and CO_2 sequestration), and could significantly contribute to the total costs and benefits. These ES will therefore be added to the existing calculation methods.

This thesis aims to quantify the effect of accounting for additional benefits when comparing living- and conventional dikes' lifetime cost and benefits for the same hydraulic boundary conditions. This can be rewritten to the following research question:

"How do the costs and benefits of conventional dikes and living dikes compare, and does the inclusion of ecosystem services change this outcome?"

3.2. Research Questions

To answer the main research question, multiple aspects need to be investigated. Specifically, a comparison between conventional and living dikes on their levels of flood protection and differing economic and environmental impact. The following sub-questions provide this insight.

SQ1: How do conventional dikes, and living dikes offer flood protection against wave overtopping, and how do their designs compare for equal hydraulic boundary conditions at the seaward edge of the conventional- and living dike?

SQ2: What is the economic- and environmental impact of conventional dikes and living dikes with ES included?

3.3. Scope

The comparison between living dikes and conventional dikes, will be performed by using an Eco-Efficiency analysis. There are two reasons to adopt this framework. First, it is a tool that is already used in construction (may it be under a different name). Second, ES can be added to this analysis according to literature. Although this is not common practice, the way an Eco-efficiency analysis is set-up, it allows to make these additions. Relevant literature on ES mention CO_2 sequestration, Biodiversity and Recreation as most important to be included in this analysis. These will therefore be included.

Dike designs are essential for a quantifiable comparison of the two alternatives. As safety is the main function of both dikes, designs are created that can withstand the same hydraulic boundary conditions. The wave attenuating effect of the foreland of a living dike is calculated, and results in a lower required free crest height. In these calculations wave overtopping is the only failure mechanism that is considered, a homogenous vegetation density is assumed, cliff erosion is ignored, and salt marsh elevation is assessed over a set timespan with no intermediate results. These assumptions allow simple yet comparable designs to be created, as an extensive comparison between the alternatives is a current gap in existing research. Preferably, a more sophisticated design model could be used. This however exceeds the planned time schedule for this research.

3.4. Case description

This study will focus on a case study at Schiermonnikoog, located in the Dutch Wadden sea. Currently the possibilities of dike reinforcement are investigated for dike section 1-2 (pictured in Figure 5). The current situation consists of a conventional dike of around 6.5m + NAP, with rock revetment and a shallow foreshore varying between 0 and 2meter +NAP. Figure 6 shows the depth profile of this area.

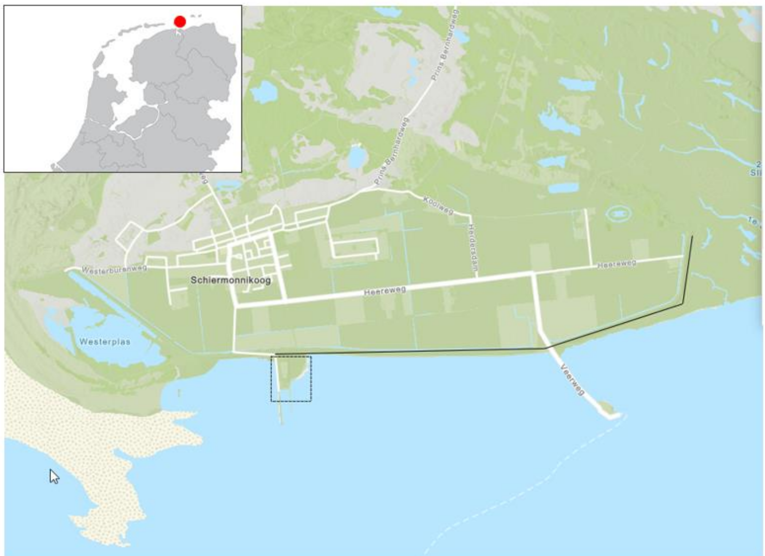

Figure 5: Location of dike section at Schiermonnikoog

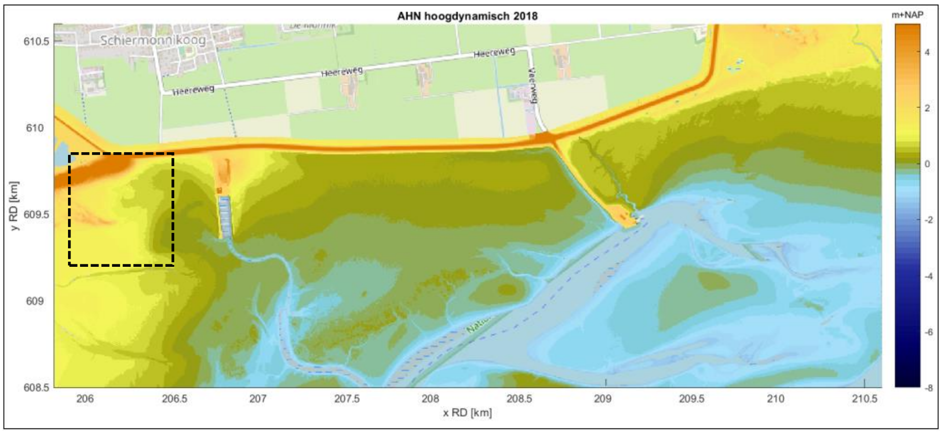

Figure 6: Depth profile at dike section (Svasek, 2023)

As can be observed from these pictures, a relatively small salt marsh is present in the western part of this dike section (see dotted area). This salt marsh is around 100m wide, and vegetation is present up to around 200 meters offshore. This can be seen in Figure 7.

Figure 7: Aerial view of the salt marsh in 2017 (left) and 2022 (right)

3.4.1. Tides and wave conditions

The dike section of Schiermonnikoog is subject to the tides. Because this area lies in the Wadden sea, the foreland is completely dry or submerged twice a day. Hence why this area falls under the category tidal flat. In Table 1, the characteristic average water levels are shown.

Table 1: Water levels at dike section 1-2

Water Levels	Water Level [m+NAP]
Average spring tide high water	1.18
Average high water	1.05
Average neap tide high water	0.86
Average sea level	0.05
Average neap tide low water	-1.00
Average low water	-1.22
Average spring tide low water	-1.38
Lowest astronomical water level	-1.68

3.4.2. Vegetation

The vegetation at the salt marshes of Schiermonnikoog is adapted to the saline conditions and include a variety of salt-tolerant species. Majorly present on the salt marsh are glasswort (*Salicornia spp*.), sea aster (*Aster Tripolium*), and common cordgrass (*Spartina Anglica*) (Bakker, 2014). These plants play a crucial role in stabilizing the soil and providing habitat for a wide range of wildlife. Additionally, sea lavender (*Limonium vulgare*) can be found on the marsh as well, which adds a purple colour during its blooming season (VVV, 2024). The leaf systems of these plants help to trap sediments and build up the marsh.

3.4.3. Morphological development

The capacity of the salt marshes in general to grow with SLR has been researched relatively extensively (Best et al., 2018; Mudd et al., 2013). Additionally, the salt marsh at Schiermonnikoog and possible future scenarios have been researched (Svasek, 2023).

The salt marsh at Schiermonnikoog is characterized by autonomous growth at multiple locations along the dike section, of which 2 are not actively stimulated by human intervention. The vertical accumulation of these salt marshes lie around 0.2 – 1 centimetre per year. A cliff is present on multiple locations, although all have been relatively stable for the past 20 years (Svasek, 2023). The growth of the salt marsh between 1998 and 2020 has been monitored and is shown in figure 8. The depicted cross section is shown in Figure 9.

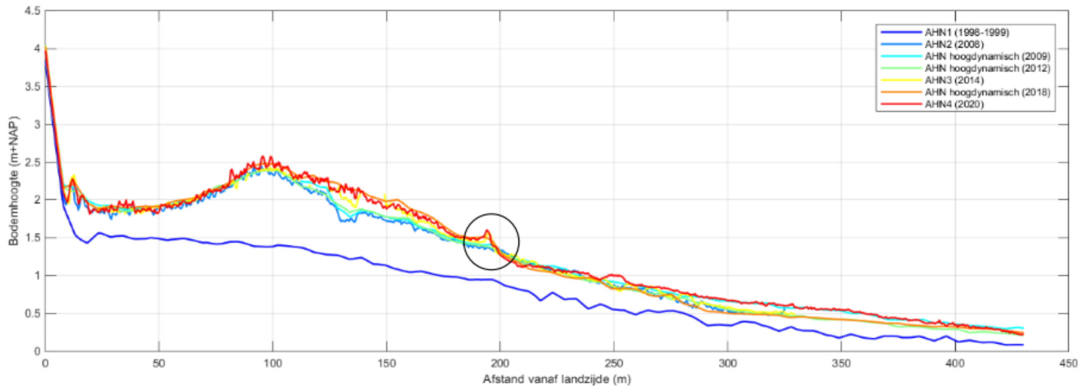

Figure 8: Cross section of depth profile development at Schiermonnikoog in 2016 (Svasek, 2023)

The black circle in Figure 8 depicts the cliff of the salt marsh at the location that is considered for dike reinforcement. At around 100 meters offshore, a large amount of growth is seen between 1998 and 2008. This could be caused by the construction of a sludge depot which can be seen on aerial footage from 2010 and onward. Because no official documentation was found on the construction of this sludge depot, and it is only seen from 2010 onwards, we need to acknowledge that there is a possibility this growth has been a natural process. The sludge depot and vegetation at the salt marsh, as well as the cross-section from Figure 8, can be seen in Figure 9.

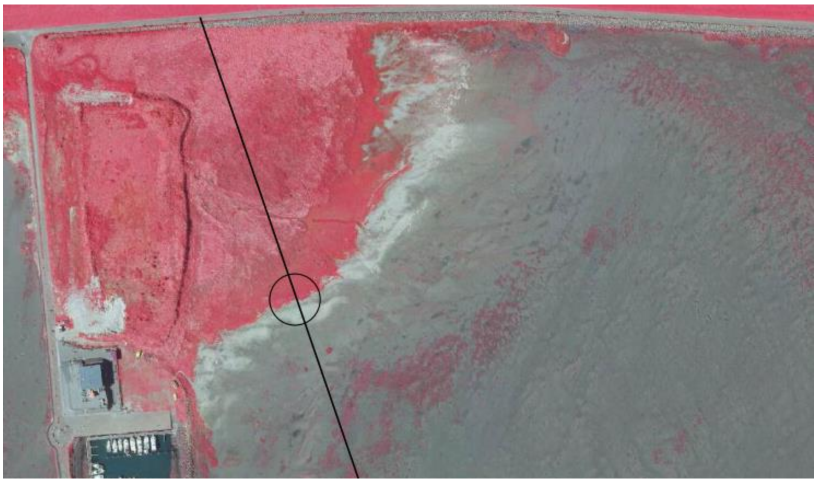

Figure 9: Salt marsh at Schiermonnikoog in 2016 with vegetation accentuated in red (Svasek, 2023)

Based on local circumstances, the salt marsh is expected to be able to grow with SLR up to around 0.8cm per year. SLR rates of 1.2cm per year could cause the salt marsh to drown if no action is taken (Svasek, 2023).

4. Methodology

To facilitate a comparison of cost and benefits between conventional and living dikes, first equivalent designs are created for both living and conventional dikes to ensure that they can withstand similar hydraulic boundary conditions at the seaward boundary of the system. For conventional dikes the dike toe is considered the system boundary, whereas for designs where a salt marsh is present the seaward edge of the marsh is considered the system boundary. This calculation is based on the failure mechanism wave overtopping. Both dike designs that are used in this research show significant similarities to alternatives that Sweco investigates for 'Wetterskip Fryslân'.

These designs are then used to determine the costs and benefits associated with each option. An eco-efficiency analysis that analyses both economic- and environmental impact is used, as this method provides a holistic perspective of costs and benefits. By comparing the results of this analysis, insights can be drawn into the feasibility of implementing both designs. Finally, a sensitivity analysis is carried out to detect potential bottlenecks and to identify suitable local conditions for living dikes.

The following chapter provides a comprehensive description of the research methodology, including data collection, analysis, and interpretation procedures, as well as a detailed explanation of the study design.

4.1. Schematization of the situation

As described in Chapter 3.4: Case description, Dike section 1-2 at Schiermonnikoog does not have a consistent foreshore. Some areas have an existing salt marsh, while the majority of the section only has mudflats at around 0 meter +NAP. Because this dike section has parts with- and without a salt marsh, both situations will be schematized and assessed in this case study. A major benefit of assessment is that results can be compared for both scenario's, which gives insight in possible suitable locations elsewhere.

The definition of design alternatives eventually determines the results. The alternatives that are compared in this report are therefore carefully selected. Although the benefits of nature are described as a benefit of the living dike alternative, these do not necessarily only apply for those alternatives. Due to changes in legislation of flood protection, the foreland of a dike is also considered in reinforcement calculations (Roode et al., 2019). This means that for a small part of the dike section where the salt marsh is already present, a conventional dike alternative would also consider hydraulic benefits of the naturally present salt marsh.

Four designs are therefore compared along the dike section in this research. These are as follows:

1) *Conventional dike with ES of existing salt marsh*
2) *Conventional dike without existing salt marsh*
3) *Conventional dike without existing salt marsh with local materials*
4) *Living dike by constructing a salt marsh with local materials*

In Figure 10, a spatial orientation of these alternatives is shown.

Figure 10: orientation of the different alternatives at location Schiermonnikoog

4.1.1. Case representation

To set up a correct model, local condition data at Schiermonnikoog are a requisite. Specifically, as water levels, wave conditions and bed levels are important local factors when calculating dike height calculations. Furthermore, as the living dike alternative also considers a salt marsh on the foreland of the dike, local information of the present marsh at Schiermonnikoog is also collected.

The chosen parameters for Schiermonnikoog are described in Table 2. And are based on the local conditions as stated in Chapter 3.4: Case description, or based on relevant literature.

Table 2: Local parameters at dike ring Schiermonnikoog, section 1-2

Parameter	Unit	Value	Source
Mean high water, MHW	m+NAP	1.05	(Svasek, 2023)
Marsh elevation, z_{marsh}	m+NAP	0	(Svasek, 2023)
Significant wave height, H_s	m	2.6	Hydra-NL
Design high water level, DWL	m	5.2	Hydra-NL
Sea Level Rise over 50 years, $SLR_{50\ years}$	m	0.5	(KNMI, 2023)
Relative Sea Level Rise, RSLR	mm/year	10	(KNMI, 2023)
Suspended Sediment Concentration, SSC	mg/L	100	(Svasek, 2023)
Sediment size (d50)	um	150	(Svasek, 2023)
Salt marsh Length, L_{marsh}	m	200	(Svasek, 2023)
Dike height	M+NAP	6.25	Actueel Hoogtebestand Nederland
Slopes of dike	m/m	1/3	Actueel Hoogtebestand Nederland

Hydra-NL is a tool to calculate statistical hydraulic boundary conditions. In this research a return period of 1/30.000 year was taken. The "Design high water level (DHW)" for this return period in this area is 5.2 meter + NAP. The significant wave height is 2.6m.

The height of the existing dike and its slope are taken from Actueel Hoogtebestand Nederland, as actual designs were not available.

The calculations will be executed for a time span of 50 years, as this is a common for dike reinforcement projects. In this time span, around 50cm of SLR is expected by the KNMI with an SSP 5.85. This comes down to a relative SLR of 1cm per year. With active maintenance the salt marsh is expected to be able to withstand this rate. Expected settlement is ignored in this report.

The definition of the individual aforementioned alternatives are described below.

4.1.1.1. Alternative 1: Conventional dike with ES of existing salt marsh

Alternative 1 considers a conventional dike reinforcement plan. This area already has a dike of around 6.5m +NAP, a salt marsh with a bed level of around 2m +NAP and a vegetated area that reaches around 200m offshore. Considering design criteria in Dutch dike reinforcement programs, the salt marsh will function as wave attenuating zone (Roode et al., 2019) as is explained in chapter 2.1 State of the art. A result of considering the wave dampening foreshore will lead to a lower required dike height and will therefore reduce reinforcement efforts. As the salt marsh will function as part of the flood protection, it should also be maintained as such. The maintenance of the salt marsh consists of placing brushwood dams. Design alternative 1 can be schematized as Figure 11.

This alternative is based on a dike that has a sand core and outer clay layer against erosion. In the current situation also rock revetment and asphalt can be found near the dike toe.

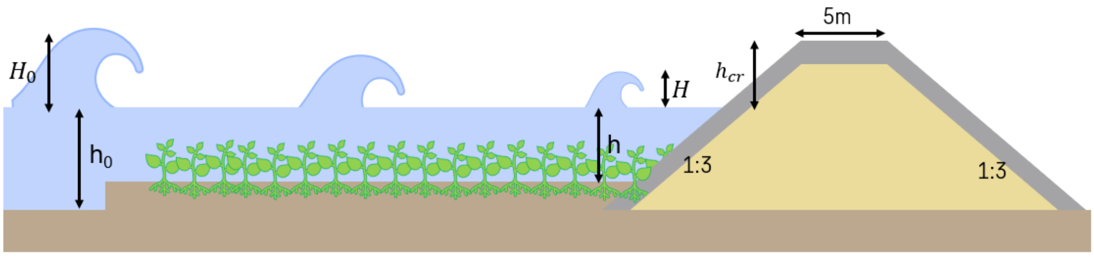

Figure 11: Alternative 1, Simplified dike design with salt marsh present

4.1.1.2. Alternative 2: Conventional dike without existing salt marsh

Alternative 2 considered the part of the dike section where no salt marsh is present yet. The current existing dike is constructed similarly to alternative one with a sand core and clay outer layer. Its height is 6.5m + NAP and the foreshore lies on average at 1m+NAP. As the foreshore lies one meter lower than the salt marsh, wave reduction is not a function of the second alternative. A schematization of alternative 2 can be seen in Figure 12.

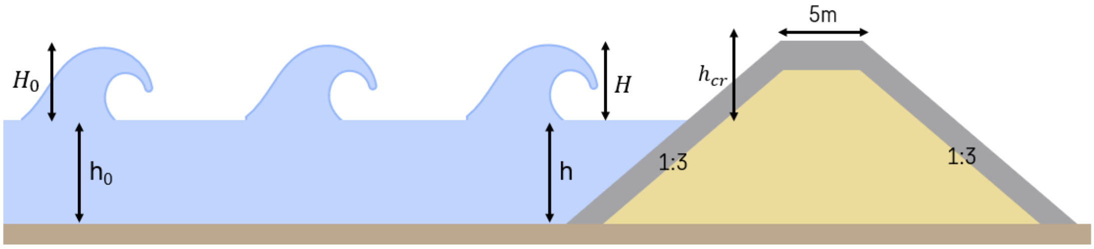

Figure 12: Alternative 2: Simplified dike design without salt marsh

4.1.1.3. Alternative 3: Conventional dike without existing salt marsh with local materials

Alternative 3 is based on equal current conditions. Instead of using clay and sand as is usual practice in dike construction, this alternative will be reinforced by using local materials. This material is usually sludge that could be dredged from nearby harbours or fairways. One downside of this material is that ca. 30% additional material is required in order to reach the same strength as high-quality construction materials (de Vries et al., 2023). Alternative 3 is schematized in Figure 13.

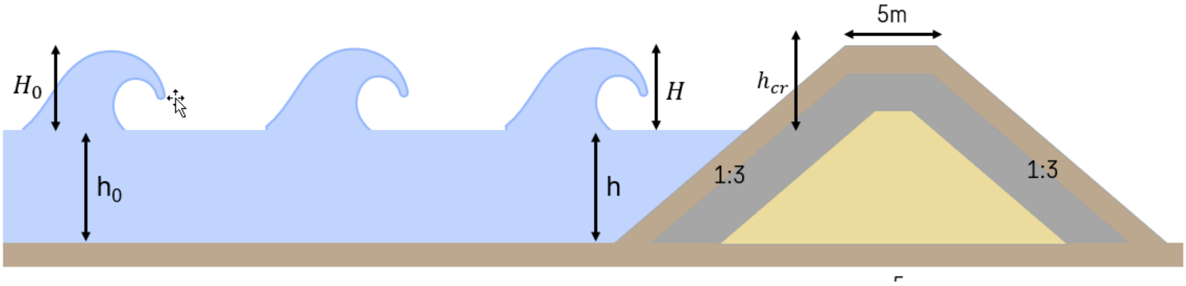

Figure 13: Alternative 3: Conventional dike reinforced with local materials

4.1.1.4. *Alternative 4: Living dike by constructing a salt marsh with local materials*

Alternative 4 is very similar to alternative 1, once it has been constructed. The benefits of a salt marsh however can only be obtained by constructing a salt marsh artificially. To create a stable salt marsh, a minimum required bed level needs to be determined first. Elevating the bed to this required level will be done by applying locally acquired sludge on the foreshore until the desired bed level is reached. A schematization of alternative 4 is shown in Figure 14.

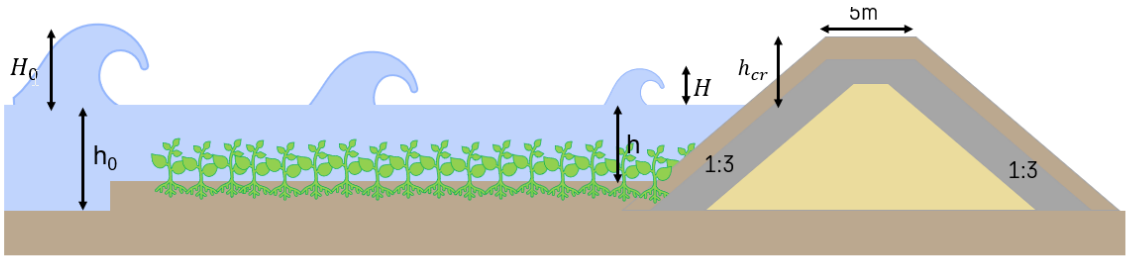

Figure 14: Alternative 4: Living dike by constructing a salt marsh

It important to mention that there is no guarantee that the applied material to form the marsh will not erode. Therefore, this alternative considers measures to protect the marsh against erosion. These measures consist of applying brushwood dam and regularly replacing them. Additionally, vegetation can be planted after constructing the marsh to prevent erosion until local species will take over the marsh. The Marconi project – a pilot on planting salt marsh vegetation, has shown that there are effective ways to do this (de Vries et al., 2021).

4.2. RQ1: How do conventional dikes, and living dikes offer flood protection against wave overtopping, and how do their designs compare for equal hydraulic boundary conditions at the seaward edge of the conventional- and living dike?

Dikes can be compared on a wide range of design characteristics. In this research, where the focus lies on comparing dike design alternatives as solution for a specific location, it is chosen to compare designs that can withstand equal hydraulic boundary conditions based on the failure mechanism wave run-up and overtopping. This failure mechanism is chosen because an estimate on dike dimensions can be obtained with relatively little information. It is also one of the first aspects that is calculated for dike designs in general.

The hydraulic boundary conditions in this study are based on a case study for dike reinforcement on 'dike section 1-2', Schiermonnikoog. The following paragraphs describe the study area, a schematization of the different design alternatives, the effect of local circumstances on required dike dimensions, and the level of construction material required for each alternative.

4.2.1. Required dike height without a salt marsh

A dike design is normally tested for a range of failure mechanisms. Wave run-up and overtopping for example are prevented by the height of a dike, as it ensures that waves that reach the dike, will not flow over. Other failure mechanisms such as erosion are tackled by widening the dike, or using hard materials on the outer slope and ensure the dike does not erode too much during a long storm. Though it is acknowledged that all failure mechanisms have influence on dike design and including them could result in a more optimal design, including these to this research would require more time than is available. Wave overtopping and wave run-up combined with a common slope give the required insight on dike dimensions for the purpose of this research.

For both wave run-up (Eq.1) and wave overtopping (Eq.2), equations have been established and used in regulations according to the 'Wettelijk beoordelingsinstrumentarium 2017' (WBI2017) and 'Beoordelings- en Ontwerpinstrumentarium' (BOI), which are Dutch design regulations. The condition that results in the highest required free crest height should be used.

$$h_{cr}=1.75*H_{m0}*(\frac{\tan(1/3)}{\sqrt{\frac{H_{m0}}{L_0}}}) \quad [1]$$

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.2 * \exp\left(-2.3\ \frac{h_{cr}}{H_{m0}}\right) \quad [2]$$

With:

h_{cr} = Free crest height above still water line [m]

H_{m0} = Significant wave height at toe of dike [m]

L_0 = Wavelength [m]

q = Maximum allowed overtopping (0.005 m^3/m)

g = Gravitational constant (9.81m/s^2)

The required free crest height as calculated should be added to the expected SLR and expected high water level. Local surges, settlement are neglected in this report. Consequently, the height as built can be calculated according to equation 3.

$$\textbf{Dike height} = h_{cr} + MHW + SLR \quad [3]$$

With:

MHW = Mean High water [m+NAP]

h_{cr} = crest height [m+NAP]

SLR = Expected sea level rise [m]

With h_{cr} calculated with equation 1 or 2, and an expected SLR scenario of 50cm in 50 years (KNMI, 2023), and MHW taken from current measurements (Svasek, 2023), the required dike height can be obtained.

4.2.2. Required dike height of a dike with salt marsh

The required dike height of a dike with salt marsh should be calculated using the same methods as a conventional dike without a salt marsh. While using the same equations as for a conventional dike, a wave height reducing factor is applied to the significant wave height at deep water to account for the wave attenuating capacity of the foreshore. Because the wave attenuating capacity is caused by both vegetation and the shallowness of the foreshore, both aspects are considered in this calculation.

Besides the wave reduction aspect, it is also important to investigate if a salt marsh has the same lifespan as the dike. Which means it is capable to grow with SLR in order to maintain its wave attenuation function. Additionally, for purposes later in this study where the costs and benefits of the dike will be determined, this aspect specifically is important.

4.2.2.1. Modelling the salt marsh elevation

A salt marsh development model by D'alpaos et. al. (2011) is used to investigate the dynamics of the salt marsh over time. This model is used to calculate the expected salt marsh elevation over a certain timespan based on local circumstances at Schiermonnikoog. Important parameters for this calculation are the suspended sediment concentration, starting elevation of the marsh, expected SLR per year, and tidal amplitude (D'Alpaos et al., 2011). An understanding of these dynamics is useful for the exploration of alternatives and to indicate possible limitations of the system. An equilibrium marsh-elevation can be obtained by the aforementioned factors and applying them to Equation 4.

$$z_{eq} = H\left(1 - \frac{R}{k}\right) \quad \textbf{[4]}$$

With:

z_{eq} = equilibrium elevation of the marsh platform [m]

H = Tidal amplitude [m]

R = Relative rate of sea level rise [m/year]

k = Maximum total accretion rate over the marsh platform [mm/year]

Rewriting equation 4 and implementing a starting condition results in equation 5.

$$z(t) = z_{\mathrm{eq}} + \left(z_0 - z_{\mathrm{eq}}\right)e^{-\frac{k}{H}t} \quad \textbf{[5]}$$

With:

$z(t)$ = elevation of the marsh platform at time = t

z_{eq} = equilibrium elevation of the marsh platform [m]

z_0 = elevation of marsh platform at t = 0

H = Tidal amplitude [m]

k = Maximum total accretion rate over the marsh platform [mm/year]

A maximum total accretion of 10mm/year has been measured based on areal footage at the project location between 1998 and 2008 (Svasek, 2023). In the following years this growth has stagnated. A possible explanation for this is that the tidal marsh has reached its upper limit under current water levels. Following this conclusion, the salt marsh at Schiermonnikoog is able to grow with SLR in expected conditions.

4.2.2.2. Wave height reduction

The breaking of waves is relatively complex. As waves approach shallow water they slow down. If the amount of energy remains constant, this results in waves getting higher. When observing waves at the beach, one could see this very clearly. However, as the water depth becomes more shallow, the waves interact with the bed friction and waves start to break. A shallow foreshore therefore reduces wave height in two ways: Some waves that normally would reach the dike toe now break before they reach the dike because of the water depth and bed roughness. Other waves reduce in height due to energy dissipation.

The wave dampening capacity of a foreshore (i.e. the vegetated salt marsh in this research), has been researched extensively with some variation in results. A study by Baker et al., (2022) suggests a wave reduction of 14.9% to 34.6% solely by vegetation. Their research uses a scale model of a salt marsh with- and without vegetation and calculates normalised wave height reduction. In Figure 15 their results are displayed. On the x-axis, the distance from the leading edge of the marsh platform is shown on a 1/20 scale. The β' value is the fitted dampening coefficient for the corresponding vegetation density.

Their research is based on water depths from 0.05 to 0.12m at the marsh, which comes down to 1.0–2.4 m at full scale. Because the MHW of 1.05m+NAP at Schiermonnikoog falls in this range this scale study is accepted.

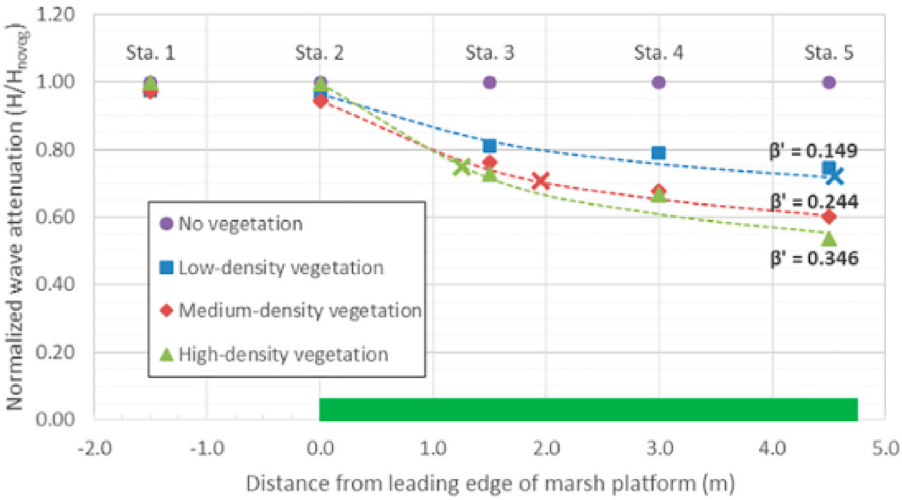

Figure 15: normalized dampening coefficient for no- to high-density vegetation (Baker et al., 2022)

Based on van der Meer et al., (2018), an additional 20% wave reduction can be expected due to shoaling and depth limited wave breaking. Based on the local parameters h/H_0 = 2, and the shallowest slope of 1:100 that is researched by van der Meer et al. (2018) (Figure 16). Multiplying these factors results in a total wave dampening coefficient of 40%.

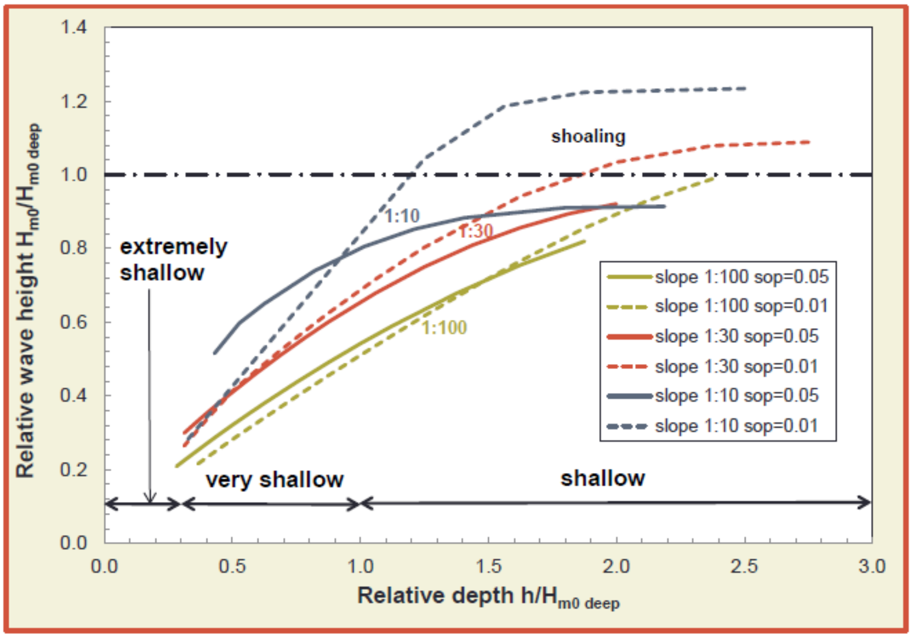

Figure 16: Relative wave height (H/H_{deep}) (J. W. van der Meer et al., 2018)

Vuik et al. 2016 suggest a much lower contribution of vegetation compared to bed friction, around 25%-50% additional contribution compared to a shallow foreshore alone. Taking into consideration these values, a wave reduction of factor of 30% is obtained. This considers a wave reduction of 20% due to the bed level, with 50% additional wave reduction.

Based on these sources and their uncertainty, the lower value of 30% wave reduction is considered in this research. Although a more specific wave dampening coefficient could be calculated for the specific parameters at Schiermonnikoog, this cannot be guaranteed when constructing a salt marsh. An average expected value of 30% therefore is more widely applicable.

$$H_{reduced} = H_0 * (1 - f_{marsh}) \quad [6]$$

With:

$H_{reduced}$ = Reducded wave height at toe of dike

H_0 = Significant wave height at toe of dike [m]

f_{marsh} = 0.3 [-]

By using $H_{reduced}$ instead of H_0 - which is used for the conventional dike - a comparison on required dike height can be made. f_{marsh} only applies when the salt marsh can keep up with SLR.

4.2.3. Calculation required building materials

Using geometry of the selected simplified dike designs, the amount of sand and clay can be calculated.

The following equations can be used for amount of sand and clay required for each alternative:

$$V_{Dike} = (h_{dike} * 3) * h_{dike} + w_{crest} * h_{dike} \quad [7]$$

$$V_{Sand} = ((h_{dike} - 1) * 3) * (h_{dike} - 1) + w_{crest} * (h_{dike} - 1) \quad [8]$$

$$V_{Clay} = V_{dike} - V_{sand} \quad [9]$$

With:

V_{Dike} = Total dike volume [m^3/m]

h_{dike} = Dike height [m]

w_{crest} = Crest width [m]

V_{Sand} = Volume sand in dike [m^3/m]

V_{Clay} = Volume clay in dike [m^3/m]

Despite the locally obtained clay not meeting all the requirements of the Technical Guidelines for Clay Dikes, the clay has been successfully applied in the pilot section of the demonstration project 'Brede Groene Dijk'. A sufficient design was made by considering the divergent properties of the clay. Approximately 20% more clay volume was applied compared to clay that fully complied with the Technical Guidelines(de Vries et al., 2023). In this report an additional volume of 30% was used, as this was the preliminary result of the report. Considering the minimal required characteristics of the construction clay and the quality of the ripened clay, 20% more volume might not be representable for locations other than the Eems Dollard where the dredged material of 'Brede Groene Dijk' was obtained. 30% more volume therefore allows for safer comparison.

In case no salt marsh is currently existing, local dredge can be used to heighten the foreshore. In this study it is assumed that the bed level should be elevated to the similar levels as the existing marsh, for the entire dike section to have a marsh that grows with SLR. This results in the following equation:

$$V_{marsh} = L_{marsh} * (h_{marsh} - h_{bed}) \quad [10]$$

With:

V_{marsh} = Total volume of the salt marsh fill [m^3/m]

L_{marsh} = Lenght of the salt marsh [m

h_{marsh} = required elevation of the salt marsh [m+NAP]

h_{bed} = current bed level [m+NAP]

Commonly in dike construction, the existing dike is used as foundation for the reinforcement. After the toplayer is excavated, additional soil is applied, after which a new top layer is installed (Royal

HaskoningDHV, 2021). The materials from the existing dike of 6.5m (AHN, 2023) wil be subtracted from the calculated quantities for every alternative. This could lead to zero required materials in case the new required dike height is lower than the current exsisiting dike.

The existing dike holds similar dimensions to the simplified design that is described in equation 7 to 9. These equations wille therefore also be used to calculate the quantities of materials that are already present at the location.

4.2.4. Sensitivity analysis

As many of the parameters carry some degree of uncertainty, a sensitivity analysis is performed. In this sensitivity analysis the impact of relevant parameters on the required dike height is calculated. This sub-chapter first introduces the respective parameters, after which values for the analysis are summarized.

4.2.4.1. Mean high water and SLR

The Mean High Water (MHW) level is derived from current measurements, while future values account for projected SLR based on KNMI scenarios (KNMI, 2023). For MHW, the probabilities from Hydra-NL were used: a 1/1000 probability corresponds to a -16% deviation, and a 1/300,000 probability corresponds to a +10% deviation. The SLR was evaluated under a variety of scenarios, with its impact directly influencing the MHW.

4.2.4.2. Bed level

The bed level variations are based on bathymetric data near the dike. These variations were incorporated to understand their effect on the dike's stability and performance. Bathymetry levels along the dike section fluctuate between ca. 0.8m+NAP and 1.2m+NAP (Svasek, 2023).

4.2.4.3. Significant wave height

Significant wave heights were sourced from Hydra-NL, with a return period of 1/1000 years corresponding to 2.02 meters, and 1/300,000 years corresponding to 3.04 meters. This range gives a clear image of the variety in wave height occurrence near the shore of Schiermonnikoog. The legally determined return period for dike design is 1/30.000 years, which corresponds to the significant wave height of 2.6m given in Table 2.

4.2.4.4. Wave height reduction factor

Literature review indicated wave height reduction factors typically range from 25% to 40%. A central value of 30% was selected, with a ±20% variation, to account for uncertainties in wave attenuation due to dike geometry and surface roughness.

4.2.4.5. Slope of Dikes

Reinforcing the dike with gentler slopes than 20% would widen the dike significantly, leading to a clash with the initial problem of intervening with Natura 2000 areas and thus impacting nature. Therefore, these values were not extensively explored to balance design feasibility and environmental impact.

4.2.4.6. Parameter input for the analysis

As can be seen in Table 3, a range of 20% variation was used for all parameters. This choice was based on several factors. Many of the values from literature and at the case study location naturally fall close to this range, making it a convenient and consistent choice. Additionally, this range is broad enough to capture significant deviations without introducing excessive variability that could obscure the final results of the thesis.

Table 3: Parameter ranges for the sensitivity analysis

Parameter	Unit	Range	Absolute value range
Mean high water, MHW	m+NAP	-20% / +20%	0.84 – 1.26
Bed level, z_{bed}	m+NAP	-20% / +20%	0.8 – 1.2
Significant wave height, H_{m0}	m	-20% / +20%	2.08 – 3.12
Wave height reduction factor	-	-20% / +20%	0.25 – 0.38
Sea level rise	mm/year	-20% / +20%	8 – 12

Slopes of dike	m/m	-20% / +20%	0.256 - 0.384

Using a uniform 20% variation across all parameters allows for a direct comparison of their relative impacts. This consistency helps in understanding which parameters most influence the dike's design and safety, resulting in a more clear interpretation of the sensitivity analysis results.

4.3. RQ2: What is the economic- and environmental impact of conventional dikes and living dikes with ES included?

The required designs for the hydraulic boundary conditions at Schiermonnikoog can be used to quantify their environmental and economic impact. Because literature recommends a combination of economic- and environmental costs, this comparison is done in the form of an Eco-efficiency analysis. The Eco efficiency Analysis consists of a LCC and LCA. In the following paragraphs the method for both assessments is described.

4.3.1. Life Cycle Assessment (LCA)

An LCA is a product related assessment tool that focusses on flows in connection with the production and consumption of goods and services (Ness et al., 2007). More specifically it analyses potential pressure of a product on the environment during raw material acquisition, production processes, usage period and disposal (Lindfors, 1995). A typical objective of an LCA is to identify the major differences in potential environmental impact between two alternative systems (Lindfors, 1995 p.17). A widely accepted LCA procedure consists of a definition of a goal and scope, a life cycle inventory, an impact assessment, and a life cycle interpretation. These steps are depicted in Figure 17.

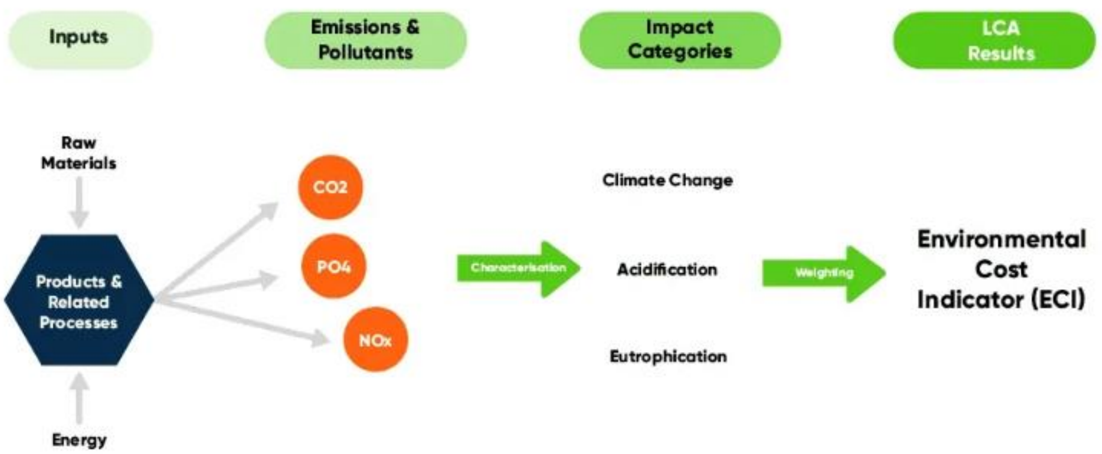

Figure 17: Environmental cost indicator (ECI) (Ecochain, 2022)

The last step in Figure 17 shows the weighing of the impact categories to an Environmental Cost Indicator (ECI). The expression of environmental Impact in a monetary value itself is a topic of debate in itself and according to ISO-standards not even allowed. In order to give more meaning to the target audience of this thesis, who might not be familiar with the expression in emissions, this research chooses to incorporate this final step.

4.3.1.1. Goal and scope definition

The goal and scope definition must contain several aspects. In this paragraph, these aspects are explained and applied for the flood protection strategies that were introduced in previous chapters.

Goal Definition

A goal definition should state the target of the LCA, the target group and whether it contains comparative assertions that are disclosed publicly.

The aim of this analysis is to compare a nature-based alternative of flood protection barriers to conventional ones on their economic- and environmental costs. The target group of this assessment are Waterboards, Consultants and Contractors.

Scope Definition

The scope definition should consist of the product description and function, Description product system and function, FU and reference flows, System boundaries and cut-off criteria, Data requirements, Allocation procedure, Impact categories and characterization models, and Assumptions and Limitations.

A conventional dike has the function to retain water to ensure safety levels stated by law. A Living dike and double levee also have additional functions that originate from the ES, such as acquiring local sediment, providing biodiversity and acting as CO_2 sink.

The Functional Unit is the "quantified performance of a product system for use as a reference unit". For a dike system the Functional Unit can be described as: "Flood protection at location X with hydraulic load Y for a timespan Z". As these variables might be variable in this research, as it will act as a general tool, they are not specified yet. The reference flows in this research are the amounts of material and energy needed in the different strategies that will be researched; 1) Conventional dike reinforcement with naturally present salt marsh, 2) Conventional dike reinforcement without salt marsh, 3) Conventional dike reinforcement with local acquired materials, and 4) Living dike by constructing salt marsh with local acquired materials.

System boundaries originate from the literature review and assessment criteria as they are applied to conventional dikes. The designs follow design requirements from Dutch law and are determined in chapter 4.1.1. The respective design period is 50 years, and life stages cradle-to-grave are considered. Cradle to Grave considers all life stages from natural resource acquisition until disposal. For the disposal stage it is assumed that materials are re-used at the same site for reinforcement, resulting in no additional costs. These stages and their processes are shown in Figure 18 (see larger figure in Appendix A: LCA system boundaries).

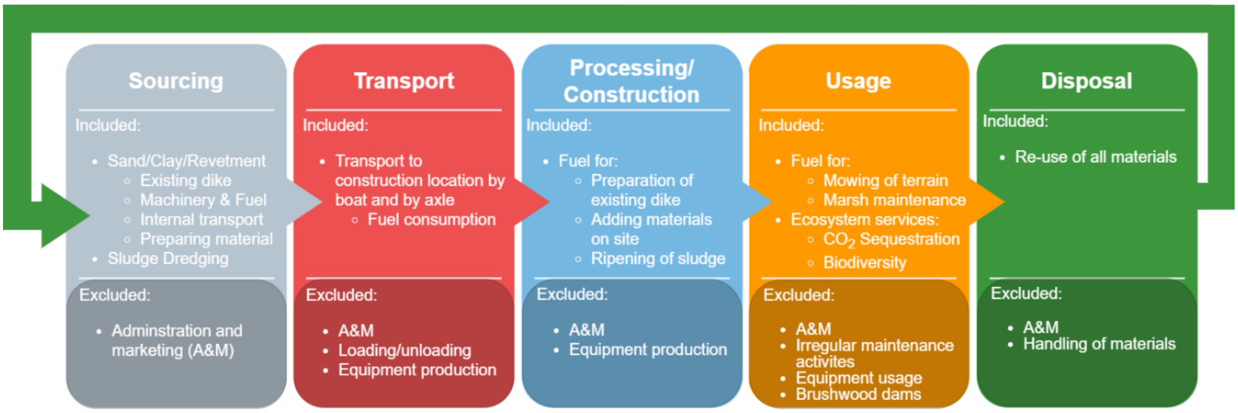

Figure 18: System boundaries of LCA

As this is relatively new research subject, it is attempted to only use European data from at least 2015. In case data is unavailable, related information is used as estimation. The exact databases that will be used depend on the material flows and will therefore be specified during the research.

Impact categories will be Global warming and eutrophication, as some of the ES are related to Carbon emissions and Nitrogen. Besides these categories, their impact will also be compared on the categories 'recourse depletion, 'acidification', and 'ecotoxicity'.

Based on this goal and scope, relevant costs and benefits for the different flood protection strategies have been summarized in Table 4. The method of assessment, and the way these cost and benefits are quantified is shown in Table 5.

Table 4: Strategies and relevant costs and benefits

Flood protection Strategy	Costs	Benefits
1) Conventional dike with ES of salt marsh	Material acquisition	Flood protection
	Material transport	Wave height reduction
	Construction	Natural CO2 sink
	Maintenance	Biodiversity
2) Conventional dike without ES of salt marsh	Material acquisition	Flood protection
	Material transport	
	Construction	
	Maintenance	
3) Conventional dike with local materials	Material acquisition	Flood protection
	Material transport	Reduced raw material costs
	Construction	Reduction of transport distance
	Maintenance	
4) Living Dike by constructing salt marsh with local materials	Material acquisition	Flood protection
	Material transport	Wave height reduction
	Construction	Reduced raw material costs
	Maintenance	Reduction of transport distance

Table 5: Cost and benefits and method of quantification

Cost/Benefit	method of assessment
Material Acquisition	LCC, LCA (Ecoinvent) + ECI
Transportation	LCC, LCA (Ecoinvent) + ECI
Construction	LCC, LCA (Ecoinvent) + ECI
Maintenance	LCC, LCA (Ecoinvent) + ECI
CO2 sink	LCC, LCA (Ecoinvent) + ECI
Biodiversity	LCC (CPB, 2019), LCA
Recreation	LCC (CBS, 2021), LCA

4.3.1.2. *Life Cycle Inventory (LCI)*

The Life Cycle Inventory is a qualitative analysis that quantifies all environmental interferences during a products lifespan. According to lectures of Sustainable Engineering, the LCI should contain the following aspects: Qualitative description of In- and Outputs of related processes, A data acquisition sheet, description of type and terminology of data, and a definition of calculation procedures.

In line with these aspects, it is recommended to start with a flowchart of all different in- and out-puts of various processes. These flows should then be quantified in a normalized way (e.g., /m of dike) and documented.

Table 6 and Table 7 show a data acquisition sheet for the LCI. This is filled out after the flowchart has been established. The data in this table will mostly consist of secondary data sources, which will be taken from LCA databases. This is because primary data sources, such as measurements and invoices are not available.

Table 6: LCI Input Table

Phase	**Process**	**Flow**	**Quantity**	**Unit**

Table 7: LCI Output Table

Phase	**Process**	**Flow**	**Quantity**	**Unit**

The four stages that are considered are; ‘Resource acquisition’, ‘Transportation’, ‘Construction’, and ‘Usage’. These stages are slightly different from conventional LCA, as the “product” is constructed on site.

In the following paragraphs, the considered stages are further explained. This more clear description will help to make sure all relevant flows are taken into account before the LCIA is calculated.

4.3.1.2.1. Resource acquisition

Resource acquisition consists of the three main construction materials; sand, clay, and rock revetment. For conventional dike construction, these materials are sourced based on quality.

Normally this means these materials are excavated along river beds or dredged and processed in order to make them suitable for construction. By using Ecoinvent databases - an organization founded by Swiss research institutions - these activities and correlating flows have been considered.

Environmental impact of sourcing and processing such materials is a result from dredging/excavating machines, their diesel and electricity consumption, and on-site transport using lorries.

A “discount” for locally obtained materials is in place as to accurately model the environmental impact of construction materials. This “discount” is implemented by reducing costs of diesel.

Sludge that is obtained from nearby harbours is normally a waste product, therefore costs of sourcing this material can be ignored in full (Besseling et al., 2019). Processing this material however does include to the lifecycle of a dike and should therefore be calculated.

The process of converting sludge to high quality clay is called “ripening”. The required steps of this process can be seen in Figure 19 and are; dredging sludge, ripening, and applying ripened material as dike material. The process of clay ripening is added to the LCA by adding diesel usage by heavy machinery involved with the ripening process. The heavy machinery that is used are a hydraulic crane and bulldozer. Both have a fuel consumption of 40L/Hour and a capacity of 90m^3/hour. This combined deployment leads to a fuel consumption of 1.016L/m^3 sludge.

The dredging itself is left out of this analysis, as the dredged material is considered waste material of maintaining fairways and harbours. Due to natural processes, these keep filling up with sediment that has to be dredged regularly.

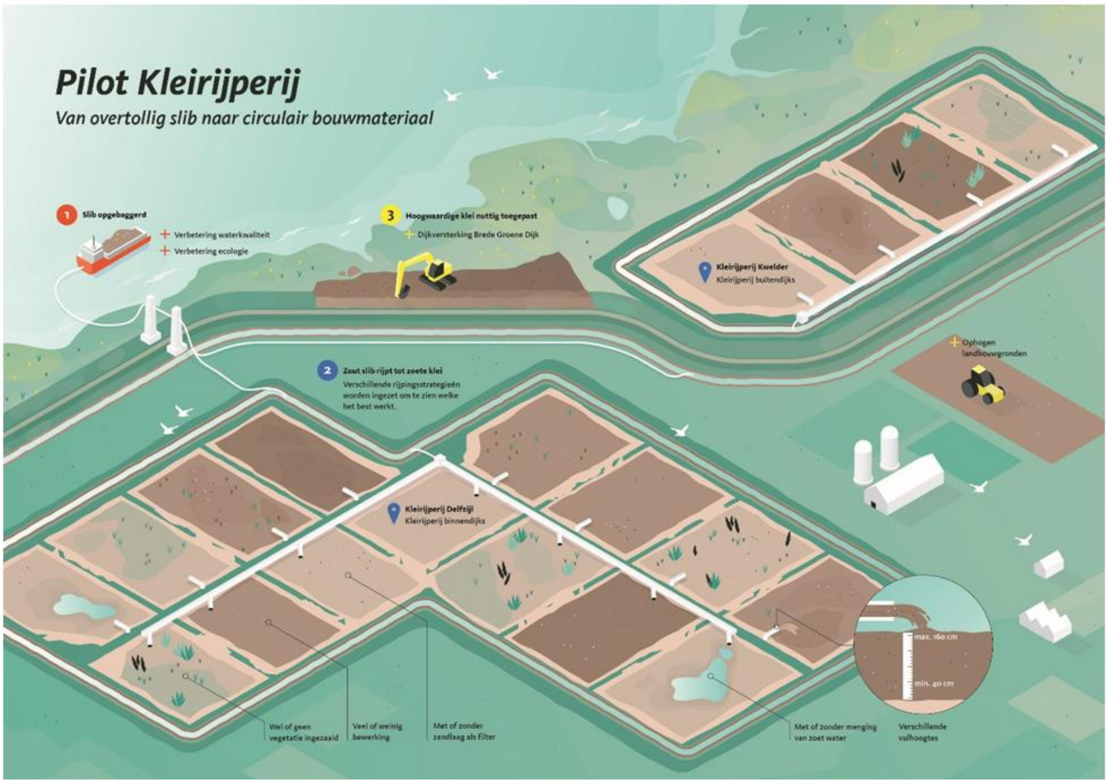

*Figure 19: Clay ripening process (*Muddy Coasts - EcoShape*, 2024)*

4.3.1.2.2. Transportation

Construction materials are selected based on quality, meaning these are sometimes sourced at large distance from the construction site and then transported. Basalt, which is used as rock revetment for example, is sometimes transported for over 200km as quarries are located in southern Germany or even Switzerland. Large portions of the journey occur by boat, though last kilometres often take place over the road (H&B Grondstoffen, 2023). Clay is sourced in Limburg, Belgium or Germany and is transported in similar fashion to rock revetment. Sand is often easier to source more locally as it is more easily available.

In case of a living dike, where locally sourced materials are used, distances over which the construction materials need to be transported is limited to several or at most tens of kilometres. For example, the harbour at Schiermonnikoog lies at 2km from the dike section and a nearby fairway around 20km. According to local news articles, the amount of dredged material should be sufficient for the construction of the dike section at Schiermonnikoog (Dagblad van het Noorden, 2018).

4.3.1.2.3. Construction

Based on a report by Royal HaskoningDHV (2021) on the usage of DuboCalc, which is a LCA tool used by construction companies, the usage of tools and their capacities has been determined.

One 150kWh excavator for example, has a maximum capacity of moving 90m^3/hour. Every hour, such an excavator uses 40L of diesel. This results in a fuel consumption of 0.44L/m^3 applied material.

4.3.1.2.4. Usage

The usage phase of the dikes is the life stage where maintenance is required, but also the phase where the benefits from ES as biodiversity, recreation and CO2 sequestration are active.

Maintenance

Both regular dikes and living dikes require maintenance. Maintenance activities that are not taken into account with construction costs and impact in the sources that are used in this report, only consist of mowing. Mowing happens 2 to 3 times a year (Gemeente Dijk en Waard, 2022). With an area of 0.0006 ha per running meter dike of grass that needs to be mowed, this only adds up to a total of 0.06-0.09ha in a period of 50 years. An Eco invent dataset is used to implement this activity in the LCA and emits 17.46kg of CO_2 equivalents per hectare.

A salt marsh requires additional maintenance. To prevent erosion of the marsh and to improve growth, often brushwood dams are placed. These brushwood dams slow flow velocities which gives the desired effect. Constructing these dams and replacing worn materials is mostly executed by human labour. The vehicles and tools they use are estimated to have similar impact as mowing.

CO2 accumulation rates

CO_2 accumulation is a natural occurring process that is an effect of plant growth. Plant biomass mostly consists of Carbon, which is accumulated due to photosynthesis. As plants grow, they take CO_2 from the air and trap it in their biomass. This phenomenon occurs to all plants present on the marsh, and is schematized in Figure 20.

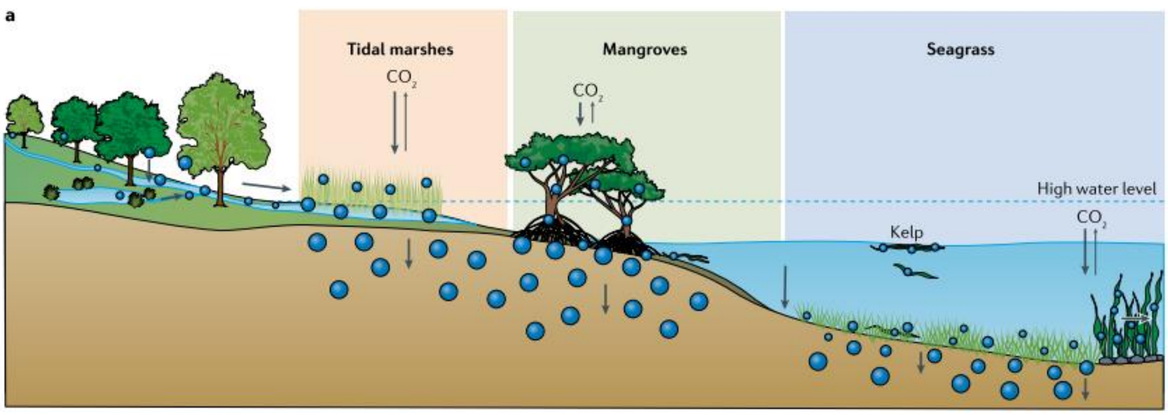

Figure 20: Carbon cycle in plants

Plants on land grow and store their carbon in aboveground biomass such as stems and leaves, and underground biomass such as roots. A salt marsh that traps sediment rises, which leads to an accumulation of underground biomass as is shown in Figure 21.

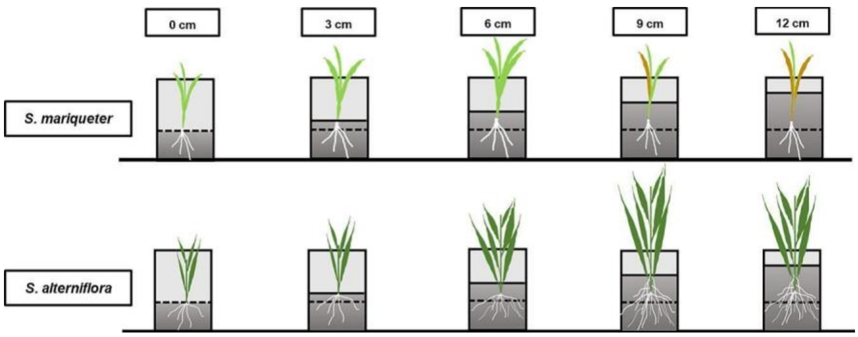

Figure 21: Carbon accumulation in rising salt marsh

Gailis et al., (2021) mention a range from 15-150 grams of carbon per square meter per year ([g/m^2/yr]) in salt marshes. Although some of this carbon is actually trapped as a result of the vegetation on the marsh, some of the Carbon was already present in the sediment in for example the water, or originating from vegetation inland. For the sake of a correct LCA it is therefore important to distinguish between autochthonous carbon (i.e. carbon that is a result of growing biomass of plants on the salt marsh), and allochthonous carbon that is formed elsewhere and therefore cannot be addressed to the functionality of the marsh. Around 60-70% of blue carbon in salt marshes is assumed to be autochthonous (Mueller et al., 2019).

The total amount of captured carbon by the salt marsh is therefore obtained by multiplying the carbon value from literature by the active surface of the marsh and the lifetime of the dike, which is 50 years in this case. Taking average values this comes down to 0.7kg CO_2 per m^2 over the dikes design period.

The captured CO_2 will be subtracted from the total carbon emissions of the dike reinforcement, resulting in a net global warming potential in Tons of CO_2.

One other remark to this CO_2 capturing is the longevity of the capturing. Mueller et al. state in their report that it is important to note that stable carbon values of constructed marshes are considerably higher than those of the tidal flats, illustrating the great potential Carbon sequestration of man-made vegetated ecosystems. This is also the substantiation of this research. Additionally, the long-term effects in marshes in general are thoroughly researched and carbon dating back thousands of years has been found (McTigue et al., 2021).

This paper however also states the biggest risk of carbon sequestration in salt marshes. In case of erosion or the drowning of a marsh, organic matter can decrease by 7-24% per year. A significant reduction that emphasizes the need for maintenance of the marsh.

Biodiversity

A normally excluded benefit of Nature-based solutions is biodiversity. Through extensive literature it must be concluded that it remains difficult to change this. The effects of improved biodiversity are hard to quantify. Though guidelines by the CPB – the Netherlands Bureau of Economics – have established a point system to address biodiversity value, this is not easy to convert to a monetary value.

Besides the quantification of the effects of biodiversity, pilot programs with Nature-based solutions report that the creation of a clay ripening area, actually has a negative effect on seasonal birds (Sweco, 2022). While taking this into account for the conclusion and recommendations of this thesis research, the LCI does not consider this as a flow. In the LCIA which is explained in the next chapter, impact on biodiversity is considered as an impact category based on result of ecotoxicity, eutrophication and acidification.(Huijbregts, 2016).

Hiking-recreation

Recreation is a significant aspect of cultural ES. It refers to the leisure activities that people engage in within natural environments. These activities can include hiking, bird watching, fishing, camping, and various water sports. Recreational activities in natural settings provide multiple benefits, such as physical health, mental well-being, and social cohesion.(Millennium Ecosystem Assessment Program, 2005). As hiking has benefits such as physical health and mental well-being, this is only considered in the LCC to prevent duplicating its impact (i.e. double counting).

4.3.1.3. Life Cycle Impact Assessment (LCIA)

In the Life Cycle Impact Assessment, the in- and outflows of the LCI are translated to environmental impacts, such as Global Warming, Smog, and Acidification. In this research the procedure according to ISO 14040 will be used which consists of the following steps: 'Selection of impact categories', 'Assignment of LCI results' (classification), and 'Calculation of category indicator results' (characterization).

The assignment of LCI results and the calculation of the LCIA results are made in Earthster as the model has already been established in previous steps of the LCA. Implementation of the inventory and its impact into this program can be seen in Figure 22.

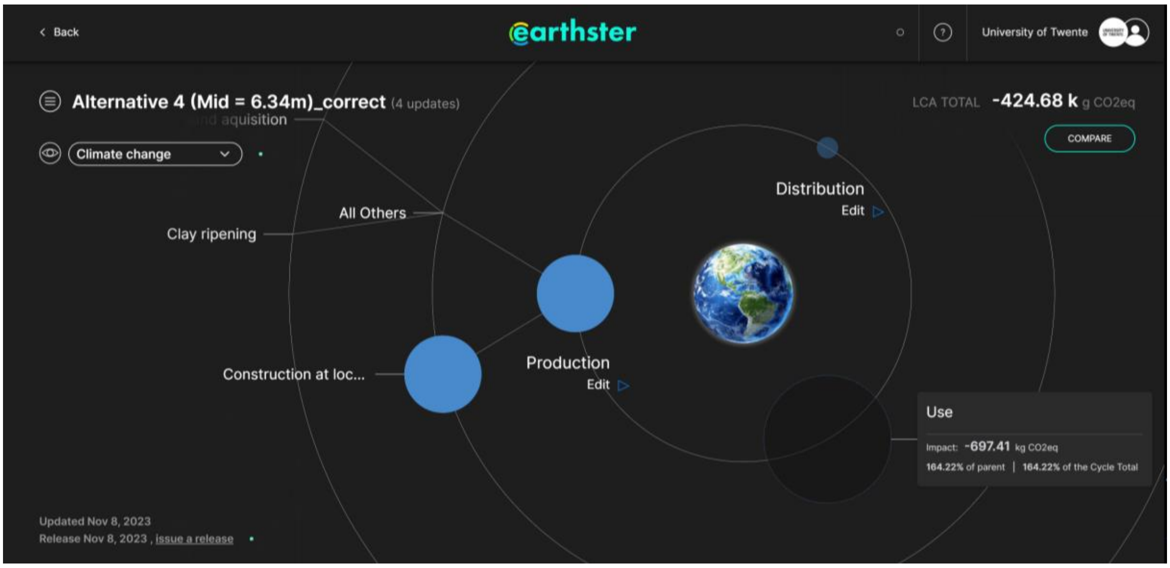

Figure 22: Life Cycle Impact Assessment model in Earthster

The impact categories that are used are ReCiPe 2016 and EF 3.1.

ReCiPe 2016 is a comprehensive Life Cycle Impact Assessment (LCIA) method that evaluates the environmental impacts of products and processes. It converts the Life Cycle Inventory (LCI) data into midpoint indicators, focusing on specific environmental issues like climate change and endpoint indicators, which aggregate impacts into areas such as human health and ecosystem quality. This method aids in interpreting complex LCI data into actionable environmental impact scores, facilitating informed decision-making in sustainability assessments. This method has been established by RIVM, Leiden university and Radboud university Nijmegen (Huijbregts, 2016).

Because not all impact categories that apply to living dikes are available in the ReCiPe method, eutrophication will be calculated according to the EF 3.1 (Environmental Footprint version 3.1) database. This is done for both terrestrial and marine eutrophication. The EF 3.1 method works in a similar way as ReCiPe. Breaking down complex environmental data into clear impact scores, supporting more effective sustainability assessments and decision-making (Andreasi Bassi et al., 2023).

The impact categories that are used in this research are expressed in different units and can therefore be hard to compare. In Table 8, the used impact categories, their characterisation model and their units are shown. Therefore, these impact categories are all compared individually.

Table 8: LCIA impact categories

Impact category	*Characterisation model*	*Units of measurement*
Global warming	ReCipe 2016	kg Carbon Dioxide (CO_2) equivalents
Terrestrial eutrophication	Environmental Footprint 3.1	Mol Nitrogen (N) equivalents
Marine Eutrophication	Environmental Footprint 3.1	grams of Nitrogen (N) equivalents
Damage to Human health	ReCipe 2016	μ Disability-adjusted life years (DALY)
Damage to Ecosystems	ReCipe 2016	μ species-year
Resource depletion	ReCipe 2016	USD (2013)
Water usage	ReCipe 2016	m^3

4.3.2. Life Cycle Costing (LCC) of direct costs

An LCC is a method to assess the costs incurred in the life cycle of an asset over a period of the analysis. An LCC commonly consists of the following steps: Goal and scope definition, inventory analysis, and the evaluation of alternatives. In order to combine the LCA and LCC results into an Eco-Efficiency analysis, the same goal and scope will be used for both assessments.

The inventory should contain all costs and income of the 'before use'- and 'during use' stage, as the end-of-life stage is neglected in this research. The costs are categorized similarly to the costs of *Table 5*, as these are the costs that are accounted for during these life stages.

Income can be generated by biodiversity and recreation. The monetary value of biodiversity can be estimated according to guidelines of the CPB (CPB, 2019), but as mentioned in the LCA chapter, the effect of improvement of biodiversity is hard to quantify. The income for recreation can be estimated according to values of the CBS. The recreational value will be mostly focussed on 'Hiking -recreation' will be quantified by the relative number of kilometres that have been walked in the area.

The costs and income and the time of this cashflow can be used to calculate the net present value (NPV). This is the financial metric that the LCC will be expressed in, and accounts for the time value of money. As it considers the moment of certain cashflow and a discount rate, a fair estimation can be made between two alternatives. Equation 11 shows the equation for the NPV.

$$\mathbf{NPV} = \frac{\boldsymbol{R_t}}{(\mathbf{1} + \boldsymbol{i})^{\boldsymbol{t}}} \qquad \textbf{[11]}$$

With:

$R_t = \text{Net cashflow at time t}$

$i = discount\ rate$

$\text{t} = \text{time of cashflow}$

To create a clear comparison between the inclusion of ES, this report will consider the direct and indirect costs and benefits related to dike construction. First the direct costs will be expressed in a monetary value based on literature.

To compare costs of impact categories, a form of weighting can be used. Two ways of calculating the environmental costs will be investigated.

An IDEMAT database can be used to calculate monetary environmental impact based on material quantities. This approach is used in construction to give an indication on the total environmental costs during the procurement process of large construction projects.

Because the approach using IDEMAT data does not consider any ES, an additional calculation will be made based on the impact categories from Earthster and their monetary values, and the inclusion of ES and the monetary benefit they provide.

The indirect costs and benefits will result in the so-called Environmental Cost Indicator (ECI). A value that then can be used to compare the alternatives.

Important to note is that although this weighting decreases the confidence of the research, it increases the meaning of the results for the target group. As monetary values are often requested in decision making, a monetary interpretation is made in the research.

4.3.2.1. Direct Costs/Benefits

Based on literature costs of construction and maintenance have been determined. These values are normalised to costs per 'running meter' so that the alternative dike designs can be compared. The direct cost and benefits are shown in Table 9.

Table 9: Direct costs and benefits of (living) dike construction

Direct cost	Time [year]	Amount [€]	Source
Construction [/m/m heightened]	0	2000	(Aerts, 2018)
Construction local soil [/m/m heightened]	0	2600	(Aerts, 2018) +30% soil
Construction salt marsh [/ha]	0	151129	Bayraktarov ESaunders MAbdullah S et al. (Table 1)
Maintenance & operation dike [/m/year]	[1-50]	150	(Jonkman et al., 2013)
Maintenance & operation salt marsh [/m/year]	[1-50]	150	(Teunis & Didderen, 2018)

4.4. Interpretation of LCI and LCIA

The direct costs are only the costs of reinforcing and maintaining the dike during its lifetime of 50 years. The environmental impact and benefits obtained from ES should also be included. These two aspects are considered indirect costs and benefits.

The indirect cost and benefits are calculated in two ways to make sure no values are double accounted for. One approach is using the IDEMAT data and multiplying these environmental costs with the quantities of material taken from the LCI for every alternative. Every cost is given as a positive value, while benefits are given as a negative value. This approach considers benefits as a discount to the costs of every alternative.

A second approach is to also include ES into the cost/benefit assessment of the dike design alternative. This is what eventually gives insight of the value of these services for the dike design alternatives. When direct and indirect costs are calculated, these can be used for the eco-efficiency analysis.

In this research both approaches are compared, so that the inclusion of ES into the LCA can be quantified. This method is chosen to not only see what the value is of ES, but also to compare this more thorough analysis to a standardized environmental cost indicator.

4.4.1. IDEMAT 2023

IDEMAT, short for 'Industrial Design & Engineering MATerials' database, is a compilation of LCI data from an non-profit spinoff of the University of Delft. Their data allows comparisons to be made between different materials and considers a scope 3 data; which means all indirect emissions that occur in the value chain of the reporting company. This is standardized dataset based on 472 peer reviewed papers (Sustainability impact metrics, 2024). The IDEMAT database also provides a monetary interpretation based on the direct and indirect emissions of the material in question.

The environmental costs per cubic meter of material according to the IDEMAT database are given in Table 10 (next page). Because the local obtained material is no standardized material, estimations are made based on comparable aspects. Low quality sludge used for the salt marsh is considered waste material and therefore has little environmental impact. High quality sludge however, has a production process of similar intensity as regular clay, and is therefore considered as such. The values from IDEMAT have machinery use included.

Table 10: Environmental costs IDEMAT data

Material	Cost [€/m^3]	Source
Clay	3.83	IDEMAT 2023
Sand	4.33	IDEMAT 2023
Revetment	7.58	IDEMAT 2023
High quality clay	3.83	-
Low quality Sludge	0	-

These costs multiplied with the material quantities from the earlier established LCI.

4.4.2. Interpretation of LCIA

A second approach is using the impact categories from the Earthster model and other ES such as carbon sequestration and recreation. These values are given in Cost per respective unit and will be multiplied with the output values from Earthster. The costs and benefits are taken from literature and shown in Table 11.

Table 11: Environmental costs and benefits of (living) dike construction

Indirect costs / Benefits	Unit	Cost/Unit [€]	Source
Carbon Sequestration	TCO2/year	-15	(Gailis et al., 2021), (The Economist, 2022)
Global warming	kg Carbon Dioxide (CO_2) equivalents	0.06 0.07	2019 (Gerlagh et al., 2022) 2024 (Trading Economics, 2024)
Terrestrial eutrophication	Mol Nitrogen (N) equivalents Kg N equivalents	0.14 5	(Jacobsen et al., 2011)
Marine Eutrophication	kg (N) equivalents	12.5	(Jacobsen et al., 2011)
Damage to Human health	DALY	100.000	(Torfs & Bossuyt, 2006)
Resource depletion	USD (2013)	-	(Direct value given from Earthster)
Hiking-recreation	€ / running meter/year	-2.4	(CBS, 2021)

The values above are taken from literature as these values have been researched in other papers and reports. Hiking recreation however is very location dependent and not yet quantified in other research. To take this benefit into account in the comparison, the value for hiking recreation was extrapolated from CBS data.

This value for 'Hiking recreation' was obtained by dividing the total amount of hiking recreation income in the Netherlands (€$1.16*10^9$) and normalising this value for number of hectares of wet nature area's.

This value is then multiplied by the area of salt marsh that is created or preserved per alternative. This approach leads to a value of €2400 / hectare / year, or €2.4 per running meter dike per year. This value seems low and counter intuitive based on the positive sentiment in other literature such as the report of Millenium ES Assessment. However, based on the accessible data and total recreation revenue, a benefit of €2.4/running/year meter seems a realistic value.

Biodiversity remains hard to quantify. Although there is research on this subject, these values are often on a willingness to pay and are quantified on a more macro level (De Bruyn et al., 2018). As the impact on biodiversity is calculated based on result of other impact categories, it is assumed that the valuation of other impact categories will also count up to some biodiversity loss.

Costs of

4.5. Eco Efficiency Analysis

In this chapter, the direct and indirect costs are compared to get a full understanding of the alternative methods for dike construction. This will first be done for the 50 years design period, after which the data will be interpreted for a longer time span.

4.5.1. Comparing calculated direct and indirect costs and benefits

By comparing and combining the direct and indirect costs, insight is created in the ratio of these costs. Also a comparison can be made between the current view on environmental costs, and the effect of including Eco system services on top of that. The values that will be compared are; direct costs, direct costs with environmental costs from IDEMAT 2023, and the direct costs with a weighted impact from the LCIA. All monetary values are all expressed in Euro per running meter dike for every alternative and can therefore be.

This data will be interpreted by comparing the ratio of direct and indirect costs, and opportunities of specific ES that have significant impact on the total costs of a specific alternative.

4.5.2. Longer timespan and other locations

The eco-efficiency analysis results in a net present value of the Living dike and conventional alternatives. An eco-efficiency analysis is set up in such a manner, that it is also possible to see which aspects of a design are costly, and which provide a lot of value.

Preliminary results of RQ1 and RQ2 show that the salt marsh characteristics could be of great influence. The salt marsh length, the bed level (and thus how much it should be elevated to establish a salt marsh) have significant impact on the costs of the living dike alternative. However, going deeper into these variables is outside of the scope of this research.

Based on findings of RQ2, it is possible to make predictions on the effect over a longer time period. This is important, as the present situation at Schiermonnikoog is almost a perfect situation for a salt marsh to establish. Though, even in this perfect situation, challenges might occur when considering longer time periods (e.g. 100 or 200 years), as there might occur a tipping point with salt marsh growth and SLR.

The sensitivity analysis shows a difference of 2 meters of hydraulic conditions, while the expected SLR for the next 50 years is only a fraction of this, 40 – 55 centimetres (KNMI, 2023). Therefore, the higher than expected scenario directly provides insight into the longer-term costs in scenarios where the SLR appears to be significantly higher (several meters).

To calculate this, a few adjustments are made to the abovementioned method. First, the annual expenses will be taken into account over a period of 200 years instead of 50. These costs aspects are; maintenance of the dike and the salt marsh, CO_2 sequestration and Hiking recreation. The impact caused by resource acquisition, transportation of materials, and construction will remain the same.

The results from this calculation will then be qualitatively interpreted for less ideal local circumstances. Additionally, the impact of required reinforcement when the dike capacity is reached will be discussed.

5. Results

To answer the main research question "How do the costs and benefits of conventional dikes and living dikes compare, and does the inclusion of ES change this outcome?", the two sub-questions are discussed in this chapter.

5.1. Results Research Question 1

SQ1: How do conventional dikes, and living dikes offer flood protection against wave overtopping, and how do their designs compare for equal hydraulic boundary conditions?

Based on equal hydraulic boundary conditions at the seaward edge of the salt marsh or the dike toe when there is no salt marsh, required dike dimensions were determined for the 4 alternative designs. First it is checked that a salt marsh can cope with SLR, after which the required dike and its corresponding dimensions are calculated. These calculations are based on the sensitivity of parameters and show a range of required materials that are used in the RQ2.

Although it is expected that the salt marsh at Schiermonnikoog should be able to grow with SLR according to existing research on the area of Schiermonnikoog (Svasek, 2023), the model by D'Alpaos et al (2011) requires maximum total accretion rate 'k' of 30mm/year in order to achieve an elevation of the salt marsh equal to a relative SLR of 10mm per year. This relative SLR requires a higher growth potential of the marsh than has been measured in previous years.

To improve trust in survival of the salt marsh, the above mentioned parameters were used to calculate the equilibrium elevation for the historical external forcing. This calculation gives an equilibrium height of 2m+NAP, similar to the marsh elevation that is found close to the harbour. Based on these values, it is assumed that the salt marsh maintain in that equilibrium. However, increased levels of SLR form an enormous risk.

Based on the capability to keep up with a relatively high SLR scenario of 10mm/year according to the D'Alpaos model with historical parameters, and the results from the Svasek report that mention that the marsh is able to survive a relative SLR of 12mm/year if maintained properly (Svasek, 2023), this report assumes that the salt marsh will not drown in the low, expected and high scenario. For the constructed salt marsh in alternatives 1, 2 and 4 maintenance is accounted for in the calculations to make sure this condition is considered.

Based on the values from literature and the assumption a salt marsh will remain stable in the future a predicted dike height is calculated for a coast with and without salt marsh. These values are shown in Table 12.

Table 12: Required dike height with- and without inclusion of salt marsh

Dike height	**m**
without salt marsh	8.6
with salt marsh	6.34

As there is uncertainty in these values a sensitivity analysis is performed. With a range of possible parameter values, the following dike heights are calculated.

Based on the parameter ranges mentioned in sensitivity analysis, the required dike height varies between 7.19 and 10 meters. 8.6 meters corresponds to the expected values according to literature. With the wave reduction applied, a required dike height of 6.34 meters corresponds to the expected values. Adding the 20% uncertainty range, these values vary between 5.38 meters and 7.3 meters. These values and the impact of parameter ranges are shown in Figure 23, and Figure 24.

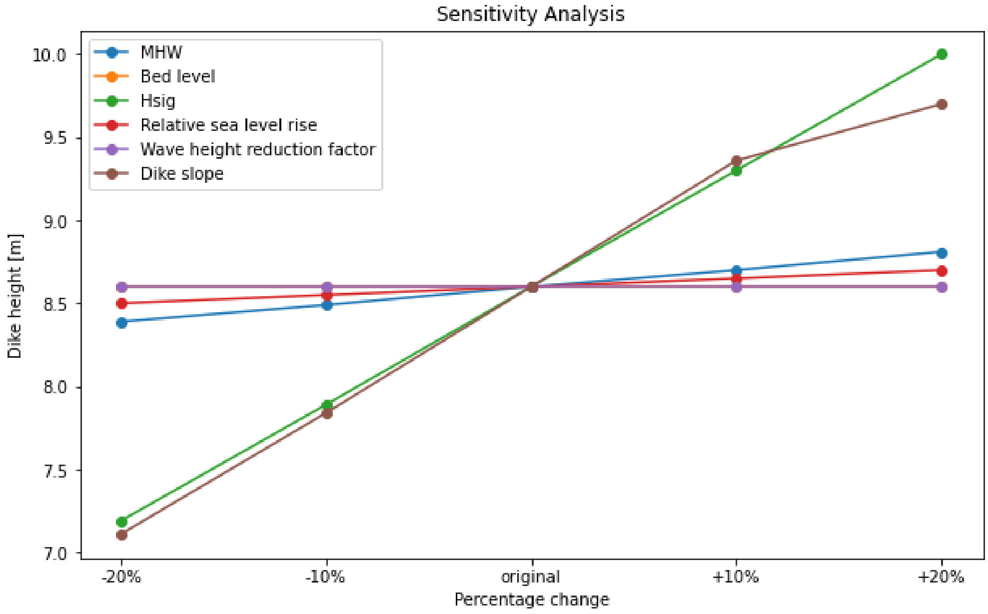

Figure 23: Sensitivity analysis of required dike height without salt marsh

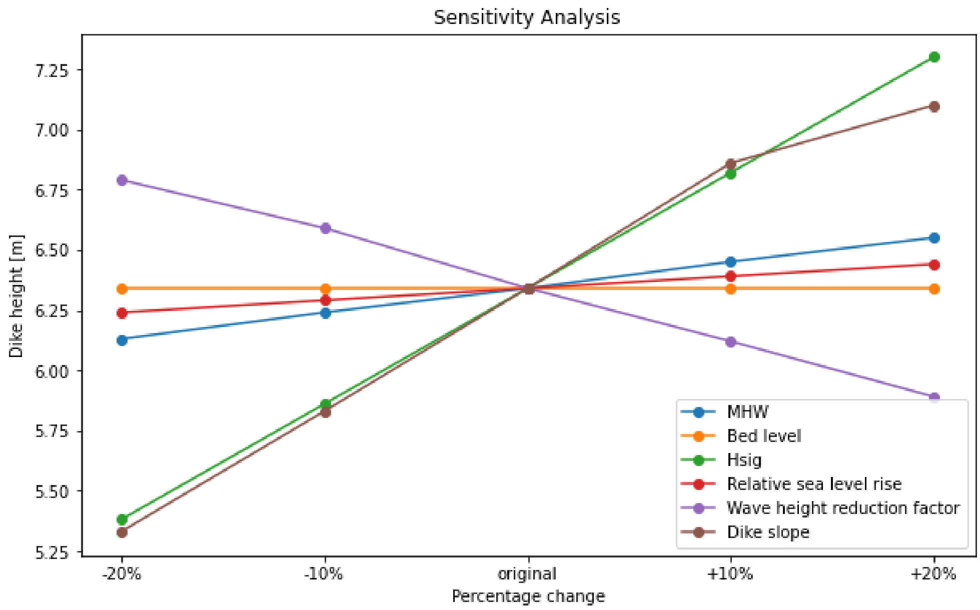

Figure 24: Sensitivity analysis of required dike height with salt marsh

From these graphs it becomes clear that mean high water and significant wave height have the biggest impact on the required dike height. Also most relations seem to have an (almost) linear relation to the dike height. This relation makes it convenient to extrapolate the results.

5.1.1. Required construction materials

Based on the sensitivity analysis, a range of dike heights is calculated per alternative. All construction materials required for these dike heights for every alternative are shown in Table 13 to Table 16 . These values consider an existing dike height of 6.5m. For dike heights below 6.5 meters, no construction materials are required for the reinforcement.

Table 13 shows that no materials are required in a low and expected scenario for alternative 1. Only when forcing parameters turn out higher than expected (i.e. dike height = 7.3m), reinforcement is required. The required materials for that reinforcement can be found in the right-most column.

Table 13: Required materials per meter dike for alternative 1) Conventional with salt marsh

Material	Dike height = 5.38	Dike height = 6.34m	Dike height = 7.3m
Sand [m^3]	0	0	32.3
Clay [m^3]	0	0	4.8
Rock Revetment [m^3]	0	0	0.2

As there is no salt marsh present in the alternative 2, the required dike height is around 2-3 meters higher. This results in significantly more required materials. Especially in the expected and lower than expected scenario, this can be noticed. As for alternative 1 there are no materials required. The required materials for this alternative are shown in Table 14.

Table 14: Required materials per meter dike for alternative 2) Conventional dike no salt marsh

Material	Dike height = 7.19m	Dike height = 8.6m	Dike height = 10m
Sand [m^3]	27.6	93.1	169.75
Clay [m^3]	4.14	12.6	21
Rock Revetment [m^3]	0	0.4	0.7

Alternative 3 shows an increase of ca. 30% in required materials, as was determined in the methodology. This increase is a direct result of the lower quality of the materials compared to clay that is normally used. The required materials for this alternative are given in Table 15.

Table 15: Required materials per meter dike for alternative 3) Conventional dike local materials

Material	Dike height = 7.19m	Dike height = 8.6m	Dike height = 10m
Sludge (high quality) [m^3]	41.26	137.41	247.97

Table 16 shows the materials for alternative 4. For all scenario's an equal amount of low quality sludge is required. This can be explained by the fact that in all three scenario's there are equal starting conditions, therefore the construction of the salt marsh is the exact same.

Table 16: Required materials per meter dike for alternative 4) Living dike Create salt marsh

Material	Dike height = 5.38m	Dike height = 6.34m	Dike height = 7.3m
Sludge (high Quality) [m^3]	0	0	48.23
Sludge (low quality) [m^3]	114.3	114.3	114.3

When comparing these tables, it can be concluded that the amount of materials required for dike construction is significantly higher when there is no salt marsh present. It can also be noted that the required amount of materials to create a salt marsh is of equal magnitude as the dike construction itself.

5.2. Results Research question 2

"What is the economic- and environmental impact of conventional dikes and living dikes with ES included?"

The LCA results, and its effects over time are discussed in the next chapters. First the life cycle inventory is established to create an overview of the processes related to the construction and maintenance of the dike as well. The impact of those processes on the environment is then quantified by the LCIA. An

ECI is then calculated with the use of an LCC combined with IDEMAT data, and secondly by adding the weighted impact of the LCIA to the direct costs.

In paragraph 5.2.4. the results of the eco efficiency analysis are discussed, after which an assessment for longer time periods is considered. These results provide an answer to the second research question.

5.2.1. Life Cycle Inventory

In this chapter, the results derived from the Life Cycle Inventory (LCI) analysis conducted for dike construction are set out. The LCI analysis has been executed for the four alternative construction methods, each evaluated for the three scenarios originating from the sensitivity analysis: low, expected, and high. These results offer insights into the required materials of the different dike construction approaches.

As the information provided in this chapter is quite comprehensive, an overview of information is given:

5.2.1.1. Summary and Interpretation:

In summary, the LCI analysis reveals significant ranges in the required materials with different dike construction methods under varying SLR scenarios. These values forebode the outcomes of the LCA as the impact of these materials will be equally interpreted from an environmental impact perspective.

5.2.2. Life Cycle Impact Assessment

With the material quantities as determined in the LCI, an LCIA has been performed. These results can be summarized as follows.

There is considerable overlap between the different environmental impact categories, which suggests that improvements in one area could extrapolate to others. For example, strategies that reduce carbon emissions often also decrease other forms of environmental impact, such as eutrophication and resource depletion. This overlap indicates that holistic environmental strategies could be particularly effective.

Given the general awareness and knowledge of carbon-related impacts compared to other categories, the analysis initially focuses on carbon sequestration and emissions. Sources on carbon emissions are well-established, making them an accurate benchmark of environmental performance. The results in this category give a clear insight into the comparative advantages of living dikes, especially for carbon capture due to the presence of salt marsh vegetation.

Besides carbon, also other impact categories such as biodiversity, eutrophication and human health, are assessed. Although these categories show similar trends to the carbon analysis, they are more complex to quantify. These results, however, show that Nature-based solutions like living dikes often have more environmental benefits than just carbon sequestration.

5.2.2.1. Carbon dioxide equivalents

In the pursuit of sustainable dike design, the carbon footprint is a well-known factor. Figure 25 illustrates the CO_2 emissions across different phases for the four dike construction alternatives. Each alternative is assessed for the three different scenarios —low, expected, and high— corresponding to the required protection levels from the sensitivity analysis.

The CO_2 emissions are segmented into three categories: production, distribution, and use. Production emissions account for the raw materials and construction processes, distribution emissions encompass transportation of materials, and use emissions are derived from the dike's operational phase, including maintenance activities and carbon capturing for scenario's where a salt marsh is present.

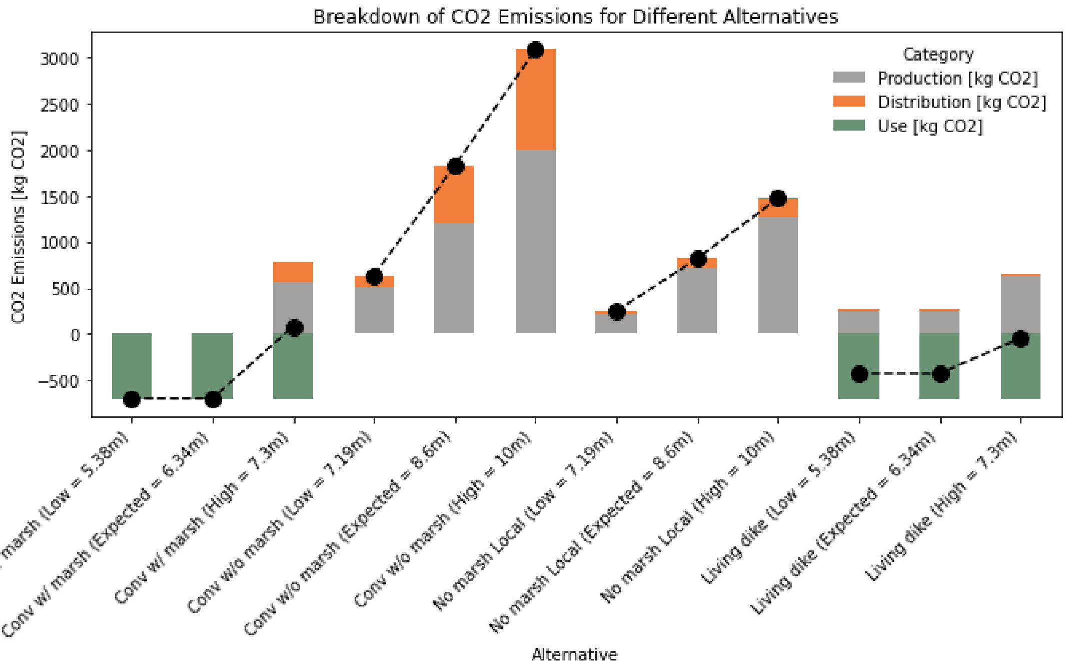

Figure 25: Breakdown of CO2 emissions over the lifetime of each alternative

Figure 25 provides multiple insights. Alternative 1 shows the lowest carbon footprint for all scenarios. The natural wave-dampening effect of salt marshes reduces the amount of required materials and lowers the 'production' and 'use' emissions. The naturally present salt marsh captures 700kg of CO_2, resulting in negative emissions for the low and expected scenario.

In Alternative 2 the absence of a salt marsh leads to an increased amount of materials and construction, resulting in higher production and distribution emissions. This alternative is as expected the alternative with most emissions.

Alternative 3's use of local materials reduces distribution emissions significantly, showing the benefits of local resource use in reducing the dike's carbon footprint. Although more material is required for this alternative, locally ripening clay is less intensive than conventional dredging and excavating of materials.

Alternative 4's long-term use emissions are remarkably lower than alternative 2 and 3. While having higher initial production emissions due to the construction of an artificial salt marsh, this is mostly compensated by the CO_2 sequestration of living dikes in the operational phase. Especially because the existing situation for alternative 2, 3 and 4 are equal, this an insightful comparison.

The results in Figure 25 indicate that the integration of carbon capturing capabilities of a salt marsh, as seen in Alternatives 1 and 4, can lead to a significant reduction in the long-term carbon footprint of dike systems.

5.2.2.1.1. Carbon footprint as a timeline

Based on Figure 25, one would suggest that the construction of a salt marsh would always result in lower carbon emissions. However, in higher than expected hydraulic conditions, additional effort for a functional flood defence might be required. This especially applies to a scenario where SLR exceeds the growing capacity of the salt marsh.

To get insight in the consequences of for example a failing salt marsh, special attention is paid the emission profiles over time, particularly in scenarios involving the use of salt marshes. This analysis is crucial in understanding the environmental impact of these alternatives under varying conditions. These results are depicted in Figure 26. The coloured line depicts the expected scenario, and the lighter coloured bandwidth shows the range from low to high scenario.

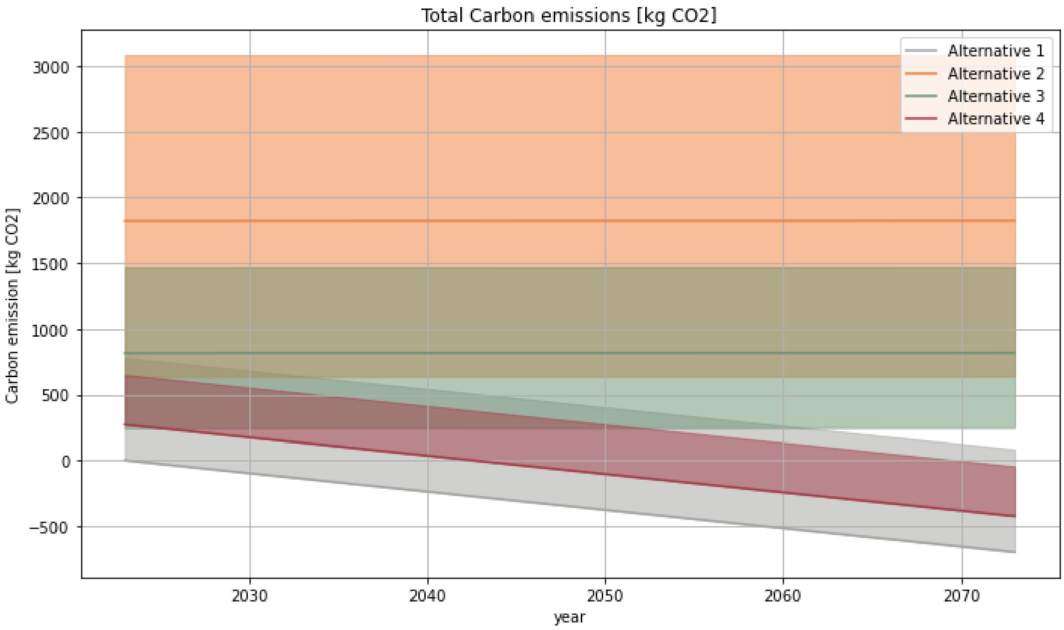

Figure 26: Net Carbon Emission per alternative (line) with a bandwidth for the low to high scenario

The analysis indicates that alternatives 1 and 4, both incorporating salt marshes, demonstrate a lower emission footprint right from the construction. This can be explained by the reduction of required dike height due to the salt marsh.

Alternative 4, which involves the construction of a salt marsh, is projected to achieve a net zero emission status by the year 2044. This is around 20 years after construction, of the typical lifespan of 50 years. This aspect proofs the long-term sustainability of incorporating natural ecosystems like salt marshes in large-scale construction projects.

The feasibility of constructing a salt marsh is dependent on the extent of SLR over the next 20 years. The projections indicate that as long as the SLR does not exceed the expected threshold of 50cm in 50 years, the construction of a salt marsh remains a viable and environmentally responsible choice.

If SLR exceeds the upper threshold after 20 years, this analysis shows that there would be no additional emissions to the construction of the salt marsh compared to constructing a conventional dike. When SLR is lower than the threshold, it will realise the potential environmental efficacy of the decision to construct a salt marsh as a sustainable choice.

To fully understand of the carbon sequestration potential of drowned salt marshes, a comprehensive review of existing literature on CO_2 capture in such ecosystems is needed. This will provide valuable insights into the long-term environmental benefits of salt marshes, even when they cannot keep up with SLR.

5.2.2.2. *Other impact categories*

A comprehensive environmental impact assessment of the dike construction alternatives has been conducted, considering a range of impact categories beyond carbon emissions. These categories include total water use, eutrophication, resource depletion, ecosystem damage, and effects on human health.

In the following paragraphs these impact categories are shown for the different alternatives, after which the results will be summarized.

5.2.2.2.1. Water Use

Figure 27 shows the total water use for each dike construction alternative under varying scenarios of low, mid, and high projections for SLR. The figure shows significant differences in water consumption between the alternatives.

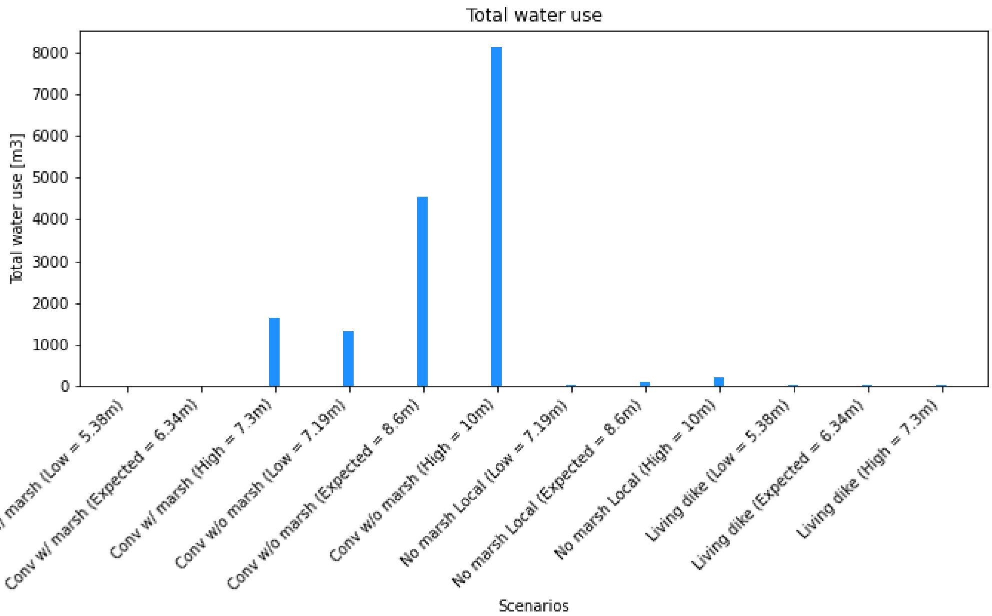

Figure 27: Total water use

Especially the expected and higher than expected scenarios for alternative 2 show substantial increase in water use.

5.2.2.2.2. Eutrophication

Figure 28 and Figure 29 show the eutrophication potential for the various dike construction alternatives. Eutrophication is the potential for nutrient enrichment in marine waters, which could lead to algal blooms and its effects on water quality and marine life. Terrestrial eutrophication can lead to certain species of flora to dominate, resulting in lower variety of plants and grasses.

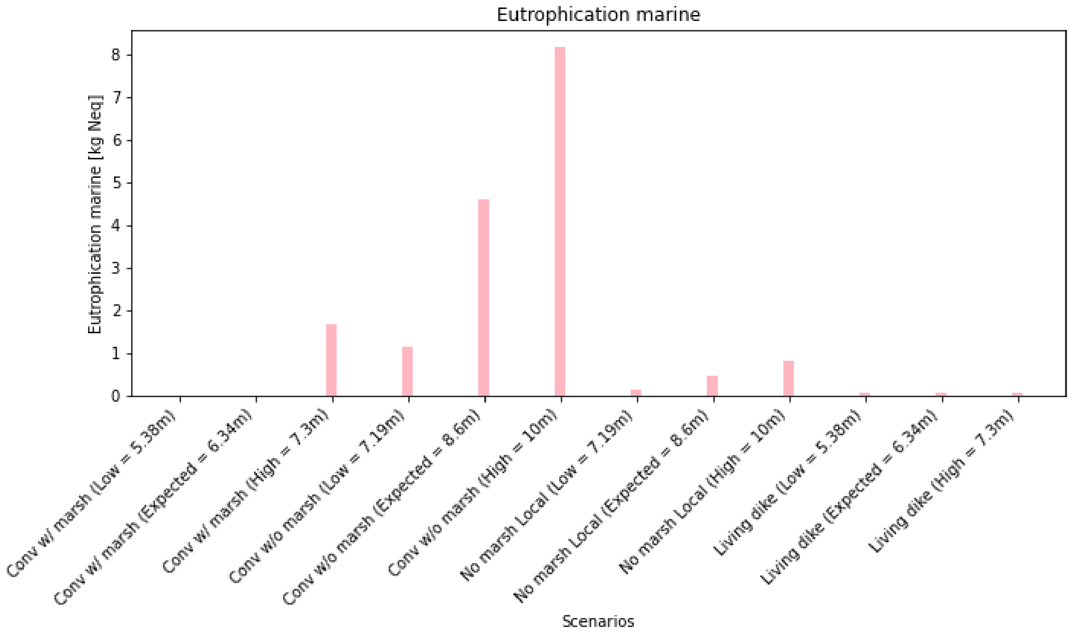

Figure 28: Eutrophication marine

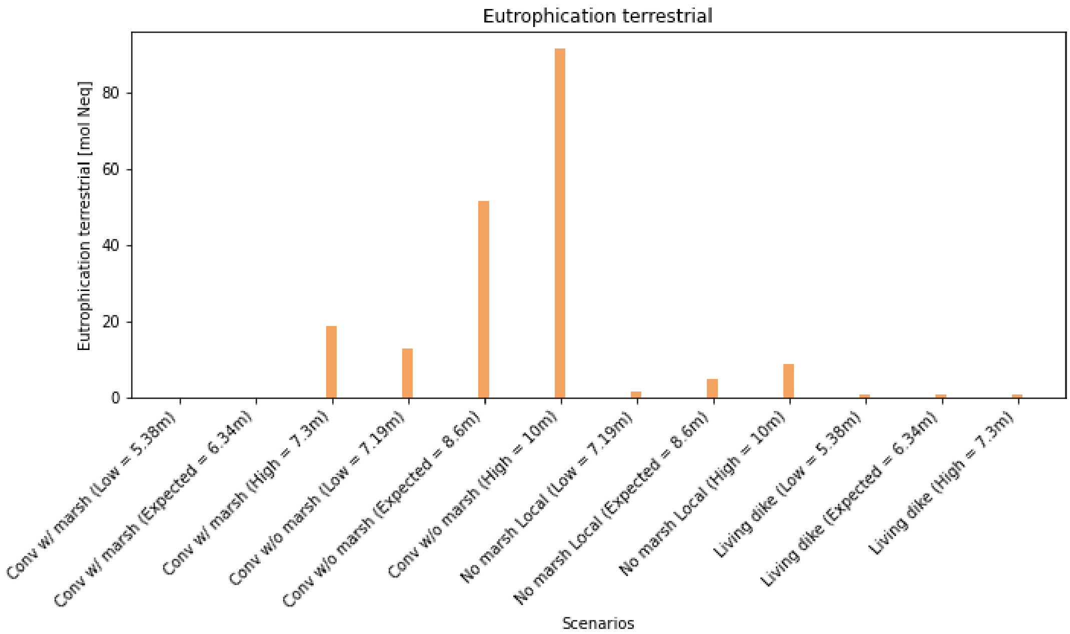

Figure 29: Eutrophication terrestrial

The data shows a peak in eutrophication potential for Alternative 2, suggesting a significant environmental impact associated with this construction method. The differences in eutrophication are an direct result of material use.

5.2.2.2.3. Resource depletion

Figure 30 shows the impact of various dike construction alternatives on resource availability, quantified in terms of total damage to resource availability (measured in USD2013). Resource depletion is an important metric in the assessment of environmental sustainability, as it expresses how much natural resources are consumed for construction. This metric also directly relates to the amount of materials used.

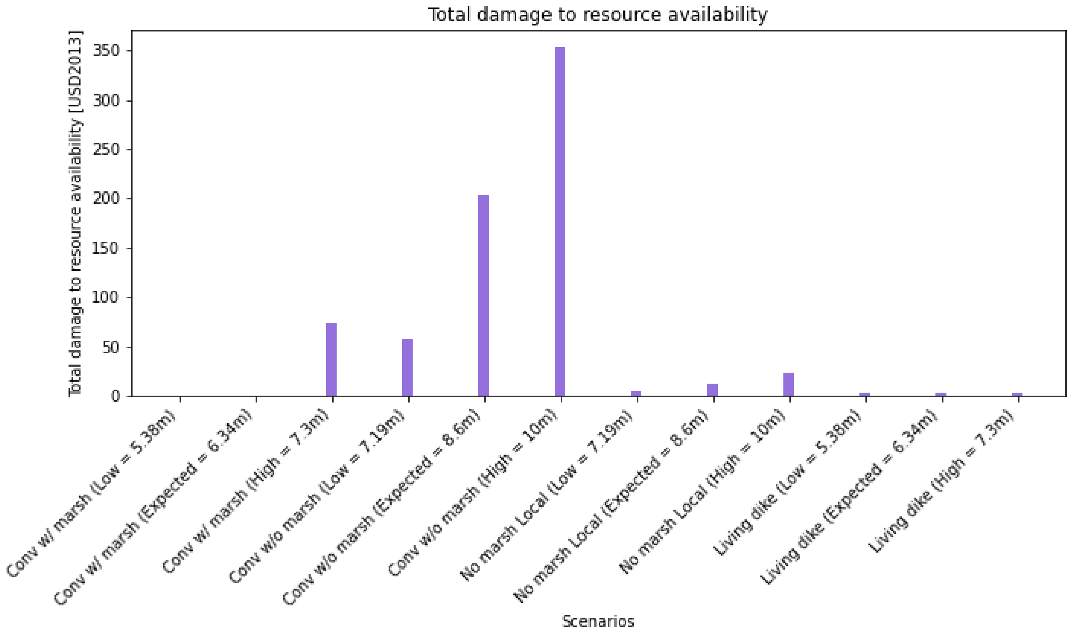

Figure 30: Total damage to resource availability

5.2.2.2.4. Ecosystem damage

Figure 31 shows the impact on ecosystems per construction alternative. This impact category expressed as species·year, a unit that reflects the number of species going extinct each year as a consequence of the construction activities. This metric quantifies the potential long-term biodiversity loss.

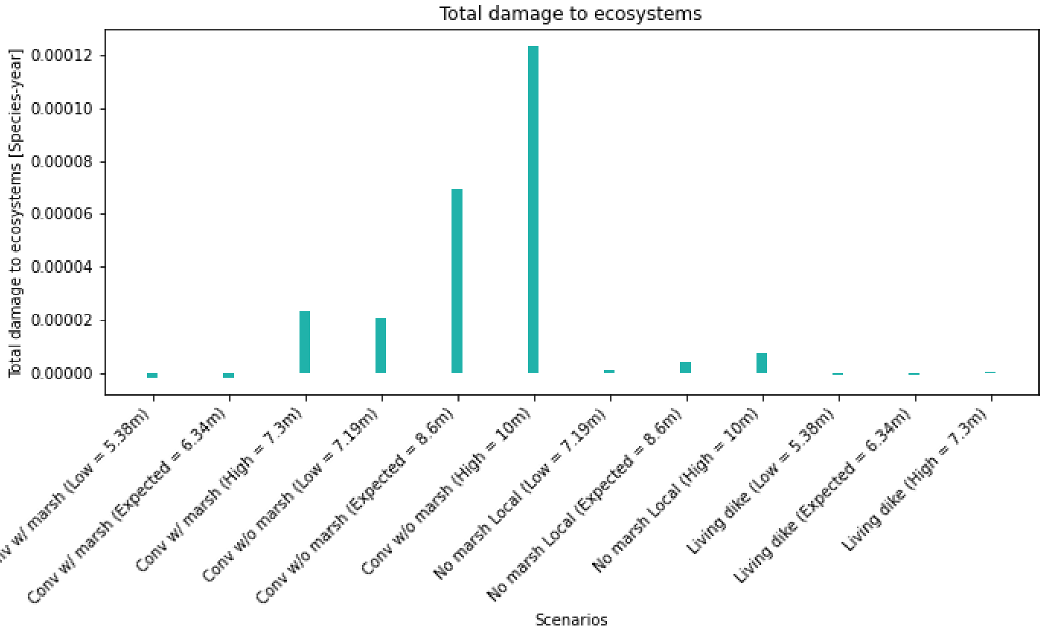

Figure 31: Total damage to ecosystems

The analysis shows that especially Alternative 2, has a significant negative effect on ecosystems. Again, this is a direct result from the amount of materials used.

An interesting finding from this result is that for alternatives 1 and 4, which involve the integration of salt marshes, a negative damage is shown in the expected and lower than expected scenario. This finding suggests that these construction approaches, add biodiversity. Based on this result, living dikes contribute to ecological preservation over the lifespan of the dikes.

5.2.2.3. Human health

Figure 32 shows the total damage to human health associated with each dike construction alternative, quantified in Disability Adjusted Life Years (DALYs). This measure accounts for the loss of healthy life years due to both morbidity and mortality linked to the construction and operational phases of dike systems.

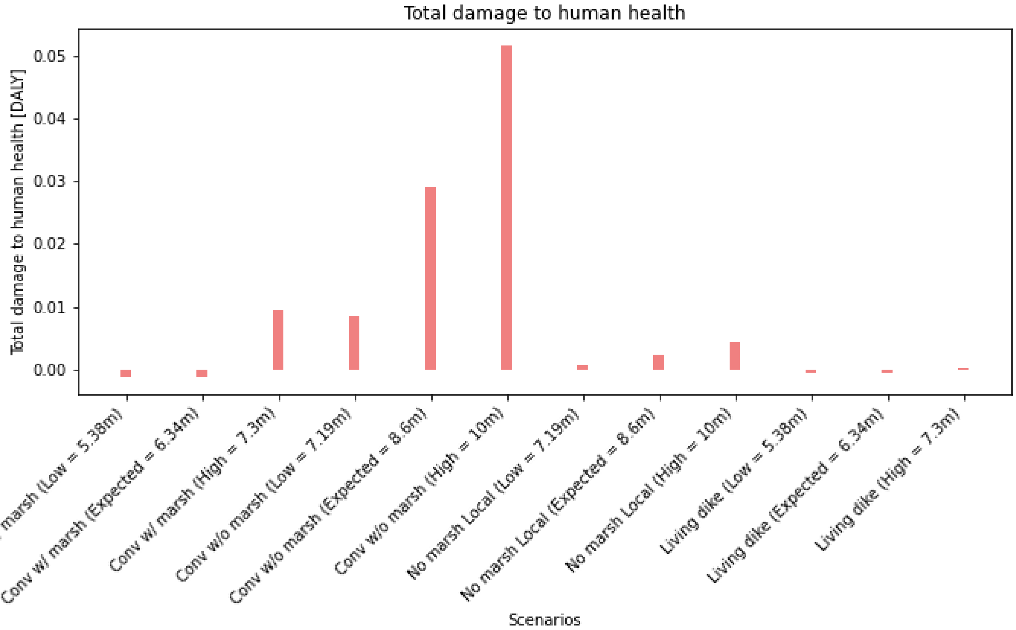

Figure 32: Total damage to human health

The graph presents a high DALY value for Alternative 2, indicating a significant negative effect on human health compared to other alternatives. Similar to the other impact categories, this is a direct result from the amount of materials used.

Additionally, this impact category shows negative results for alternatives 1 and 4. The negative value suggests that these alternatives potentially contribute to better health and healthier ecosystems that benefit society as a whole.

5.2.2.4. General results

The analysis, as illustrated in the above figures Figure 27 to Figure 32show the impacts across these categories for each of the four construction alternatives under low, expected, and high hydraulic boundary conditions.

The impact categories water use, eutrophication, and resource depletion, the impact is directly linked to the choice of construction materials and their required quantities. The solutions that use dredged sludge as construction material score significantly better than using conventional sources.

A very interesting finding is that in the categories human health and ecosystem damage, negative results are observed for alternatives 1 and 4. This shows the potential positive effects on biodiversity and human health specifically linked to the salt marsh that are present. This result backs the theory of Nature-based solutions providing additional benefits.

The figures serve as a highlight the importance of a sustainable approach that benefits multiple environmental and health-related impact categories.

5.2.3. Life Cycle Costing (LCC) of direct costs

Based on the values in Table 11, the net present value of each alternative is calculated. The following Table 17 shows the net present value of the four alternatives. The initial investment and maintenance of dike and salt marsh are considered in this calculation.

Table 17: Net present value of the three alternatives based on direct costs

Alternative	Direct cost [€/per running meter]		
	Low scenario	**Mid scenario**	**High scenario**
Alternative 1	12395	12395	13995
Alternative 2	6380	9200	12000
Alternative 3	6794	10460	14100
Alternative 4	13906	13906	15956

Figure 33 shows these Net Present Values of the dikes and their cost build up.

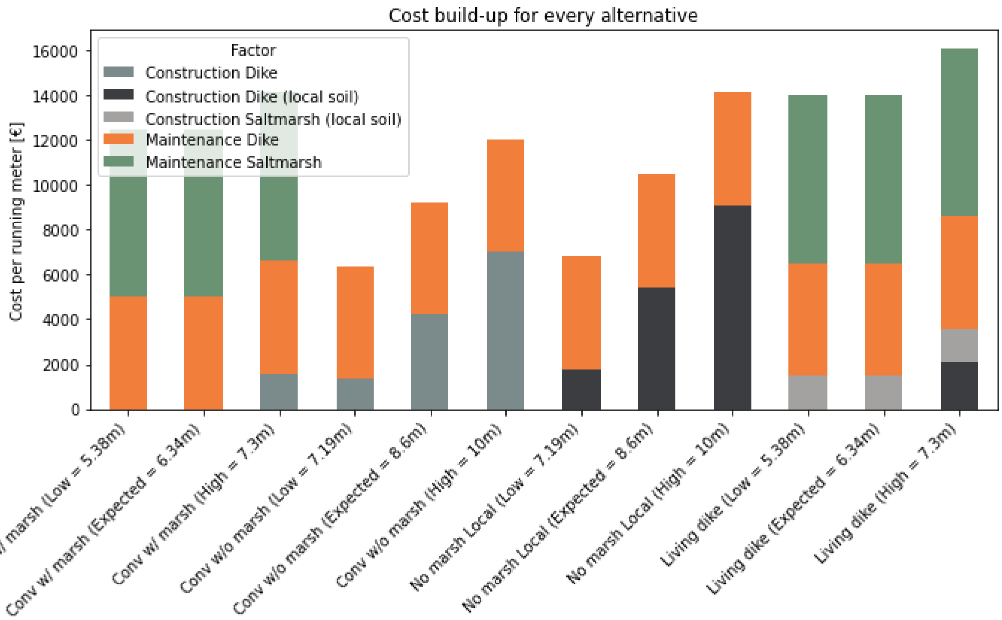

Figure 33: Cost build-up of every alternative

Alternative 1 shows relative consistent costs, at €12,395 per running meter for the lower scenario, and €13,995 for the high scenario. This makes Alternative 1 financially predictable. This alternative, however, is dependent on the presence of a salt marsh, therefore it's not universally applicable in all locations, limiting its practical implementation.

Alternative 2 shows the lowest direct costs at €6,380 per running meter for the lower scenario to €12,000 in the high scenario. This alternative is interesting due to its low direct costs compared to others. However, the increase in construction costs in the expected and high scenarios suggests that higher long-term costs can be expected with repeated reinforcement. Alternative 3 has 20% higher costs compared to alternative 2 due to the larger quantities of construction materials, the general impression is however very similar to that of alternative 2.

Alternative 4 presents the highest direct costs across all scenarios, with €13,906 per running meter in both the low and mid scenarios, and increasing to €15,956 in the high scenario. Similar to alternative 1 this alternative is stable, but mostly due to the relative large part of maintenance costs.

Based on only construction costs, the construction of a dike is very appealing. Alternatives 2 and 3 offer higher initial costs but become expensive over time. Alternative 1, while stable, is limited by its dependency on local circumstances such as the presence of a salt marsh.

From these results it can be concluded that most of the costs of constructing a living dike originate from maintaining the salt marsh, not from construction itself.

5.2.4. Interpretation LCIA

In this section the interpretation of the LCIA results are shown. Weighing the environmental costs gives a better understanding of the total costs and benefits.

These results are all based on European (Swiss and Dutch) data from 2020 to 2024, as is in line with the scope definition as determined in chapter 4.3.1.1: Goal and scope definition. Also the system boundaries were respected. Therefore it is assumed the LCIA conducted in this research is complete and consistent.

First, the IDEMAT 2023 interpretation is given, after which the weighted impact of ES is shown.

5.2.4.1. IDEMAT 2023

The IDEMAT 2023 data indicates significant variations in environmental costs between the four flood defence alternatives, particularly in the high scenario. The results are shown in in Table 18 and Figure 34.

Table 18: Environmental cost based on IDEMAT data

Alternative	**IDEMAT cost and benfit [€/per running meter]**		
	Low scenario	**Mid scenario**	**High scenario**
Alternative 1	0.00	0.00	159.76
Alternative 2	135.36	454.41	820.75
Alternative 3	158.03	526.28	949.73
Alternative 4	0.00	0.00	184.72

Alternative 1 has no additional environmental costs in low and mid scenarios as result that there are no materials required. This price rises to €159.76 per running meter in the high scenario, indicating a relatively low impact under extreme conditions.

Alternative 2 shows moderate environmental costs of €135.36 per running meter in the low scenario, increasing to €454.41 in the expected scenario and €820.75 in the high scenario, as result from the higher material usage. Alternative 3 is 30% more expensive, due to the direct link of materials.

Alternative 4 also incurs no environmental costs in low and mid scenarios, with a modest increase to €184.72 per running meter in the high scenario, indicating a relatively low impact compared to Alternatives 2 and 3. This is because a large portion of the required material is low quality sludge with no environmental impact.

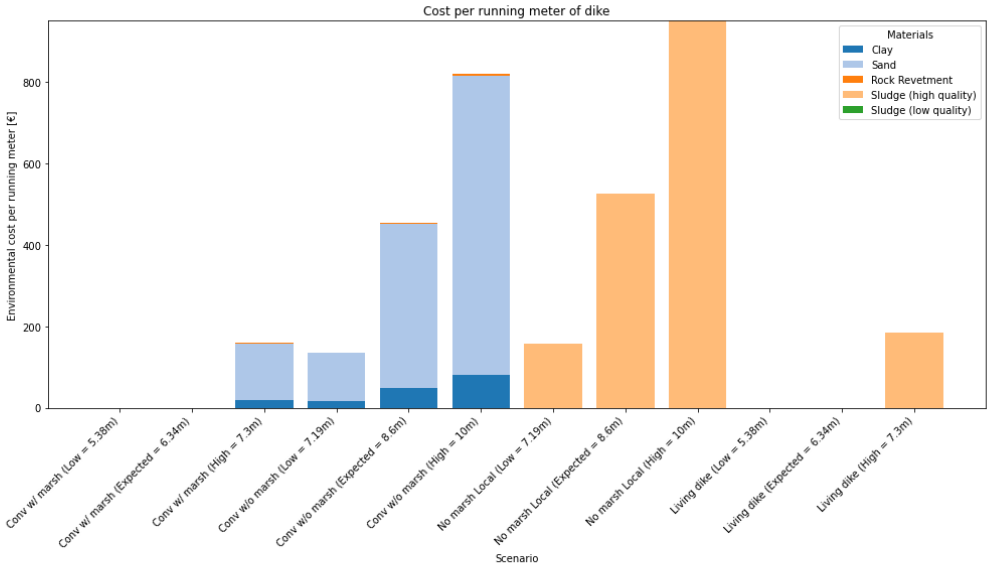

Figure 34: Environmental cost per running meter of dike

This interpretation of the environmental cost shows relative advantages and disadvantages of each alternative. Alternative 1 and 4 score best due to their low quantities of required material. No benefits of can be derived from the usage of locally used materials.

5.2.4.2. Interpretation of LCIA

The LCIA results provide a more complete view of the environmental costs and benefits for each flood defence alternative. The following table summarizes the results.

Table 19: Interpretation of LCIA with inclusion of ES

Alternative	**Impact categorie cost and benfit [€/per running meter]**		
	Low scenario	**Mid scenario**	**High scenario**
Alternative 1	-281.08	-281.08	938.43
Alternative 2	974.16	3311.44	5849.36
Alternative 3	98.06	314.63	564.07
Alternative 4	-191.49	-191.49	-94.63

Figure 35 illustrates these impacts across different categories. Showing the relative costs of each impact category.

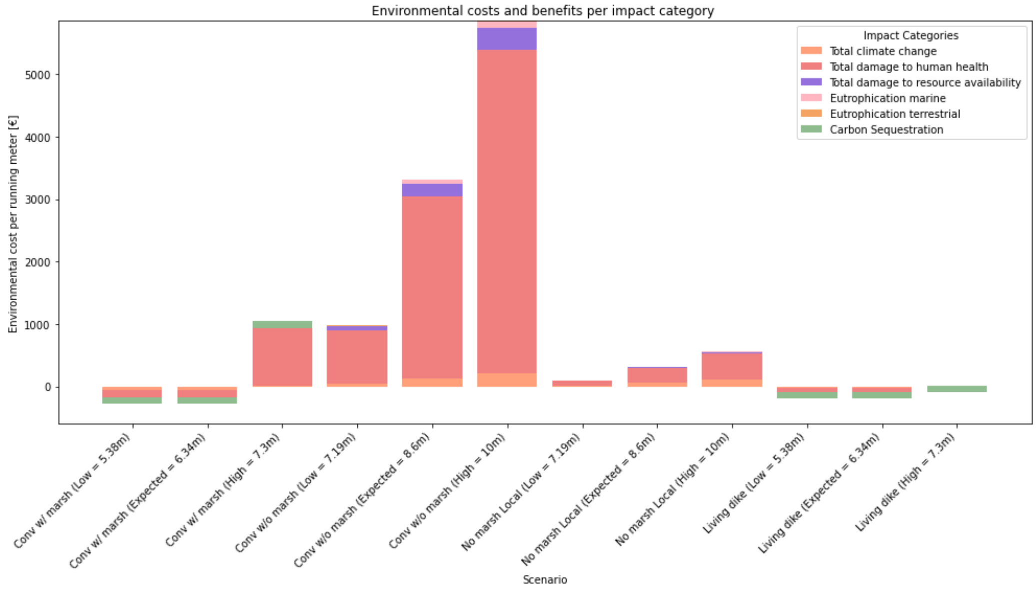

Figure 35: Environmental cost and benefits with ES included

The LCIA interpretation shows that Alternative 1 results in negative environmental costs of €-281.08 per running meter in both the low and mid scenarios, reflecting in nett benefits due to carbon sequestration and other ES. Alternative 4 has negative environmental costs for all scenarios.

When comparing these negative values to alternative 2 and 3, significant differences can be seen. While alternative 3 is much less impactful than Alternative 2, it still shows that its benefits do not weigh up to the environmental impact.

Overall, integrating natural elements such as marshes (in Alternatives 1 and 4) or using local materials (alternative 3) to dike construction provides significant environmental benefits, making them preferable flood defence solutions from an environmental perspective.

5.2.5. Eco Efficiency Analysis

The Eco Efficiency analysis, which includes direct costs, the IDEMAT interpretation, and LCIA interpretation, provides an insight in the financial and environmental implications for each flood defence alternative. Figure 36 shows costs and benefits for every alternative from lower to higher than expected hydraulic conditions.

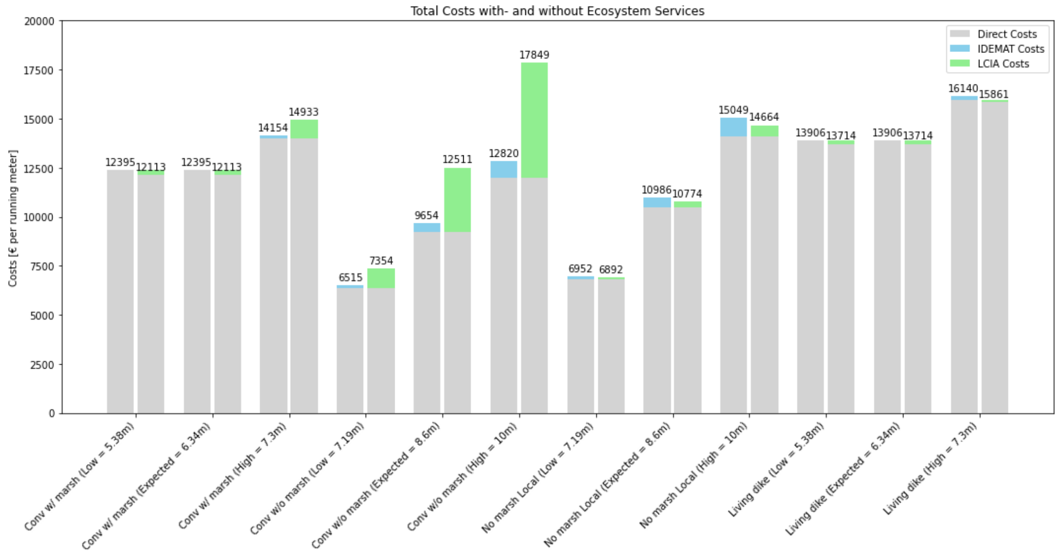

Figure 36: Eco-Efficiency expressed in total costs per running meter

Alternative 1 shows a relatively low increase in cost when hydraulic boundary conditions are higher. This is a result from the relatively low reinforcement requirements and large part of maintenance costs. When comparing the IDEMAT- and LCIA interpretation, it can be noticed that without ES a net cost is introduced to the reinforcement, while the inclusion of ES result in a net benefit on top of direct costs.

Although having relatively low direct costs, high environmental burden and resource usage makes the difference between alternative 2 and the other alternatives smaller. Despite being cost-effective in initial scenarios, its long-term sustainability is questionable.

When looking at alternative 3, reinforcement with local materials, it can be noticed that with ES included, alternative three has the lowest costs. Without ES, this alternative would not score best, as the direct costs are higher than for alternative 2.

The Living dike maintains relatively high total costs across all scenarios, with high direct costs and low to negative environmental costs. An interesting result is the outcome for higher than expected hydraulic conditions. When comparing the direct costs and environmental costs without ES, the alternative remains more expensive than conventional reinforcement. When including ES however, the total cost is lower.

Overall, the analysis highlights that conventional alternatives (2 and 3) become relatively more expensive in higher scenarios due to increased environmental costs. On the other hand, alternatives that integrate natural elements, such as Alternatives 1 and 4, show more stable costs, and overall low environmental costs. Particularly in. Based on these results it is important to consider both direct and environmental costs in flood defence planning to ensure long-term sustainability and cost-effectiveness. Including ES in the environmental costs does change the preferred alternative, especially for higher than expected hydraulic boundary conditions.

5.2.5.1. Longer timespan and other locations

As described in the methodology, the sensitivity analysis overlaps with extreme long time changes in SLR. Therefore, the higher than expected boundary conditions provide insight in the longer term costs and benefits. Due to the increased lifetime, a longer period of maintenance of both dike and salt marsh is necessary.

Figure 37 illustrates the direct costs, IDEMAT interpretation, and LCIA interpretation for a SLR scenario of 2 meters, with a design period of 200 years.

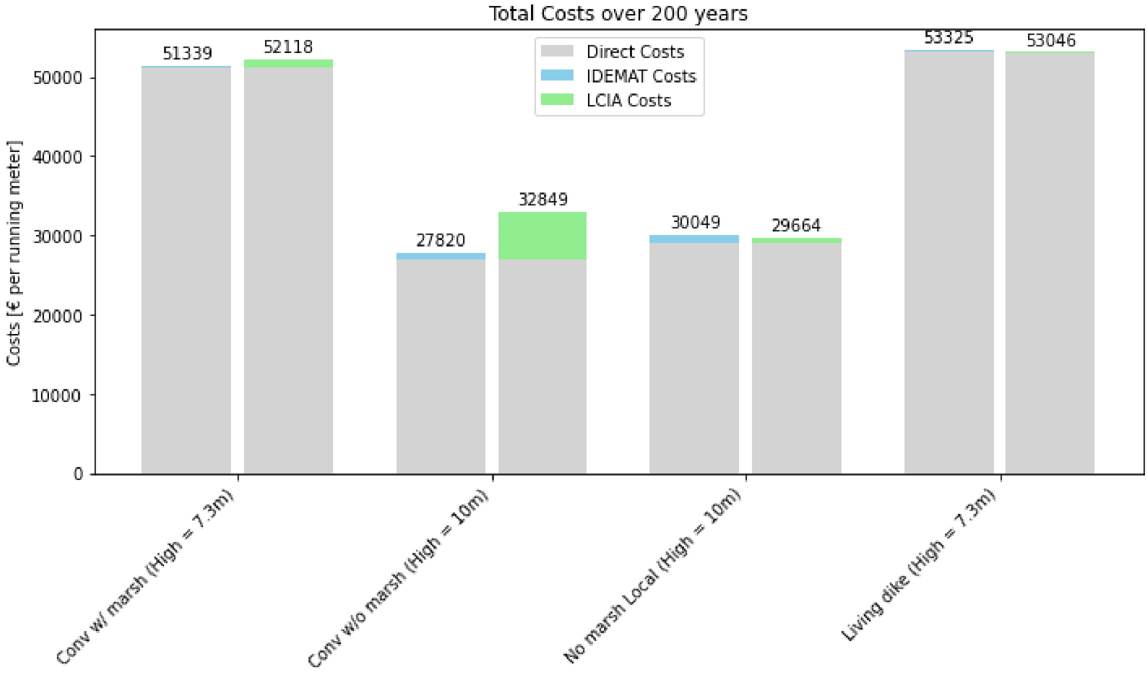

Figure 37: Total costs and benefits over 200 year timespan

The most important thing that can be assessed from this graph is the very high costs of alternatives where a salt marsh is part of the flood defence. This is a result from the 200 year period of time over which maintenance is required. While ES like CO_2 capturing benefits from Nature-based solutions are significant in the assessment over 50 years of time, they do not offset the maintenance costs of salt marshes.

In case a salt marsh would drown under these conditions, their direct costs and environmental costs would increase even further as the alternatives without salt marsh still would work as expected, while alternatives with salt marshes would require additional reinforcement.

When comparing alternative 2 and 3, the conventional alternative and an alternative with local materials. The conclusion of lower total cost for local materials still holds.

In case the salt marsh is still present and functioning after 200 years, all designs would require reinforcement as their capacity is reached. Based on these results, construction with local materials would result in the lowest total cost.

On other locations that do not provide ideal circumstances for salt marshes, the probability of drowning and/or erosion will be higher. On these locations the results skew even further towards alternative 2 or 3, with alternative 3 being the preferred option due to its lower environmental impact.

To summarize, alternatives without a salt marsh have lower total costs over a longer time period. Nature-based solutions, despite costs, offer greater sustainability and environmental benefits over time. Including ES in the calculation of total cost and benefits indicates that using local materials eventually will result in lower total costs than conventional construction materials. The inclusion of ES however, does not offset the higher direct costs that are a result from the high maintenance costs. Especially on locations that decrease the odds of survival of a salt marsh, reinforcement with local materials and exclusion of the salt marsh as part of the flood protection is favoured.

6. Discussion

The results of this thesis highlight several critical aspects of flood defence strategies, focussing on the differences between conventional dikes and living dikes, and the inclusion of ES in the valuation. The analysis unfortunately includes uncertainties, system design considerations, and potential benefits of Nature-based solutions. These aspects and their influence on the final results are discussed in the following paragraphs.

The study emphasizes various uncertainties in flood defence planning, such as external forcing factors, SLR, wave height at the dike toe, and wave height during storm surges. These uncertainties complicate the design of effective flood defences. Although a sensitivity analysis was applied to account for these uncertainties, a combination of multiple uncertainties was not accounted for. Although a combination of uncertainties could bring design requirements between alternatives closer to one another, it is more likely that the favourability of Living dikes becomes lower. A major aspect of this is the closely linked dynamics of the system, where one not optimal parameter can disturb a required equilibrium of a salt marsh.

Secondly, some simplifications in the dike design resulted in favouring the alternatives with a salt marsh. In this report the hydraulic boundary conditions are assumed to be similar near the dike toe, as near the seaward edge of the salt marsh. However, in reality it is more likely that the hydraulic conditions at the edge of the salt marsh are higher than near the dike toe due to being closer to open waters. This would decrease the effectivity of the wave dampening coefficient and thus increasing the reinforcement requirements of alternatives that incorporate a salt marsh in their design.

The quality and sustainability of construction materials also have some uncertainty, but this research only calculated with an average value based on literature. This uncertainty applies to both conventional as locally sourced materials, which leads to a neutral impact on the final results. Lower quality locally sourced construction materials will result in higher reinforcement and maintenance costs. However, environmental costs of a specific batch of clay and sand could also be higher than average.

Another important aspect is that other Nature-based solutions, like double levees, might yield different results. A double levee for example, would require higher initial direct costs, but would increase stability of the system with potentially lower maintenance costs and delayed required reinforcement. Such alternatives should be explored to provide a more comprehensive understanding of the potential benefits and challenges of Nature-based flood defences.

The resilience of a salt marsh to SLR remains a significant uncertainty in this research. Latest research indicates that salt marshes can adapt to gradual SLR, but rapid increases could overwhelm their growth capacity, leading to higher maintenance costs or failure of the marsh. Although this uncertainty has been limited by extensive literature research and the inclusion of the model by D'Alpaos, this remains one of the biggest uncertainties in this thesis.

Some impact categories in the LCIA are not fully accounted for due to superficial modelling and data limitations. These limitations are the clay ripening process that was manually created, and the LCA system boundaries that were confined to a certain degree. Additionally, considering sludge as a waste material might not entirely represent its environmental impact accurately.

From a cost perspective, the costs in the Life Cycle Costing (LCC) analysis are generalized based on literature, reflecting a macro approach. Although this would approach holds for long term decision making and renewed policies that steer towards a specific reinforcement alternative, this does introduce a degree of uncertainty for specific reinforcement projects.

The valuation of ES remained one of the most difficult aspects of this thesis due to the limited amount of available resources, and the bias in valuation of emissions based on human interpretation and European policies. The price of Carbon has significantly fluctuated over the past decades and even over the past couple of years. Although a rise in valuation has occurred, it is very likely that prices will increase further as the world will experience more negative effects of climate change related to these emissions. With increased valuation of emissions, the inclusion of ES will yield more benefits, while conventional construction methods will result in higher (environmental) costs.

Lastly, biodiversity impacts remain difficult to quantify. This research based the impact on the Earthster model to prevent double counting benefits of the salt marsh, while biodiversity on its own can influence its environment indirectly as well.

The limitations and uncertainties combined highlight the need for more detailed and comprehensive data to improve the accuracy and strength of future analyses.

7. Conclusion

To compare the costs and benefits of conventional- and living dikes, and effect of including ES, the design alternatives are compared based on flood protection capacity.

Conventional dikes and living dikes both provide effective flood protection against wave overtopping, but their designs differ significantly. Living dikes integrate salt marshes, which reduce wave energy before it reaches the dike, resulting in lower required dike heights from 8,60m to 6,34m. Because on most locations dike reinforcement builds upon existing dikes, cooperating the salt marsh into the dike design can postpone reinforcement of the dike itself. Using locally sources materials however, results in larger amount of required construction materials due to its lower quality. This increase is ca. 30%.

Based on designs that withstand similar hydraulic boundary conditions, it can be concluded that from an ecological perspective, constructing salt marshes is beneficial. The major reasons for this are their ability to sequester carbon, enhance biodiversity, and provide other ES that are beneficial for human health. Financially, however, the current valuation of these ecological benefits does not offset the additional costs of constructing and maintaining living dikes. The study highlights the need to reconsider how emissions and ES are valued, especially over longer timespans, as these benefits become less pronounced when compared to the direct costs of maintenance.

Based on a design period of 50 years, costs of constructing and maintaining are higher for alternatives with salt marsh than for conventional dike construction strategies. With direct costs of €6.380-€12.000 per running meter dike for an conventional alternative, and €13.906-€15.956 per running meter dike for the creation of a Living dike.

When including the environmental impact based on required materials similar to the current practice of calculation, the environmental impact has an insignificant contribution to the total costs and benefits. Although the impact itself shows significant benefits for Living dikes, this does not come forward when expressing this impact monetarily.

Cooperating ES in this assessment has limited effect on the final results. Only for higher than expected hydraulic conditions, the negative effect on the environment by conventional design alternatives and the positive effects of a Living dikes switch the outcome. The cost related to ES are €974-€5849 per running meter dike for a conventional design, while a net benefit of €191-€94 is seen for a Living dike.

The benefits of Carbon sequestration and positive impact on the environment lower the costs drastically, while high emissions of conventional designs add up to around 30% to the total direct costs. In the specific scenario of higher than expected hydraulic conditions, the Living dike alternative has lower total costs than the conventional dike construction method.

Overall, alternative 3, a dike without salt marsh that is constructed with locally acquired materials is most beneficial financially. Although securing 30% higher direct costs due to the larger amount of required materials (€6.892-€14.664 per running meter dike), the environmental impact at €98-€564 per running meter dike is significantly lower than that of conventional materials at €974-€5849. This difference is a result of using waste sludge instead of high quality materials that are shipped over long distances.

When increasing the time span of the eco-efficiency analysis from 50 to 200 years, the maintenance costs of both dike and salt marsh dominate the results. Therefore, all alternatives with a salt marsh are unfavoured alternatives. The environmental impact, with- and without ES, does not weigh up to the high amount of direct costs of maintenance €30.000 per running meter dike. The environmental impact of maintenance is relatively low (ca. 1%) compared to that of resource acquisition, transportation and construction.

In summary, conventional dikes appear more cost-effective initially and over longer periods of time. Living dikes offer substantial long-term ecological benefits that can outweigh their higher initial costs, but only in scenarios that also threaten their stability. The inclusion of ES only significantly change the cost-benefit analysis for this specific outcome. Using locally acquired materials is the favoured alternative when including ES and the interpretation of their impact on the environment, while without the inclusion of ES conventional materials are favoured.

This emphasises that the inclusion of ES does in fact influence the outcome when comparing total costs of dike construction alternatives, and that the valuation of ES is something to further investigate.

8. Recommendations

Based on the findings and discussions in this thesis, several recommendations can be made to further improve the implementation and valuation of flood defence strategies, particularly those integrating Nature-based solutions.

It is essential to conduct more pilot projects at locations with suitable conditions for natural or existing marshes. These pilots will provide valuable data and insights into the practical challenges and benefits of living dikes, including their construction, maintenance, and long-term effectiveness. By observing and measuring real-world performance, these projects can help refine design and implementation strategies, ensuring more reliable and effective flood defences.

A more comprehensive and detailed valuation of ES is crucial. The current valuation methods do not fully capture the wide range of benefits provided by ES. Incorporating more precise and extensive valuation techniques will better reflect the true value of Nature-based solutions and use of local materials, providing a stronger economic case for their implementation.

The monetary valuation of environmental impacts and benefits should be increased based on a long-term vision. The current valuation tends to underestimate the long-term benefits of Nature-based solutions. A shift towards a long-term perspective will help in recognizing the enduring advantages of living dikes, such as sustained carbon sequestration and ongoing ES.

By implementing these recommendations, policymakers and planners can better assess the viability and benefits of living dikes and other Nature-based solutions. This will facilitate the development of more sustainable, cost-effective, and resilient flood defence systems that are well-equipped to handle future challenges such as SLR and climate change.

Bibliography

Aerts, J. C. J. H. (2018). A review of cost estimates for flood adaptation. In *Water (Switzerland)* (Vol. 10, Issue 11). MDPI AG. https://doi.org/10.3390/w10111646

Allen, J. R. L., & Rae, J. E. (1988). VERTICAL SALT-MARSH ACCRETION SINCE THE ROMAN PERIOD IN THE SEVERN ESTUARY, SOUTHWEST BRITAIN. In *Marine Geology* (Vol. 83).

Andreasi Bassi, Susanna., Biganzoli, Fabrizio., Ferrara, Nicola., Amadei, Andrea., Valente, Antonio., Sala, Serenella., Ardente, Fulvio., & European Commission. Joint Research Centre. (2023). *Updated characterisation and normalisation factors for the environmental footprint 3.1 method.*

Baaij, B. M., Kooijman, J., Limpens, J., Marijnissen, R. J. C., & van Loon-Steensma, J. M. (2021). Monitoring Impact of Salt-Marsh Vegetation Characteristics on Sedimentation: an Outlook for Nature-Based Flood Protection. *Wetlands*, *41*(6). https://doi.org/10.1007/s13157-021-01467-w

Baker, S., Murphy, E., Cornett, A., & Knox, P. (2022). Experimental Study of Wave Attenuation Across an Artificial Salt Marsh. *Frontiers in Built Environment*, *8*. https://doi.org/10.3389/fbuil.2022.893664

Bakker, J. P. (2014). *Ecology of salt marshes*.

Baveye, P. C. (2017). Quantification of ecosystem services: Beyond all the "guesstimates", how do we get real data? In *Ecosystem Services* (Vol. 24, pp. 47–49). Elsevier B.V. https://doi.org/10.1016/j.ecoser.2017.02.006

Besseling, E., Sittoni, L., & Janssen, S. (2019). *Onderzoek circulair gebruik van baggerspecie bij de waterschappen*.

Best, S. N., Van der Wegen, M., Dijkstra, J., Willemsen, P. W. J. M., Borsje, B. W., & Roelvink, D. J. A. (2018). Do salt marshes survive sea level rise? Modelling wave action, morphodynamics and vegetation dynamics. *Environmental Modelling and Software*, *109*, 152–166. https://doi.org/10.1016/j.envsoft.2018.08.004

Boerema, A., Rebelo, A. J., Bodi, M. B., Esler, K. J., & Meire, P. (2017). Are ecosystem services adequately quantified? In *Journal of Applied Ecology* (Vol. 54, Issue 2, pp. 358–370). Blackwell Publishing Ltd. https://doi.org/10.1111/1365-2664.12696

cbs. (2021). *5. Ecosysteemdiensten*. https://www.cbs.nl/nl-nl/longread/aanvullende-statistische-diensten/2021/natuurlijk-kapitaalrekeningen-nederland-2013-2018/5-ecosysteemdiensten

CBS. (2021). *5. Ecosysteemdiensten | CBS*. https://www.cbs.nl/nl-nl/longread/aanvullende-statistische-diensten/2021/natuurlijk-kapitaalrekeningen-nederland-2013-2018/5-ecosysteemdiensten

CPB. (2019). *CPB BACKGROUND DOCUMENT-Biodiversity in Dutch CBA practice Biodiversity in the Dutch practice of cost-benefit analysis*.

D'Alpaos, A., Mudd, S. M., & Carniello, L. (2011). Dynamic response of marshes to perturbations in suspended sediment concentrations and rates of relative sea level rise. *Journal of Geophysical Research: Earth Surface*, *116*(4). https://doi.org/10.1029/2011JF002093

De Bruyn, S., Bijleveld, M., De Graaff, L., Schep, E., Schroten, A., Vergeer, R., & Ahdour, S. (2018). *Environmental Prices Handbook EU28 versionN54-Environmental Prices Handbook Environmental Prices Handbook EU28 version*.

de Vries, B., de Reus, S., Nijborg, N., & van der Star, W. (2023). *Pilot Kleirijperij: van slib tot dijk*. www.ecoshape.nl

de Vries, B., Willemsen, P., van Puijenbroek, M., Coumou, L., Baptist, M., Cleveringa, J., Dankers, P., & Elschot, K. (2021). *Salt marsh pilot Marconi Monitoring results*. www.ecoshape.nl

Demmers, I. M. A. A., Verdonschot, R., Bapist, M., van Loon-Steensma, J., van Hattum, T., Verdonschot, P., & Biemans, H. (2022). *Nature-based solutions for water management - WUR*. https://www.wur.nl/en/show-longread/Nature-based-solutions-for-water-management.htm

Dijkwerkers. (2018). *Handboek Dijkenbouw - Uitvoering versterking en nieuwbouw*. SBR.

Ecochain. (2022). *Milieukostenindicator (MKI) - Overzicht - Ecochain*. https://ecochain.com/nl/knowledge-nl/milieukosten-indicator-mki/

EcoShape. (2023). *Muddy Coasts - EcoShape*. https://www.ecoshape.org/en/landscapes/muddycoasts/

EcoShape. (2024). *About EcoShape - EcoShape*. https://www.ecoshape.org/en/about/

Ekins, P., & Zenghelis, D. (2021). The costs and benefits of environmental sustainability. *Sustainability Science*, *16*(3), 949–965. https://doi.org/10.1007/s11625-021-00910-5

Fagherazzi, S., Mariotti, G., & Wiberg, P. L. (2013). Marsh collapse does not require sea level rise. *Oceanography*, *26*(3), 70–77. https://doi.org/10.5670/oceanog.2013.47

Gailis, M., Kohfeld, K. E., Pellatt, M. G., & Carlson, D. (2021). Quantifying blue carbon for the largest salt marsh in southern British Columbia: implications for regional coastal management. *Coastal Engineering Journal*. https://doi.org/10.1080/21664250.2021.1894815

Gemeente Dijk en Waard. (2022). *Maaien | Gemeente Dijk en Waard*. https://www.dijkenwaard.nl/wonen-en-leven/groen/maaien

Gerlagh, R., Heijmans, R. J. R. K., & Einar Rosendahl, K. (2022). Shifting concerns for the EU ETS: Are carbon prices becoming too high? *Environmental Research Letters*, *17*(5). https://doi.org/10.1088/1748-9326/ac63d6

Haasnoot, M., Kwadijk, J., Van Alphen, J., Le Bars, D., Van Den Hurk, B., Diermanse, F., Van Der Spek, A., Oude Essink, G., Delsman, J., & Mens, M. (2020). Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environmental Research Letters*, *15*(3). https://doi.org/10.1088/1748-9326/ab666c

Hanna, D. E. L., Tomscha, S. A., Ouellet Dallaire, C., & Bennett, E. M. (2018). A review of riverine ecosystem service quantification: Research gaps and recommendations. In *Journal of Applied Ecology* (Vol. 55, Issue 3, pp. 1299–1311). Blackwell Publishing Ltd. https://doi.org/10.1111/1365-2664.13045

H&B Grondstoffen. (2023). *Leverancier Basalt - H & B Grondstoffen*. https://hb-grondstoffen.nl/producten/waterbouwmaterialen/basalt-waterbouw/

Home | AHN. (2023). https://www.ahn.nl/

Huijbregts, M. A. J. (2016). *ReCiPe 2016 A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization*.

IDEMAT Calculation Rules - Sustainability Impact Metrics. (n.d.). Retrieved August 20, 2024, from https://www.ecocostsvalue.com/data-tools-books/idemat-calculation-rules/

Jacobsen, B. H., Rabl, A., Gren, I.-M., Holland, M., Klimont, Z., Hicks, K., Brouwer, R., Dickens, R., Willems, J., Termansen, M., Velthof, G., Alkemade, R., Van Oorschot, M., Webb, J., Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., … Grizzetti, B. (2011). *Costs and benefi ts of nitrogen in the environment*.

Jonkman, S. N., Hillen, M. M., Nicholls, R. J., Kanning, W., & Van Ledden, M. (2013). Costs of adapting coastal defences to sea-level rise - New estimates and their implications. *Journal of Coastal Research*, *29*(5), 1212–1226. https://doi.org/10.2112/JCOASTRES-D-12-00230.1

Kirwan, M. L., Guntenspergen, G. R., D'Alpaos, A., Morris, J. T., Mudd, S. M., & Temmerman, S. (2010). Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters*, *37*(23). https://doi.org/10.1029/2010GL045489

KNMI. (2023). *KNMI Klimaatdashboard*.

Kwakernaak, C., & Lenselink, G. (2015). *Economische en ecologische perspectieven van een dubbele dijk langs de Eems-Dollard*.

Lacy, J. R., Foster-Martinez, M. R., Allen, R. M., Ferner, M. C., & Callaway, J. C. (2020). Seasonal Variation in Sediment Delivery Across the Bay-Marsh Interface of an Estuarine Salt Marsh. *Journal of Geophysical Research: Oceans*, *125*(1). https://doi.org/10.1029/2019JC015268

Lindfors, L.-G. (1995). *Nordic Guidelines on Life Cycle Assessment*.

Mariotti, G., & Fagherazzi, S. (2010). A numerical model for the coupled long-term evolution of salt marshes and tidal flats. *Journal of Geophysical Research: Earth Surface*, *115*(1). https://doi.org/10.1029/2009JF001326

Maza, M., Lara, J. L., & Losada, I. J. (2022). A paradigm shift in the quantification of wave energy attenuation due to saltmarshes based on their standing biomass. *Scientific Reports*, *12*(1), 13883. https://doi.org/10.1038/s41598-022-18143-6

McTigue, N. D., Walker, Q. A., & Currin, C. A. (2021). Refining Estimates of Greenhouse Gas Emissions From Salt Marsh “Blue Carbon” Erosion and Decomposition. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.661442

Millennium Ecosystem Assessment Program. (2005). *Ecosystems and human well-being : wetlands and water synthesis : a report of the Millennium Ecosystem Assessment.* World Resources Institute.

Mudd, S. M., Fagherazzi, S., Morris, J. T., & Furbish, D. J. (2013). *Flow, Sedimentation, and Biomass Production on a Vegetated Salt Marsh in South Carolina: Toward a Predictive Model of Marsh Morphologic and Ecologic Evolution* (pp. 165–188). https://doi.org/10.1029/ce059p0165

Muddy Coasts - EcoShape. (2024). https://www.ecoshape.org/en/landscapes/muddycoasts/

Mueller, P., Do, H. T., Jensen, K., & Nolte, S. (2019). Origin of organic carbon in the topsoil of Wadden Sea salt marshes. *Marine Ecology Progress Series*, *624*, 39–50. https://doi.org/10.3354/meps13009

Nature-Based Solutions Initiative. (2022, February 22). *Nature-Based Solutions Initiative | Revised climate pledges show enhanced ambition for nature-based solutions*. https://www.naturebasedsolutionsinitiative.org/news/nbs-policy-platform-ndc-submissions/

Ness, B., Urbel-Piirsalu, E., Anderberg, S., & Olsson, L. (2007). Categorising tools for sustainability assessment. In *Ecological Economics* (Vol. 60, Issue 3, pp. 498–508). https://doi.org/10.1016/j.ecolecon.2006.07.023

Nijkamp, P., Vindigni, G., & Nunes, P. A. L. D. (2008). Economic valuation of biodiversity: A comparative study. *Ecological Economics*, *67*(2), 217–231. https://doi.org/10.1016/j.ecolecon.2008.03.003

Rijksoverheid. (2017). *Beoordelingsinstrumentarium (WBI2017) - Helpdesk water*. https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/primaire/beoordelen/beoordelingsinstrumentarium-wbi2017-0/

Rijksoverheid. (2021). *BWBR0037552_Hoofdstuk2-geldend_van_01-07-2021_tm_heden_zichtdatum_01-02-2023*.

Rijkswaterstaat. (2023). *Sand Motor pilot for natural coastal protection*. https://www.rijkswaterstaat.nl/en/expertise/water

Roode, N., Maaskant, B., & Boon, M. (2019). *STOWA 2019-09 Handreiking voorlandkeringen*.

Royal HaskoningDHV. (2021). *Handreiking “DuboCalc in dijkversterkingsprojecten.”*

Russi, D., Ten Brink, P., Farmer, A., Badura, T., Coates, D., Förster, J., Kumar, R., & Davidson, N. (2013). *The economics of ecosystems and biodiversity for water and wetlands*. www.ieep.eu.

Sagoff, M. (2011). The quantification and valuation of ecosystem services. *Ecological Economics*, *70*(3), 497–502. https://doi.org/10.1016/j.ecolecon.2010.10.006

Schuerch, M., Dolch, T., Reise, K., & Vafeidis, A. T. (2014). Unravelling interactions between salt marsh evolution and sedimentary processes in the Wadden Sea (southeastern North Sea). *Progress in Physical Geography*, *38*(6), 691–715. https://doi.org/10.1177/0309133314548746

Springer - Rouwette, A. (2019). *Dijkversterking Zwolle-Olst Onderbouwing voorkeursalternatief Versie 2.0*.

Stroming. (2012). *Oeverdijken: kans voor veiligheid en natuur*.

Svasek. (2023). *Haalbaarheid morfologische ingrepen vooroever Waddenzeedijk Schiermonnikoog*. www.svasek.com

Temmerman, S., Govers, G., Meire, P., & Wartel, S. (2003). *Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium*. www.elsevier.com/locate/margeo

Teunis, M., & Didderen, K. (2018). *Blue Carbon in Nederlandse kwelders*.

The Economist. (2022). *Are blue carbon markets becoming mainstream?* https://impact.economist.com/ocean/ocean-health/are-blue-carbon-markets-becoming-mainstream

Torfs, R., & Bossuyt, M. (2006). *Using_DALYs_and_External_Costs_for_Environmental*.

Trading Economics. (2024). *EU Carbon Permits - Price - Chart - Historical Data - News*. https://tradingeconomics.com/commodity/carbon

van der Meer, J. W., Allsop, N. H. W., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P., & Zanuttigh, B. (2018). *EurOtop Manual on wave overtopping of sea defences and related structures An overtopping manual largely based on European research, but for worldwide application Second Edition 2018*. www.overtopping-manual.com

van der Meer, Y. (2019). *Life Cycle Sustainability Assessment* (pp. 1–13). https://doi.org/10.1007/978-3-319-71058-7_18-1

Van der Wilde, C. P., & Newell, J. P. (2021). Ecosystem services and life cycle assessment: A bibliometric review. In *Resources, Conservation and Recycling* (Vol. 169). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2021.105461

van Dobben, H. F., de Groot, A. V., & Bakker, J. P. (2022). Salt Marsh Accretion With and Without Deep Soil Subsidence as a Proxy for Sea-Level Rise. *Estuaries and Coasts*. https://doi.org/10.1007/s12237-021-01034-w

Vereniging voor Vreemdelingenverkeer. (2024). *Salt Marshes at Schiermonnikoog | VVV Schiermonnikoog*. https://www.vvvschiermonnikoog.com/schiermonnikoog/national-park/landscapes-schiermonnikoog/salt-marshes

Visentin, C., Trentin, A. W. da S., Braun, A. B., & Thomé, A. (2020). Life cycle sustainability assessment: A systematic literature review through the application perspective, indicators, and methodologies. In *Journal of Cleaner Production* (Vol. 270). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.122509

Vuik, V., Borsje, B. W., Willemsen, P. W. J. M., & Jonkman, S. N. (2019). Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. *Ocean and Coastal Management*, *171*, 96–110. https://doi.org/10.1016/j.ocecoaman.2019.01.010

Warmink, J. J. (2018). *Course reader Hydraulic Engineering 2018-00038-2A*.

West Coast Environmental Law. (2018). *West Coast Environmental Law Design Basis for the Living Dike Concept*.

Witteveen+Bos. (2022). *What are Nature-Based Solutions (NBS)? | Nature Based Solutions*. https://www.nature-basedsolutions.com/

Zhang, Y., Singh, S., & Bakshi, B. R. (2010). Accounting for ecosystem services in life cycle assessment part I: A critical review. In *Environmental Science and Technology* (Vol. 44, Issue 7, pp. 2232–2242). https://doi.org/10.1021/es9021156

Appendix A: LCA system boundaries

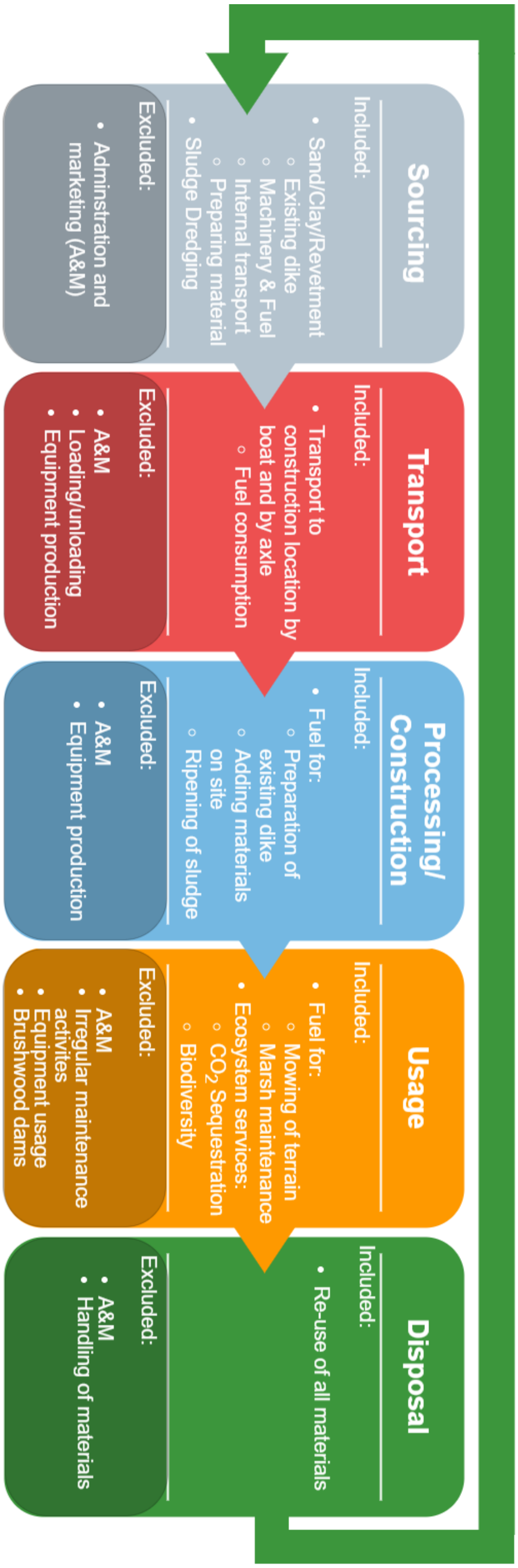

Figure 38: LCA system boundaries

Appendix B: Life Cycle Inventory tables

8.1.1.1. Alternative 1: Conventional dike with ES of existing salt marsh

The following tables show the results of alternative 1.

8.1.1.1.1. Lower than expected scenario:

Table 20: LCI Alternative 1, dike height 6,34m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	Clay excavation	Clay	0	m3	0	kg
	Sand excavation	Sand	0	m3	0	kg
	Revetment block production	Revetment blocks	0	m3	0	kg
Transportation	Clay by axle	Clay	10	Km	0	Metric-ton*km
	Clay by boat	Clay	2	Km	0	Metric-ton*km
	Sand by axle	Sand	10	Km	0	Metric-ton*km
	Sand by boat	Sand	2	Km	0	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	0	L	0	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg
	CO2 capturing by marsh	CO^2			-700	kg

8.1.1.1.2. Expected scenario:

Table 21: LCI Alternative 1, dike height 6,34m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	Clay excavation	Clay	0	m3	0	kg
	Sand excavation	Sand	0	m3	0	kg
	Revetment block production	Revetment blocks	0	m3	0	kg
Transportation	Clay by axle	Clay	10	Km	0	Metric-ton*km
	Clay by boat	Clay	2	Km	0	Metric-ton*km
	Sand by axle	Sand	10	Km	0	Metric-ton*km
	Sand by boat	Sand	2	Km	0	Metric-ton*km

Manufacturing	Applying materials by excavator	Diesel	0	L	0	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg
	CO2 capturing by marsh	CO^2			-700	kg

8.1.1.1.3. Higher than expected scenario:

Table 22: LCI Alternative 1, dike height 7,30m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	Clay excavation	Clay	4.8	m3	8640	kg
	Sand excavation	Sand	32.3	m3	54910	kg
	Revetment block production	Revetment blocks	0.2	m3	600	kg
Transportation	Clay by axle	Clay	10	Km	86.4	Metric-ton*km
	Clay by boat	Clay	200	Km	1728	Metric-ton*km
	Sand by axle	Sand	10	Km	549.1	Metric-ton*km
	Sand by boat	Sand	50	Km	2745.5	Metric-ton*km
	Revetment by axle	Revetment blocks	10	Km	6	Metric-ton*km
	Revetment by boat	Revetment blocks	200	Km	120	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	96.4	L	80.98	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg
	CO2 capturing by marsh	CO^2			-700	kg

8.1.1.2. Alternative 2: Conventional dike without existing salt marsh

The following tables show the results of alternative 2.

8.1.1.2.1. Lower than expected scenario:

Table 23: LCI Alternative 2, dike height 7,19m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	Clay excavation	Clay	4.14	m3	7452	kg
	Sand excavation	Sand	27.6	m3	46920	kg

	Revetment block production	Revetment blocks	0.2	m3	600	kg
Transportation	Clay by axle	Clay	10	Km	74.52	Metric-ton*km
	Clay by boat	Clay	200	Km	1490.4	Metric-ton*km
	Sand by axle	Sand	10	Km	469.2	Metric-ton*km
	Sand by boat	Sand	50	Km	2346	Metric-ton*km
	Revetment by axle	Revetment blocks	10	Km	6	Metric-ton*km
	Revetment by boat	Revetment blocks	200	Km	120	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	96.4	L	80.98	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg

8.1.1.2.2. Expected scenario:

Table 24: LCI Alternative 2, dike height 8,60m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	Clay excavation	Clay	12.6	m3	22680	kg
	Sand excavation	Sand	93.1	m3	158270	kg
	Revetment block production	Revetment blocks	0.4	m3	1200	kg
Transportation	Clay by axle	Clay	10	Km	226.8	Metric-ton*km
	Clay by boat	Clay	200	Km	4536	Metric-ton*km
	Sand by axle	Sand	10	Km	1582.7	Metric-ton*km
	Sand by boat	Sand	50	Km	7913.5	Metric-ton*km
	Revetment by axle	Revetment blocks	10	Km	12	Metric-ton*km
	Revetment by boat	Revetment blocks	200	Km	240	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	127.2	L	106.85	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg

8.1.1.2.3. Higher than expected scenario:

Table 25: LCI Alternative 2, dike height 10,0m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	Clay excavation	Clay	21	m3	37800	kg
	Sand excavation	Sand	169.75	m3	288575	kg
	Revetment block production	Revetment blocks	0.7	m3	2100	kg
Transportation	Clay by axle	Clay	10	Km	378	Metric-ton*km
	Clay by boat	Clay	200	Km	7560	Metric-ton*km
	Sand by axle	Sand	10	Km	2885.75	Metric-ton*km
	Sand by boat	Sand	50	Km	14428.75	Metric-ton*km
	Revetment by axle	Revetment blocks	10	Km	21	Metric-ton*km
	Revetment by boat	Revetment blocks	200	Km	420	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	164	L	137.76	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg

8.1.1.3. *Alternative 3: Conventional dike without existing salt marsh with local materials*

The following tables show the results of alternative 3.

8.1.1.3.1. Lower than expected scenario:

Table 26: LCI Alternative 3, dike height 7,19m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	High Quality sludge	Clay	41.26	m3	66016	kg
	Clay Ripening	Diesel	42.84	L	35.99	kg
Transportation	Clay by axle	Clay	10	Km	660.16	Metric-ton*km
	Clay by boat	Clay	10	Km	660.16	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	42.36	L	35.58	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg

8.1.1.3.2. Expected scenario:

Table 27: LCI Alternative 3, dike height 8,60m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	High Quality sludge	Clay	137.41	m3	219856	kg
	Clay Ripening	Diesel	142.8	L	119.95	kg
Transportation	Clay by axle	Clay	10	Km	2198.56	Metric-ton*km
	Clay by boat	Clay	10	Km	2198.56	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	141.2	L	118.61	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg

8.1.1.3.3. Higher than expected scenario:

Table 28: LCI Alternative 3, dike height 10,0m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	High Quality sludge	Clay	247.97	m3	396752	kg
	Clay Ripening	Diesel	257	L	215.88	kg
Transportation	Clay by axle	Clay	10	Km	3967.52	Metric-ton*km
	Clay by boat	Clay	10	Km	3967.52	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	254.16	L	213.49	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg

8.1.1.4. *Alternative 4: Living dike by constructing a salt marsh with local materials*

The following tables show the results of alternative 4.

8.1.1.4.1. Lower than expected scenario:

Table 29: LCI Alternative 4, dike height 6,34m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	High Quality sludge	Clay	0	m3	0	kg

	Low Quality sludge	Sand	114.3	m3	194310	kg
	Clay Ripening	Diesel	0	L	0	kg
Transportation	Clay by axle	Clay	10	Km	0	Metric-ton*km
	Clay by boat	Clay	10	Km	0	Metric-ton*km
	Sand by axle	Sand	10	Km	0	Metric-ton*km
	Sand by boat	Sand	2	Km	388.62	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	101.6	L	85.34	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg
	CO2 capturing by marsh	CO^2			-700	kg

8.1.1.4.2. Expected scenario:

Table 30: LCI Alternative 4, dike height 6,34m

Phase	**Process**	**Flow**	**Quantity**	**Unit**	**Quantity**	**Unit**
Resource Acquisition	High Quality sludge	Clay	0	m3	0	kg
	Low Quality sludge	Sand	114.3	m3	194310	kg
	Clay Ripening	Diesel	0	L	0	kg
Transportation	Clay by axle	Clay	10	Km	0	Metric-ton*km
	Clay by boat	Clay	10	Km	0	Metric-ton*km
	Sand by axle	Sand	10	Km	0	Metric-ton*km
	Sand by boat	Sand	2	Km	388.62	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	101.6	L	85.34	kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg
	CO2 capturing by marsh	CO^2			-700	kg

8.1.1.4.3. Higher than expected scenario:

Table 31: LCI Alternative 4, dike height 7,30m

Phase	Process	Flow	Quantity	Unit	Quantity	Unit
Resource Acquisition	High Quality sludge	Clay	48.23	m3	77168	kg
	Low Quality sludge	Sand	114.3	m3	194310	kg
	Clay Ripening	Diesel	49.98	L	41.98	kg
Transportation	Clay by axle	Clay	10	Km	771.68	Metric-ton*km
	Clay by boat	Clay	10	Km	771.68	Metric-ton*km
	Sand by axle	Sand	10	Km	1943.1	Metric-ton*km
	Sand by boat	Sand	2	Km	388.62	Metric-ton*km
Manufacturing	Applying materials by excavator	Diesel	203.2	L		kg
Usage and maintenance	Mowing	CO^2	0.0012	ha/year	0.06	kg
	CO2 capturing by marsh	CO^2			-700	kg