Improving Flood Safety and Ferry Navigation in the Changing Environment of Holwerd

Study Report

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CIE4061-09 Multidisciplinary Project

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EXECUTIVE SUMMARY

Relative sea level rise and climate change represent long-term threats for the ecosystems and flood defence system in the Wadden Sea. Moreover, the flood-dominant tidal basins in the area lead to sedimentation in the navigational channels used by the ferry services that connect the mainland to the Dutch Wadden islands. This report provides flood safety and coastal zone management solutions for the village of Holwerd, in the province of Friesland. High morphological dynamics and biodiversity characterizes this environment. Within this context, the Holwerd municipality, Wetterskip and Rijkswaterstaat were identified as key players to this study from a stakeholder perspective.

Alternative preliminary designs were presented to increase the resilience of the local sea dike and to recommend solutions for improving the ferry connection between Holwerd and the island of Ameland due to current dredging operations considered as excessive and causing ferry delays. Careful consideration was given to designs due to the Wadden Sea being a UNESCO World Heritage Site and therefore protected under environmental legislation. Therefore, minimal negative environmental and ecological impacts were strived for in design of both the alternative dike designs and ferry connection alternatives. The impact that these alternatives may have on the socio-economy of Holwerd was also assessed where applicable.

Some alternatives were initially eliminated due to fatal flaws and the remaining options were evaluated by means of a multi-criteria analysis. The main criteria considered were the environmental impact, practical implementation, socio-economic impact, safety risk and reliability. Costs were evaluated through a subsequent cost-value assessment. The Wide Green Dike concept was the selected preferred solution as a reinforcement design to withstand extreme wave heights and water levels with a 1000-year return period, including sea level rise projections for the next century. This was achieved by performing an extreme water level analysis and wave transformation using the software Delft3D Wave. The Wide Green Dike concept would therefore ensure that the Holwerd sea dike still sufficiently meets the Dutch flood safety standards in the future. In relation to the navigability of the ferry, channel bend cuts are the feasible short-term solutions to reduce the sailing time by 10 minutes. The long-term solution, adjusting vessel fleet sizes, potentially decreases the current maintenance dredging volume by 20%. The beneficial use of the dredged material for dike reinforcement and salt marsh development are suggested as integrated Building with Nature solutions to provide additional ecosystem services. Environmental Impact Assessments were conducted to identify potential risks related to each of the preferred alternatives and provide mitigation measures to ensure an appropriate project implementation.

1. INTRODUCTION

1.1 Problem Statement

Holwerd is a small village located along the coast of the Dutch Wadden Sea, in the north of the Friesland province, the Netherlands. A ferry service, located at Holwerd, connects the mainland to one of the barrier islands, Ameland. The locations of both Holwerd village and the island of Ameland are indicated in Figure 1-1.

At present, a sea dike sufficiently protects Holwerd and its surrounding area against flooding from the Wadden Sea. It is however predicted that in future years the dike will no longer be sufficient in meeting the current flood safety standard of 1/1000 per year. This is due to the expected sea level rise, caused by climate change. Regarding the ferry connection between Holwerd and Ameland, it has been identified that ongoing morphological changes are affecting the navigation channel, resulting in an increase in the amount and cost of maintenance dredging as well as delays in ferry transit.

This project investigates the above future changes to the region in order to develop alternative risk reducing measures against flooding and to address the ferry connection and navigation issues.

Figure 1-1: Project site location (Microsoft, 2018)

1.2 Project Objective

The objective of the study is to investigate measures needed to address the future changes in the region, namely:

- Increased water levels and extreme wave heights due to climate change; and
- Changing morphology causing problems for ferry transit to/from the Ameland island.

Therefore, this study respectively comprises analyses of:

- Alternative flood defence options for strengthening Holwerd's sea dike, other than dike heightening, and their effects on the flood safety in the area; and

- Alternative interventions which will reduce dredging costs and help resolve navigation issues of the ferry service connection along the tidal ferry channel.

These analyses are carried out in the aim to propose preferred solutions for consideration of updating Holwerd's safety defence and coastal zone management plan.

1.3 Report Structure

This report presents the alternatives, first identified at conceptual level and, where applicable, further analysed as more detailed preliminary designs. The problem description and objective of the study is explained in Section 1, and the scope of work and methodology approach, as well as a stakeholder analysis is provided in Section 2. Section 3 briefly introduces key aspects of the literature study and is followed by a review of the site information in Section 4. Local hydrodynamic conditions are discussed in Section 5, followed by the functional requirements in Section 6.

The current flood safety scenario and ferry connection problems are detailed in Sections 7 and 8 respectively. Alternatives are introduced as conceptual ideas in Section 9, a number of which are further developed into preliminary designs in Sections 10 and 11. Section 12 presents the multi-criteria analysis (MCA) used to compare and evaluate the alternatives. This is followed by a discussion of the preferred solutions in Section 13 and identified risks in Section 14. The conclusions of the preliminary design phase and recommendations for the next study phase follow in Section 15.

2. STUDY APPROACH

2.1 Scope of Work

The scope of work for the project is listed in terms of a work-breakdown structure below:

- Project management
  - Stakeholder engagement and liaison with specialists
  - Client meetings
  - Site visit
- Literature review
  - Review of relevant previous studies
  - Data collection (Site information, water levels, wave conditions, dike sections, dredging requirements)
- Site information
  - Status quo assessment
- Climate change
  - Future trends and extrapolation of data
- Options development
  - Functional requirements
  - Flood defence alternatives
  - Ferry connection alternatives
  - Conceptual designs
  - Preliminary designs
- Alternatives assessment
  - Cost estimation
  - Multi-criteria analysis (MCA)
  - Select preferred solutions
- Environmental Impact Assessment (EIA)
- Reporting and presentations

2.2 Study Methodology

2.2.1 Introduction

The project follows a 5-step study methodology developed by Roozenburg and Eekels (1995), consisting of analysis, synthesis, simulation, evaluation, and decision, as illustrated Figure 2-1. This approach is further elaborated on in the subsections below.

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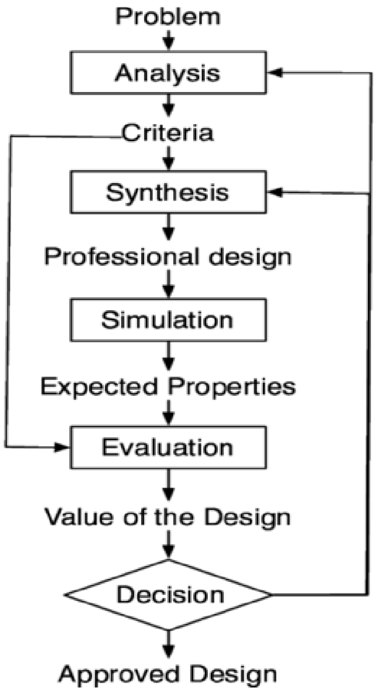

Figure 2-1: Basic design cycle (Roozenburg & Eekels, 1995)

2.2.2 Analysis

An important aspect of this project is gaining contextual understanding of the problem, the local conditions, opportunities and constraints. Thus, the initial work included a literature review and analysis of site conditions through obtaining data for input to the design alternatives.

Data collection and processing thereof, includes the following: wave data, water levels, tidal currents and meteorological data. Allowance is made to account for climate change in terms of projected sea level rise (SLR), higher offshore wind speeds and a consequent increase in wave heights. Required data also includes bathymetry, topography (e.g. dike elevation), soil conditions and vegetation type within the project location area.

2.2.3 Synthesis

The synthesis step involves the development of concepts: flood defence options which will increase the dike's safety and options which will address the ferry connection problems.

2.2.4 Simulation

The concept alternatives which are developed in the previous step are investigated further and designed to sufficient detail to develop preliminary designs. This is after evaluation step 1, see below.

2.2.5 Evaluation

Evaluation of the alternatives follows a 2-step process. The first step, a first-order analysis already eliminates a number of the conceptual options based on high-level research or possible fatal flaws in

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terms of the functional requirements. The remaining alternatives are considered feasible at a conceptual level and proceed to the next phase of study, *Simulation*, in which a more in-depth analysis of each alternative is done to complete a preliminary design. In the second evaluation step, these preliminary designs are compared and rated using a multi-criteria analysis (MCA). The MCA, a decision tool for objectively weighing options on a number of criteria, helps to determine the preferred solution(s) according to pre-selected criteria.

2.2.6 Decision-making

The final step in the design process is to select the preferred alternative based on the MCA and highest value-cost ratio. This alternative can either be further enhanced by value engineering or combining it with elements of the other alternatives, hence an integrated design. The selected solution drives the need for further assessments and a detailed design study, prior to development of a new flood safety and coastal zone management plan for the area of Holwerd.

2.3 Stakeholder Analysis

Given the complex and multi-disciplinary nature of this project, with consideration to both the dike for flood safety and the vessel navigation across the Wadden Sea, many stakeholders are identified for this study. Stakeholders may either be affected by the decisions of the project, or may in some way be accountable for (i.e. influential) the provision of proposed developments and hence also any related outcome.

Stakeholders are identified through analysis of the key disciplines related to the strategic objectives of this study. In order to effectively develop and design the required alternatives, one should consider the interests and influence of all parties/actors throughout the design process. Besides safety and design itself, the environment of the site location is important. Due to the Wadden Sea being protected as a UNESCO World Heritage site, any potential environmental and/or ecological impacts that could result from human interventions in the area should be assessed. With that, there are national regulations and legislation to consider. Figure 2-2 below shows the different stakeholders and their interests or key roles with respect to this study.

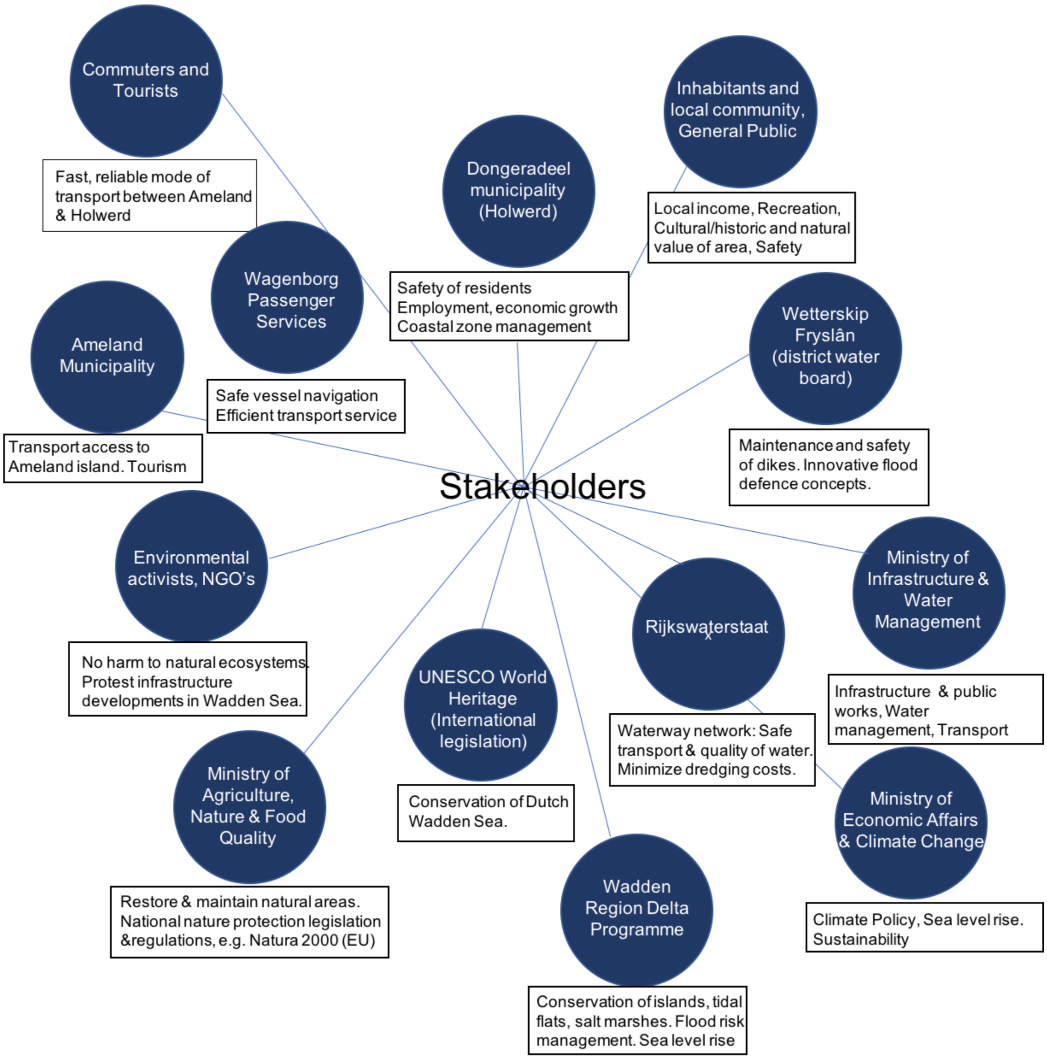

Figure 2-2: Stakeholders and their key interests

Considering the varying interests and requirements of the different stakeholders as presented above, it is beneficial to assess their influence in decision making to determine the most important stakeholders for this study and indirectly the functional requirements. A power versus interest grid is used for this and shown in Figure 2-3, taking into account *both* the flood risk and ferry navigation aspects of the project. Note that some stakeholders are only concerned with or affected by one of the two developments, hence their overall interest may decrease.

The following stakeholders are identified as key players due to their direct involvement in the study and influence on the decision-making process:

- Holwerd municipality
  - Client of the project and concerned about the flood safety of the town and its residents. Interested and affected by developments concerning the ferry connection to Ameland, related to the local coastal zone management plan.
- Rijkswaterstaat
  - Within the Ministry of Infrastructure and Water Management, Rijkswaterstaat is responsible for the management and maintenance of the waterway, i.e. dredging of channel and funding thereof.

- Wetterskip Fryslân
  - The local water board is responsible for dike reinforcements and maintenance.

At the same time, it is important to meet the needs of and comply to regulations of national and international authorities, e.g. Nature Conservation Act, Natura 2000 and UNESCO. Interests of the local community (partly accounted for by the municipality) and users of any proposed developments, as well as the socio-economic status of Holwerd and its inhabitants, need to be taken into consideration, however this is not as stringent as legislation protecting the Wadden Sea.

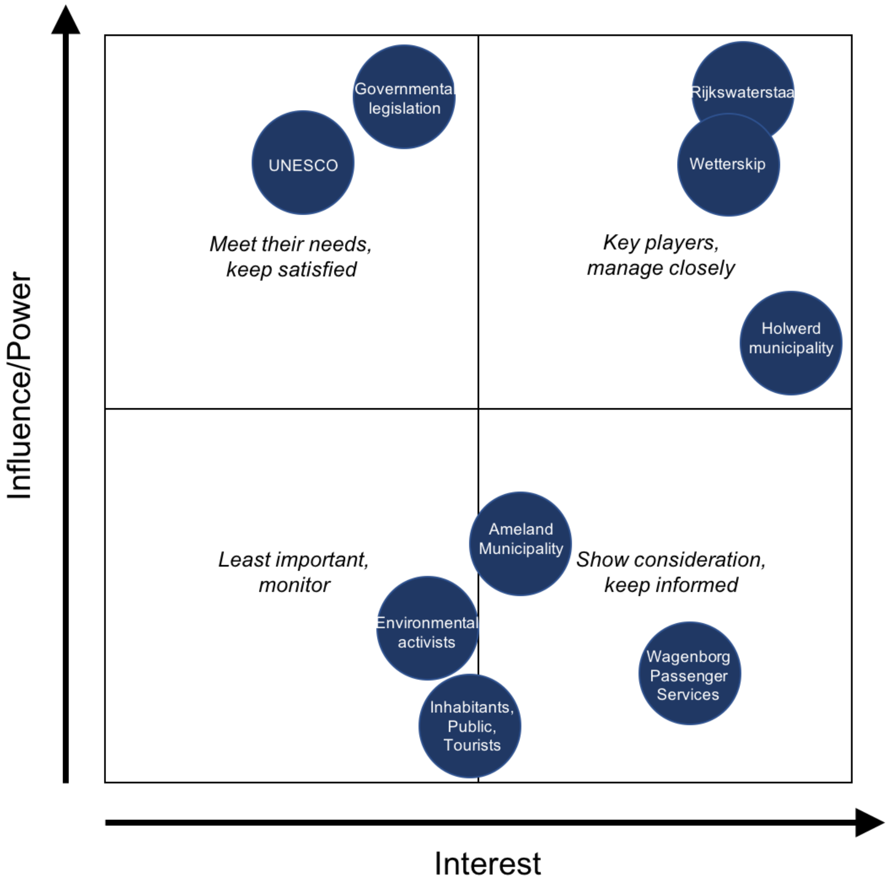

Figure 2-3: Power versus interest grid for stakeholders

3. LITERATURE REVIEW

3.1 Introduction

An extensive literature review was conducted, in particular regarding the ecological value of the protected area, impact of climate change on the Wadden Sea region, flood risk management within the Netherlands and alternative flood safety measures to strengthen sea dikes. Previous studies concerning the current challenges of the ferry transit, the Ameland basin morphology and dredging requirements were also referred to.

The following sections include summaries of the research done related to understanding the system from an ecological perspective and the two major future changes in the area of Holwerd, i.e. sea level rise due to climate change and changes in the morphology of the Ameland tidal basin.

3.2 Wadden Sea as a UNESCO World Heritage Site

The Wadden Sea is the “largest unbroken system of intertidal sand and mudflats in the world” (UNESCO, 2018). Therefore, for its outstanding universal value on geological and ecological processes, the United Nations, Educational, Scientific and Cultural Organization (UNESCO) declared the Wadden Sea a World Heritage Site in 2009 (Reise, et al., 2010). It consists of a dynamic landscape covering zones of land, sea and freshwater environments. Habitats are rich in species which continuously adapt to the demanding and ever-changing environmental conditions of the area. It is also considered one of the most important areas in the world for migratory birds. Because of its unique nature values, its preservation is considered of global importance (Common Wadden Sea Secretariat, 2018).

The Wadden Sea is considered an intertidal ecosystem where natural processes should be left to continue functioning largely undisturbed. Given the area’s protected status, any interventions planned for the area, should have minimal to no negative impacts on the surrounding ecosystems, and permits are required under Natura 2000 and conservation legislation of the Netherlands (Common Wadden Sea Secretariat, 2016).

3.3 Vegetated Foreshores

3.3.1 Introduction to salt marshes

Salt marshes is one such important ecosystem within the Wadden Sea, formed by natural forces in the upper part of the intertidal zone, i.e. interface between land and sea (Common Wadden Sea Secretariat, 2013).

This is of importance to this study as the main vegetation to the north of Holwerd’s sea dike is composed of salt marshes as shown in the map in Figure 3-1. These are herbaceous ecosystems that include salt-tolerant plants (halophytes), common in saline coastal wetlands in temperate climates and higher latitudes (Loon-Steensma, 2014). Salt marsh plains are formed by gradual accretion of sediments above average high tide levels. The accretion occurs not only due to the capacity of the halophytes to slow down water flow and allow sediments to accumulate, but also due to its roots being able to hold these sediments in place (Loon-Steensma, 2014). All salt marshes in the Wadden Sea are part of Natura 2000 areas.

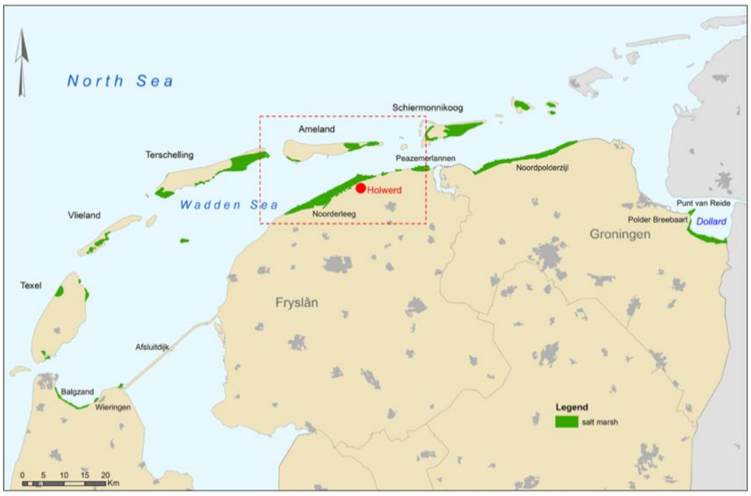

Figure 3-1: Salt marshes along the Wadden Sea coast (Adapted from (Loon-Steensma, 2015))

According to Esselink et al. (2017), there are four main types of salt marsh developments in the Wadden Sea region: green beaches, barrier-connected salt marshes, hallig salt marsh islands, and foreland salt marshes. This last classification is the most common in the Wadden Sea region and defines the salt marshes in Holwerd. Foreland salt marshes occur in clayey areas and are resultant from anthropogenic activities related to the construction of sedimentation fields and ditching. The man-made foreland salt marshes are usually protected by brushwood groynes.

3.3.2 Historical development of salt marshes

Holwerd has been subject to numerous human and natural developments that greatly influenced the local morphology. In 1878, a closure dam was built to connect the town to Ameland and reclaim land. But the state of the dam deteriorated over time and its remnant was used as a pier for ships, where today this is part of the ferry terminal (Boonstra, 2015). In the 50's, brushwood groynes were built on both sides of the pier, with the purpose of trapping sediments and creating salt marshes (Kadaster, 2017). Since then, the ferry terminal has been expanded and salt marshes developed more in the west than in the east side. Figure 3-2 shows a summary of these developments.

Figure 3-2: History of developments in Holwerd (Kadaster, 2017)

3.3.3 Salt marshes as flood protection

During storm events, strong waves break in shallow water depths and may threaten the stability of dikes and cause erosion. Vegetation in shallow areas dissipates wave energy by creating friction that reduces wave heights (Loon-Steensma, 2014). Measurements on the Norfolk coast of the UK have shown a significant wave height average reduction of 61% over a 180 m wide salt marsh, compared to only 15% reduction over a 197 m wide sand flat (Moller, et al., 2001). It has also been demonstrated that vegetation decreases tidal marsh surface flows (Leonard, et al., 2002).

These features of salt marshes proved to be relevant for flood protection so that this type of vegetation is integrated to innovative dike concepts such as the eco-engineering and wide green dikes (Loon-Steensma, 2014). The application of these new dike concepts, along with a sand replenishment programme, are part of the comprehensive flood safety strategy for the Wadden Sea in the Delta Programme, illustrated in Figure 3-3.

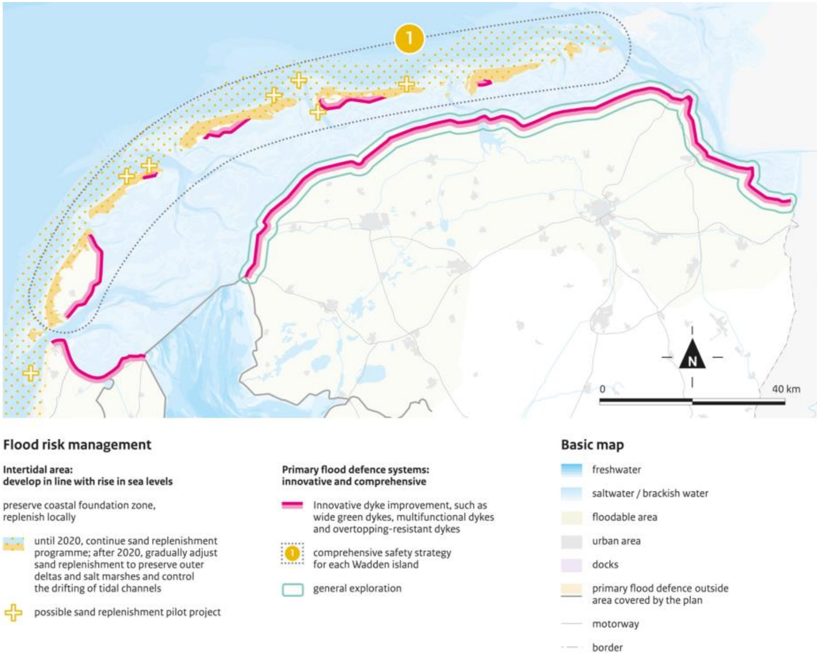

Figure 3-3: Strategy for flood risk management (The Ministry of Infrastructure and the Environment, 2014)

Due to the extensive ecological value of this vegetation, the Common Wadden Sea Secretariat (CWSS) included preservation targets for salt marshes in the Wadden Sea Plan 2010. These include keeping a large variety of salt marsh species and an increased area of salt marshes in favourable natural conditions (Common Wadden Sea Secretariat, 2010).

Climate change and human activities such as agricultural exploitation represent a threat to the preservation of salt marshes. Sea level rise has the potential to erode the vegetation if the salt marshes cannot keep pace. To allow a safe sedimentation rate, the maintenance of the width of the area is important.

Measurements of vertical accretion rates of saltmarshes in Noarderleech, some 15 km south of Holwerd, showed the effects of grazing: taller ungrazed vegetation traps more sediment. In ungrazed salt marsh areas the vertical accretion rate varied from 10.7 to 36.7 mm/year, while in grazed areas it oscillated between 0.3 to 31.5 mm/year. Consequently, even the vertical accretion rates of grazed salt marshes in this region (Holwerd included) should be adequate to keep pace with sea level rise and land subsidence (Beintema & Biowrite, 2007).

3.4 Climate Change

3.4.1 Background

Since the early 1970s, glacier mass loss and ocean thermal expansion from warming, together explain about 75% of the observed global mean sea level rise. Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, causing irreversible impacts for both people and ecosystems (IPCC, 2013).

There are several possible consequences of climate change that have to be taken in to account especially during the decision-making process of engineering applications. Sea Level Rise (SLR), increased wind speed and storm surge intensity can be considered as most important amongst others. But according to literature, no significant change of storminess is expected in Wadden Sea region in this century. Hence, strong SLR constitutes the main challenge (Hofstede, 2014). This study focuses on sea level rise as one of the major effects of climate change.

If SLR becomes stronger than sediment accumulation on the intertidal flats and salt marshes in the Ameland tidal basin, the flats may be submerged and permanent shallow water bodies may expand (Johannes, et al., 2017). Further, high sea level rise will result in larger over-depth in the Wadden Sea, which might cause stronger amplification of *the tide* (Wang, et al., 2012). Drowning of the tidal flats has serious negative consequences like coastal flooding.

3.4.2 SLR predictions

According to the fifth Intergovernmental Panel on Climate Change assessment report (IPCC, 2014), a global mean Sea Level Rise (SLR) of between 0.28 m and 0.98 m is projected for this century. However, a recent study's findings included a global mean SLR of between 0.28 m and 1.31 m in this century; an estimated rise in sea level which is even larger than the IPCC prediction in 2014, as shown graphically in Figure 3-4 (Mengel, et al., 2016).

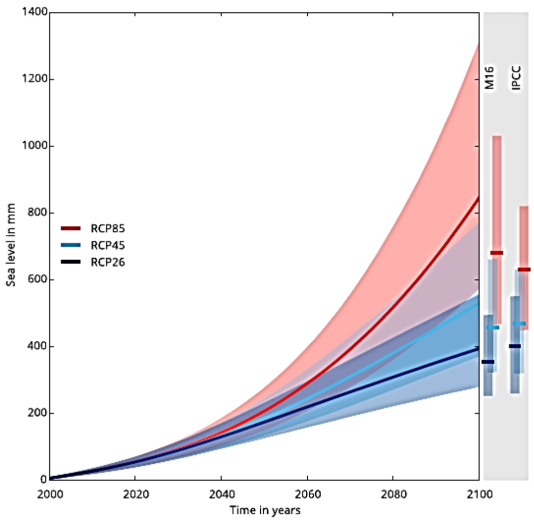

Figure 3-4: Global mean sea level rise (Mengel, et al., 2016)

Bars to the right in Figure 3-4 show the 5th to 95th percentile range of this study (M16) and of IPCC 2014. Seventy percent of the coastlines worldwide are projected to experience a SLR change within +/- 20% of the global mean. Expected global variation of change in average sea level relative to the 1986–2005 period is shown in Figure 3-5 below.

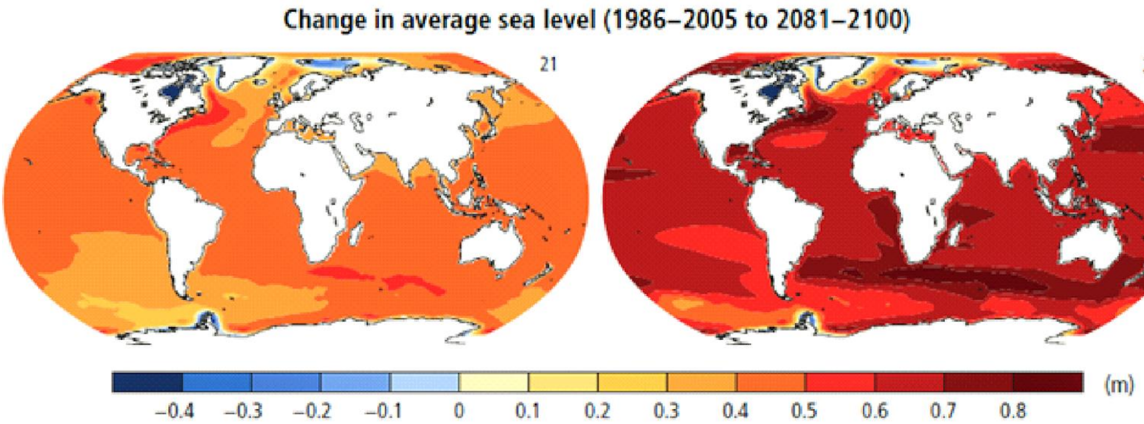

Figure 3-5: Change in average sea level, relative to the 1986–2005 period (IPCC, 2014)

However, no single place on earth will have the same local change in sea level as the global average. One needs to understand and consider all relevant and underlying processes associated with regional patterns influencing sea level rises in order to estimate a more accurate change in sea level for future scenarios.

It is expected that there will be a sea level rise of between 0.60 m and 0.70 m in Netherlands for this century according to the IPCC 2014 predictions. As per KNMI (Koninklijk Nederlands Meteorologische Instituut) Climate Change Scenarios 2006 for the Netherlands, 0.35 m of sea level rise is expected between 1990 and 2050. Moreover, the rate of SLR is expected to increase to about 1 cm/year between 2050 – 2100 (Hurk, et al., 2006).

In the Wadden Sea, the observed rate of SLR amounted to about 1.6-2.0 mm/year during the 1990s (Brouns, 1992). But, a strong and significant acceleration in SLR in the Wadden Sea in this century is highly probable which may lead to a number of changes in the unique morphological behaviour of the Wadden Sea area (Johannes, et al., 2017). Moreover, another study projects a 0.15 m SLR by 2050 in the Wadden Sea area (Steensma, 2014).

Based on the above literature findings, considering a 0.15 m SLR in 2050 and a rate of 1 cm/year SLR between 2050 – 2100, an estimated sea level rise of 0.65 m by 2100 can be expected specific to the Wadden Sea area. However, the Wadden Sea area experiences significant land subsidence due to extensive gas extraction which strongly affects the relative sea level rise. Land subsidence is predicted to be around 0.1 m over the next 50 years (Dissanayake, et al., 2012).

Therefore, considering increased upper limit of the recently predicted global mean sea level rise (Mengel, et al., 2016) and potential of bottom subsidence in the Wadden Sea area, a conservative value of **1 m of SLR by 2100** is assumed for further assessments of this study regarding the safety of the Holwerd sea dike.

3.5 Morphological Changes

During recent years the ferry connection between Holwerd and the village of Nes on Ameland is said to have become somewhat unreliable due to increased sailing time and delays (Jager & de Kleuver, 2016). This is apparent from the past four years' annual reports published by Wagenborg Passenger Service, stating that, for example specifically in 2017, up to 33.8% of the sailings were delayed by more than 10 minutes (Wagenborg Passagiersdiensten B.V., 2018a). This Holwerd-Ameland ferry connection problem has been in the spotlight for years due to regularly occurring delays (Deltares, 2015a).

The most frequently mentioned causes of these delays and interruptions are the morphological conditions and sedimentation problems which have resulted in a sharp increase in dredging volumes, specifically in the navigation channel (Jager & de Kleuver, 2016).

Details specific to the ferry navigation channel, which has a length of 12 km, and the required maintenance dredging thereof is included in Section 8 of this report. This section however summarises the desktop study performed to investigate the underlying physical causes and impact of the changes in morphology which are affecting the ferry connection.

Figure 3-6 shows the bathymetry map of the Ameland tidal basin and the location of the ferry navigation channel connecting Holwerd and the village of Nes. Also shown on the map, is the tidal watershed (*wantij* in Dutch) which separates the distinct catchment areas of the Ameland and Pinkegat inlets. It is interesting to note that other than the ferry commute, tourists are able to reach Ameland by mudflat hiking (*wadlopen* in Dutch) from the mainland to Ameland during low tide. This is a popular recreational and educational activity during the summer months.

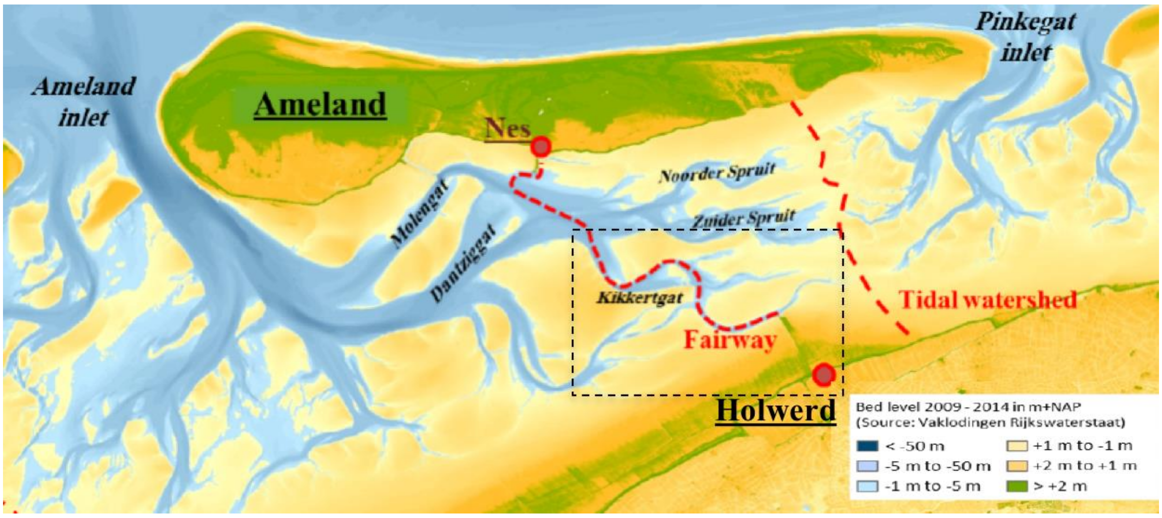

Figure 3-6: Bathymetry map of Ameland basin, location of the fairway and tidal watershed (van Til, 2017)

The Kikkertgat channel section is of specific importance concerning its meandering evolution and sedimentation process. Figure 3-7 illustrates the migrating meanders in Kikkertgat from 1993 to 2016. This evolving geometry has been obtained from superimposing historical bathymetry maps shown in Appendix A. The evolving geometry of this channel section has resulted in the navigation channel length increasing its length with an additional 1 km from the original 11 km long channel. The longer sailing distance has in turn caused a longer sailing time to/from Ameland; a journey which now typically takes 45 to 50 minutes (Wagenborg Passagiersdiensten B.V., 2018b).

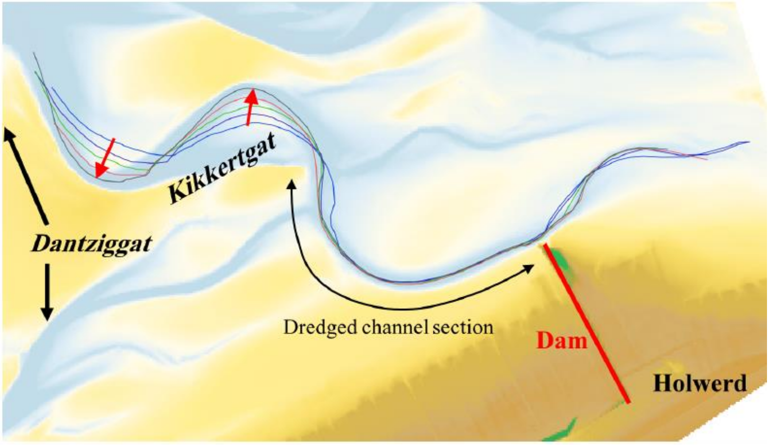

Figure 3-7: Meandering evolution of Kikkertgat channel bend during the period 1993-2016 (van Til, 2017)

Another physical process responsible for the problem and change in the Kikkertgat channel is the reduction of the water volume that flows through the channels. This mechanism can be attributed to the stronger meandering of the Dantziggat channel and potentially the movement of the tidal watershed, although no uniform conclusion has been drawn in literature regarding the watershed movement and its influence on the tidal prism. Previous studies however do indicate that a relation exists between the meandering evolution of the channels and the dredging activities (van Til, 2017).

Tidal basins, such as in the Wadden Sea are deposition areas for fine sediments. A reduction of the tidal prism, which is related to the storage capacity of the channels, results in a gradual decrease in volume of water. Dredging activities undertaken to maintain the navigable depth of the channel and increase the channel width, results in an increase in the cross-section of the navigation channel. For a constant volume of water, these factors result in flow velocities reducing, allowing sedimentation to take place (Bosboom & Stive, 2015). Therefore, the channel adapts by reducing in width and depth in an attempt to reach the state of equilibrium once again.

With the tidal basin being characterised as a flood-dominant basin, net sediment import and deposit is further enhanced (Herman, et al., 2016). This has led to the significant increase in the annul dredging volume, and hence costs, a point of concern for Rijkswaterstaat and other associated stakeholders.

4. SITE INFORMATION

4.1 Land Use and Topography

The village of Holwerd covers an area of approximately 0.47 km^2. This residential area is surrounded by mainly agricultural land (with underlying clay soil conditions) as illustrated on the land use map in Figure 4-1. Seawards from the dike, an area of wet natural terrain is seen along the foreshore. This comprises the salt marshes characteristic to the Dutch Wadden Sea coast as introduced in Section 3.3.

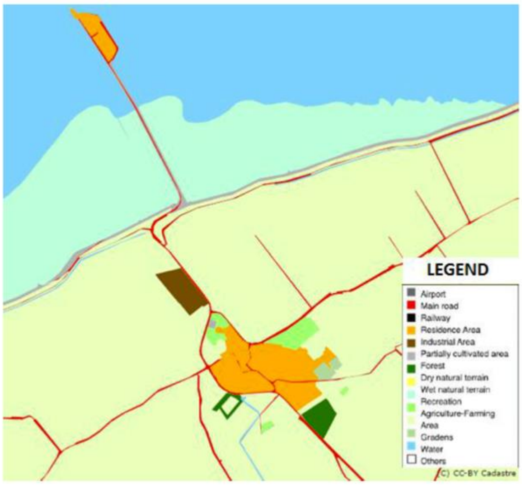

Figure 4-1: Land use around Holwerd (PDOK Viewer, 2018)

Figure 4-2 presents the elevation levels of the Holwerd region. The salt marshes, seaward of the dike, have measured average heights of +1.5 m to +2.0 m NAP (*Normaal Amsterdams Peil* in Dutch, NAP is the Dutch reference height). The dike reaches a height of ± 8 m NAP. Landwards, it is noticeable that most areas are very low-lying, ranging between 1.0 m and 1.4 m high, with Holwerd village itself being on higher land, approximately 5.0 m to 6.0 m high.

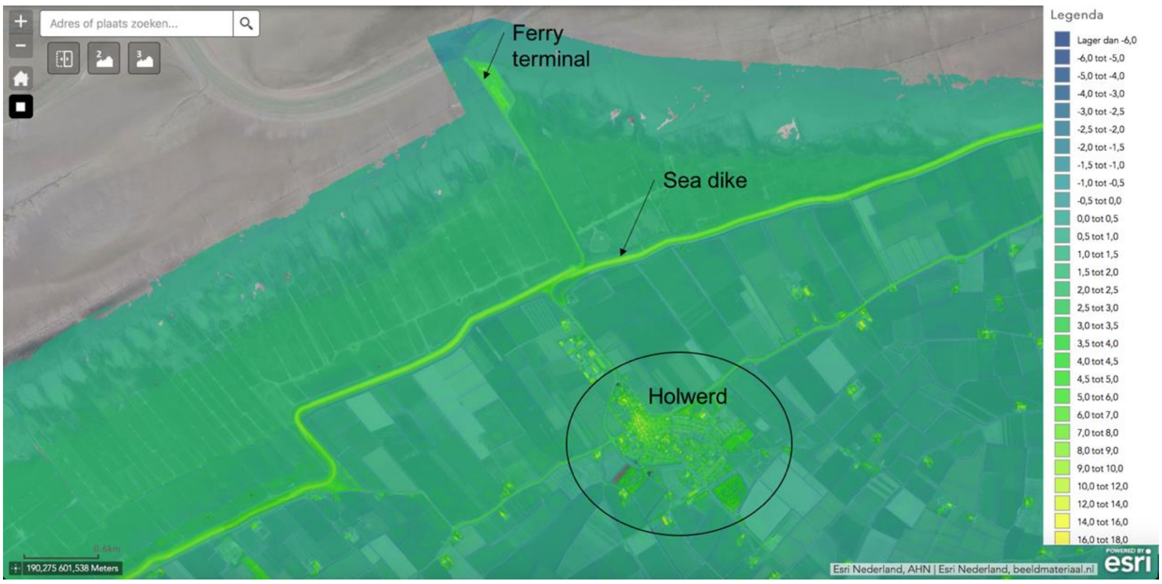

Figure 4-2: Elevation data (AHN Viewer, 2018)

Figure 4-2 is also used to show the proximity of the village of Holwerd to the sea dike and ferry terminal. The shortest distance from the edge of the village to the sea dike is approximately 0.9 km and the road leading from Holwerd's centre to the ferry terminal is almost 3 km.

4.2 Site Visit

A site visit to Holwerd was conducted by all team members on 19 March 2018 to inspect the village and its surrounding areas, the sea dike and ferry terminal. The sections below present the key information obtained from the site visit.

4.2.1 Socio-economic considerations

The site visit has shown that the village of Holwerd can be regarded as a remote town which is gradually becoming an unattractive and somewhat impoverished town. Decisions in the past have negatively affected the village of Holwerd and its attractiveness. Some businesses have closed down, resulting in fewer services and facilities and hence a decrease in quality of life. Unemployment has led to residents leaving the town, especially the youth who tend to move to the bigger cities in search of better job opportunities. A number of buildings were seen to be on sale, while others have been left vacant and are in a state of deterioration.

Holwerd has even been described as a "ghost town". A decline in population, starting in the early 2000's, has been recorded for Holwerd, as shown in Table 4-1.

Table 4-1: Holwerd population statistics (Holwerd aan Zee, 2017)

1999	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
1687	1762	1778	1620	1600	1530	1500	1480	1490	1500	1500	1495	1520	1475

However, according to statistics of Dongeradeel municipality which summarises the latest count of the total number of inhabitants per town, Holwerd has a population of 1607 as of 1 January 2017 (Dongeradeel.nl, 2017). This is a bigger population than the latest number referenced in Table 4-1. Nevertheless, the state of the village, it's opportunities and attractiveness is of growing concern to the residents of Holwerd.

Holwerd is seen mainly as a connection to the island of Ameland. However, with the ferry terminal being located 3 km away, and with no attractions in the village to draw the attention of tourists and commuters, people generally only pass by when heading to Ameland.

4.2.2 Sea dike

Figure 4-3 shows aerial photos of the dike, both taken from the north-east direction showing the bend in the road which then leads towards the ferry terminal. The large extent of the foreland-type salt marshes in this region near Holwerd is evident in these photos.

Figure 4-3: Aerial photos of Holwerd sea dike (Source: https://beeldbank.rws.nl/Gebied/Map?mapId=107)

The seaward and landside slopes of the sea dike are shown in Figure 4-4 below. The seaward slope is made of an asphalt layer and the landside slope is seen to have a grass cover.

Figure 4-4: Holwerd sea dike slopes. Seaward side (*left*) and Landside (*right*)

4.2.3 Salt marshes

The salt marshes located between Holwerd's dike and the ferry terminal cover a large area with an extension that varies from 1.5 km until a complete retreat eastward, at one point at the edge of Holwerd's perimeter. This configuration represents an almost triangular shape of the vegetation, as shown in Figure 4-5.

Figure 4-5: Salt marshes area in Holwerd (Google Earth, 2017)

4.2.4 Ferry terminal

The ferry terminal, with a large parking area, is shown in the aerial photo in Figure 4-6. The navigation channel shown in the right is towards the direction south of the terminal, i.e. to the immediate left of the terminal when looking towards Ameland. This short straight section then turns into the first bend in the navigation channel leading towards the village of Nes on Ameland.

Figure 4-6: Ferry terminal (*left*) and navigation channel (*right*)

5. HYDRODYNAMIC CONDITIONS

5.1 Bathymetry

The bathymetry for the site under consideration is shown in Figure 5-1. The bathymetric data was obtained from the Vaklodingen dataset from Rijkswaterstaat. Measurements are in terms of the NAP reference level.

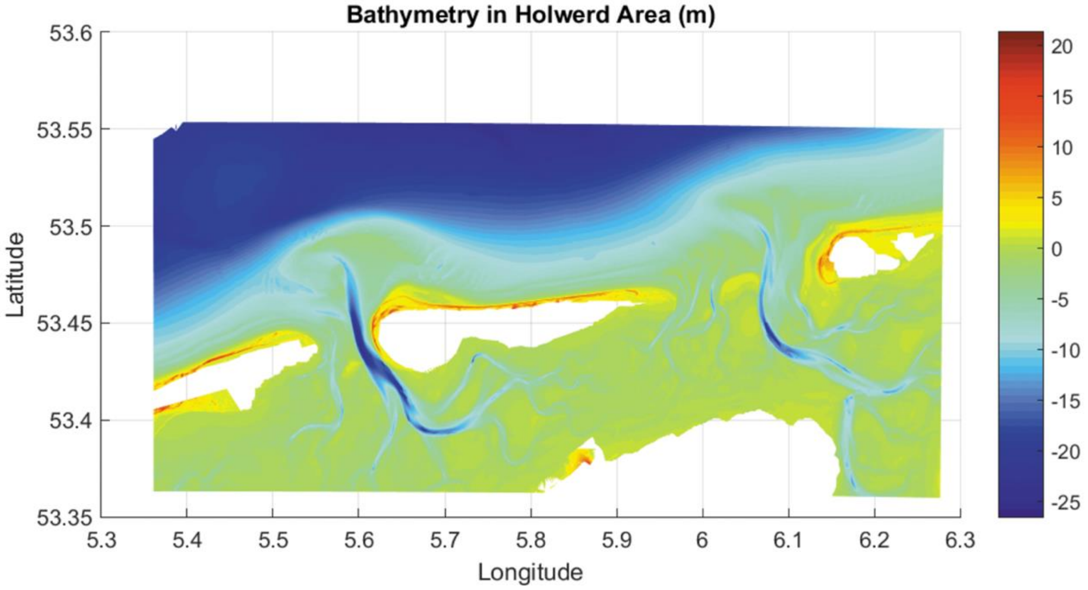

Figure 5-1: Bathymetry plot (Vaklodingen, 2018)

With the shallow channels and little intertidal storage, the Ameland tidal basin is considered flood dominant (Bosboom & Stive, 2015).

5.2 Tides and Currents

The Ameland tidal basin and ferry navigation channel is characterised as having a semidiurnal predominant tide, based on a form factor of 0.13, calculated from the tidal constituents for the area (Bosboom & Stive, 2015).

Water levels with reference to NAP are provided in Table 5-1 below. These water levels show an average astronomical tidal range of approximately 3.5 m. More specifically, a tidal range of 1.8 m can be observed at neap tide and approximately 2.5 m at springtide.

Table 5-1: Tide levels for Holwerd (Rijkswaterstaat, 2018a)

Tide level	Water level (+m NAP)
HAT	+1.49
MHWS	+1.18
MHWN	+0.87
MSL	+0.04
MLWN	-1.01
MLWS	-1.44
LAT	-1.91

The peak tidal velocities are in the range of 0.45 to 0.5 m/s during springtide. During flood and ebb, the peak velocities are about 0.7-1 m/s.

5.3 Water Levels

The accurate prediction of extreme high-water levels is very important for coastal flood mitigation. Hence a detailed assessment of the predicted design water levels for Holwerd has been performed with an extreme value analysis to determine the worst-case scenario. The analysis was based on water level measurements obtained from Rijkswaterstaat. Water level data from 1972 to 2018 was obtained, but there were no data available for the periods of 2000-2011 and 2013-2015. Therefore, complete data records were available only for 32 years. There was no proper reason available for the occurrence of these gaps and it was assumed that the measurements were carried out using the same instrument throughout the whole period from 1972 to 2018.

An extreme water level analysis was performed using the annual maxima method. Therefore, annual maximum values of all 32 years were obtained as shown in Figure 5-2. All the values are well above the highest astronomical tide (HAT) of 1.49 m as presented in Table 5-1.

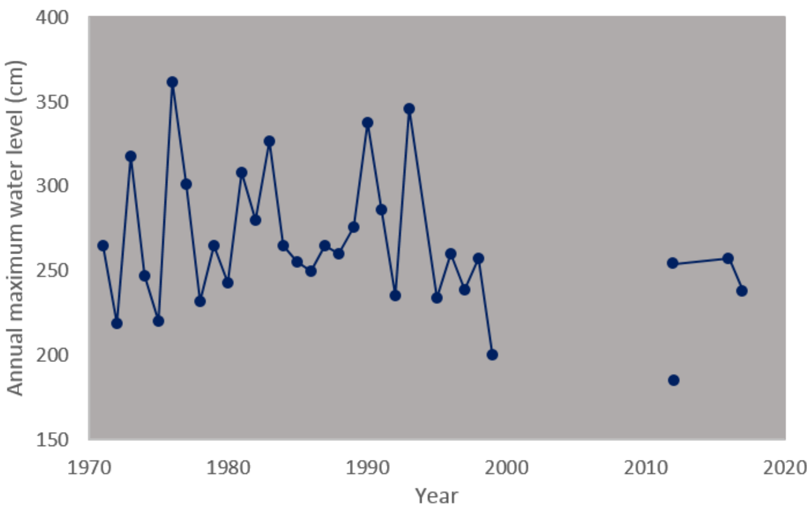

Figure 5-2: Time series of Annual maximum water levels

In order to determine the extreme water level in 1000-year return period (YRP), extrapolation was done by fitting annual maximum water level data to the Generalized Extreme Value Distribution (GEV). More details regarding the GEV model, Parameter estimation and statistical analysis are included in Appendix B: Extreme Water Level Analysis.

According to the results obtained from the statistical analysis, the extreme water level related to the 1000 YRP is 452.96 cm NAP.

Sea level rise needs to be accounted for as discussed in Section 3.4. Hence a final design water level for 1000 YRP was calculated as 553 cm (NAP), taking both the extreme water level and 1 m of SLR into account.

5.4 Wave Conditions

To evaluate Holwerd's dike safety under climate change conditions, a design significant wave height $H_{s,}$ that statistically represents extreme storm events at the location of the dike, has to be determined. Moreover, the mean wave period T_m and mean wave direction are important as well.

An extreme wave height analysis has been performed using the wave data acquired and thereafter the results converted to nearshore conditions through a wave transformation. The software Delft3D Wave was selected to perform the wave transformation for its suitability regarding complex geometries such as the tidal inlets in the Wadden Sea. Delft3D Wave computes the wave propagation using a third-generation SWAN (Simulating Waves Nearshore) model, the standard for this type of application (Delft Hydraulics, 1999). Delft Dashboard was used as a tool to generate grid and bathymetry models specifically for Delft3D Wave.

Details regarding the data processing, statistical modelling and nearshore transformation using these software are included in Appendix B. Below follows a summary thereof.

Significant wave height data was obtained from the station Schiermonnikoog Noord, operated by Rijkswaterstaat (Rijkswaterstaat, 2018b). This station, shown in Figure 5-3 is located at a latitude of 53°36' N and longitude 6°10' E, approximately 28 km from Holwerd's dike. Hourly intervals of significant wave heights, mean wave periods and mean wave directions were acquired for a period of 28 years form 13/04/1989 to 01/11/2017.

Figure 5-3: Location of the wave data station (Google Earth, 2017)

The offshore wave conditions can be characterised as follows: H_S = 11.5 m, T_m = 12 s. These hydraulic parameters were assumed as the boundary condition all along the seaward edge of the barrier island.

The software Delft Dashboard was used to create a model of the Ameland tidal basin and its inlets to perform a wave transformation from offshore to nearshore wave conditions (near the dike at Holwerd), thus modelling offshore storm waves and accounting for potential locally generated wind waves within the tidal basin. Figure 5-4 shows the grid with the associated bathymetry (in the present situation) and the four output locations (yellow dots) near the seaward edge of Holwerd's sea dike.

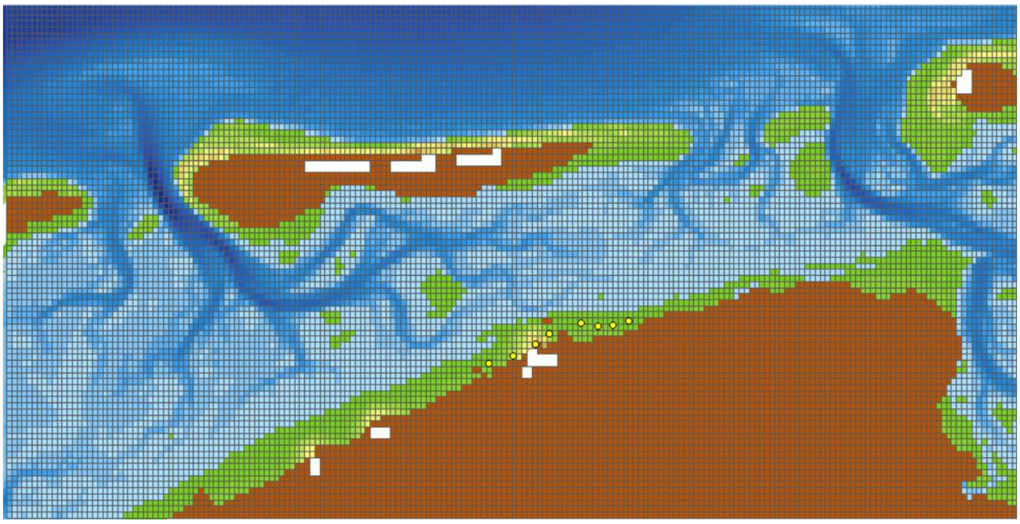

Figure 5-4: Generated model used for the wave transformation

The generated model in Delft Dashboard was then applied in the software Delft3D Wave. From the wave transformation, for a return period of 1000 years, the following hydrodynamic parameters were calculated at the dike's location:

- H_s = 2.00 m;
- T_m = 3.95 s;
- Wave direction = 339 °N.

This wave condition assumes the worst-case scenario, not taking into account wave damping by salt marshes.

These are the parameters used when assessing the performance of the dike and its safety against failure. Figure 5-5 shows the plot of the extreme wave heights over the entire area, resultant from the wave transformation.

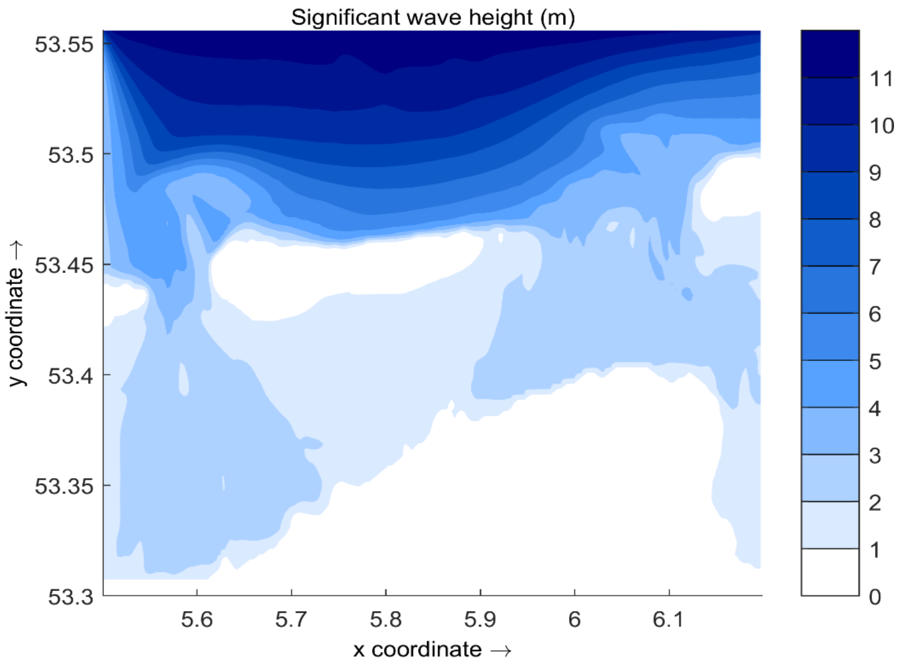

Figure 5-5: Distribution of extreme significant wave heights

6. FUNCTIONAL REQUIREMENTS

6.1 Battery Limits

After the site visit, the project's battery limits could be more accurately defined, as indicated in Figure 6-1. The dike section considered for further analysis is defined as the 5.5 km stretch of dike (shown in yellow) which falls within the Holwerd perimeter boundary, where on the east side the salt marshes retreat in a triangular shape as previously illustrated in Figure 4-5. The blue perimeter shows that the channels in the Ameland tidal basin (most importantly, the current ferry navigation channel) and associated morphology is relevant to the study, but the tidal inlets themselves (on either side of Ameland) are not considered in this study.

Figure 6-1: Study battery limits

6.2 Functional Design Requirements

From the stakeholder analysis presented in Section 2.3, the following functional requirements for the design of alternatives are identified:

- Spatial restrictions
- Minimal ecological impact on existing salt marshes
- Limited morphological impact
- Compliance to legislation
- Reduce risk of flooding, without heightening the dike
- Safety for ferry navigation
- Non-excessive costs and maintenance

6.3 Flood Safety Requirements

6.3.1 Return period

For the dike section considered, a return period of 1000 years is used for the design water level and wave heights (hydraulic conditions computed as in Section 0) as part of the project requirements. This means there is a 0.1% chance of these hydraulic conditions being exceeded in any one year which could potentially lead to a breach in the dike, i.e. dike failure.

6.3.2 Design life

Any new dike strengthening developments or constructions considered in this study is to be designed to a 50-year design life, a common design life chosen for many civil or coastal engineering infrastructure.

6.3.3 Safety Standard

For the reliability of the flood defence, overtopping discharge and individual risk needs to be within the safety standard values.

Within the Dutch major hazards policy, local individual risk (LIR) is defined as the probability of death of an average, unprotected person that is constantly present at a certain location (Jonkman, et al., 2017).The proposed local individual risk is:

$$LIR \leq \beta \cdot 10^{-4}$$

β is a policy factor that changes according to the voluntariness of exposure to the risk. For flooding in the Netherlands β is assumed equal to 0.1 (Jonkman, et al., 2017). The risk of an individual dying due to a flood should therefore be 10^{-5} or lower.

For overtopping, which is caused by waves running up the slope of dikes, a limit state is usually defined in terms of critical discharges. Very small overtopping discharges of 0.1 $l/(s \cdot m)$ or smaller is typically assumed to not be problematic and hence would not result in dike failure.

Due to sea level rise, extreme water levels and wave heights could result in too large overtopping discharges, potentially leading to dike failure. Accounting for the expected sea level rise, dike failure will be assessed against a design limit of 5 $l/(s \cdot m)$ for an inner slope consisting of good quality clay covered by grass (Jonkman, et al., 2017).

6.4 Ferry Navigational Requirements

6.4.1 Design Vessel

Wagenborg Passenger Services, the shipping company that operates the Holwerd-Ameland ferry service, own and make use of two same-sized ferries, the MS Sier (1995) and the MS Oerd (2003) for transport to/from Ameland (Wagenborg Passagiersdiensten B.V., 2018c). The ship parameters characteristic of both these ferry vessels are presented in Table 6-1.

Table 6-1: Design ship particulars (Bolt, 2017)

Ship particular	Dimensions – MS Sier	Dimensions – MS Oerd
Length (Lpp)	73.20 m	73.20 m
Beam (B)	15.9 m	15.9 m
Draft (max)	1.7 m	1.7 m
Draft (design)	1.65 m	1.65 m
Deck bridge height	14.45	14.45
Propulsion power	4 x 650 kW	4 x 745 kW
Vessel speed	10.8 kn	10.8 kn
Number of passengers	1200	1200
Number of passenger cars	72	72

Figure 6-2: Ferry vessels operating the Holwerd-Ameland connection, MS Sier (*left*) and MS Oerd (*right*)

6.4.2 Minimum depth required

For safe navigation through the channel between Holwerd and Nes, a minimum depth of 4 m below mean sea level (MSL), assumed equal to NAP, is required (Leovanrijn-sediment.com, 2017).

7. STATUS QUO ASSESSMENT – FLOOD SAFETY

7.1 Holwerd Sea Dike

In the present situation, the town of Holwerd is protected against flooding from the Wadden Sea by a sea dike. This sea dike, with cross-section shown in Figure 7-1, consists of a sand core and an outer protection layer of clay and grass. The middle and lower part on the seaward side is coated in asphalt, with a revetment of concrete blocks protecting the toe of the dike. These two features protect the outer slopes against wave impact. The dike presents a maximum crest height of approximately +8.5 m NAP The core is drained by a drainage pipe and wooden posts[2].

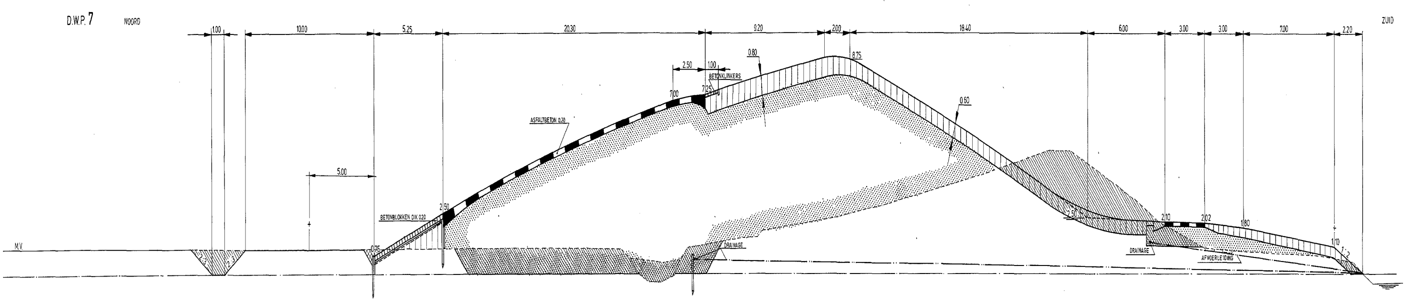

Figure 7-1: Dike cross-section

The dike is currently designed to withstand storming surges with a probability of 1/1000 year. In the sections that follow, grass quality and dike strength are assessed to determine whether the dike (in its present condition) will fail with the future load conditions as a result of climate change and sea level rise. Dike failure is evaluated in terms of maximum overtopping discharges allowed.

7.2 Overtopping

For a coastal dike, there are different failure modes, such as overtopping and overflow, erosion of the outer protection layer, sliding of the inner slope and piping. To assess dike failure, this study considers overtopping only, as it is assumed to generally have the highest probability of occurrence in coastal dikes (Jonkman, et al., 2017).

The main failure mechanism associated with run up and overtopping is the stability of the inner slope of the levee. Overtopping water can erode the inner slope which can lead to progressive damage and eventually collapse.

The values for the hydraulic conditions, as predicted for the future scenario in Sections 5.3 and 5.4 are used in the calculations. The design wave height and water level therefore results to 2.1 m and 5.5 m NAP, as presented in Table 7-1 below.

[2] Paul Buring (PBuring@wetterskipfryslan.nl), Wetterskip Fryslân, email correspondence, 12/03/18

Table 7-1: Design conditions

	H_{mo} (m)	Water level (+m NAP)
1/1000 years	1.89	5.5
10%	0.2	-
Design value	2.1	5.5

For wave run-up, the TAW formula was used:

$$\frac{R_{u2\%}}{H_{mo}} = 4 - \frac{1.5}{\sqrt{\xi_{m-1,0}}}$$

$R_{u2\%}$ is the wave run-up level which is exceeded by 2% of the incoming waves. H_{mo} is the significant wave height, taken as the design wave height of 2.1 m, and $\xi_{m-1,0}$ is the Iribarren number which for this case is equal to 1.32. This results in a wave run-up level of 5.3 m.

The Van der Meer formula is used to compute the overtopping discharge:

$$\frac{q}{\sqrt{g \cdot H_{mo}^3}} = \frac{0.026}{\sqrt{tan\alpha}} \cdot \xi_{m-1,0} \cdot \exp\{-(2.5 \cdot \frac{R_c}{\xi_{m-1,0} \cdot H_{mo}})^{1.3}\}$$

Where q is the mean overtopping discharge, α is the dike slope, and R_c the crest height above the mean water level. $\Upsilon b, \Upsilon \beta, \Upsilon f$ are the reduction coefficient taking into account the presence of a berm, the roughness of the cover and the wave angle attack. Their values are all 1, thus giving no reduction. Considering the design hydraulic conditions, a 1000-year return period, and a crest height of 2.7 m, a discharge of 14.3 $l/(s \cdot m)$ results. This is above the safety limit of 5 $l/(s \cdot m)$, as presented in Section 0, and so the dike does not satisfy the reliability standard. Thus, dike failure is assumed to occur in the future if no dike reinforcement occurs.

Wave angle of attack was considered normal to the dike, in order to have the highest wave overtopping value and follow a more conservative approach.

In the further steps of developing and analysing alternatives for dike strengthening, the possibility of integrating the present flood defence system with Multifunctional dikes and Eco-engineering concepts will be studied to determine how they affect the safety standards and to find the most applicable solution for the area to prevent potential dike failure in the future.

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8. STATUS QUO ASSESSMENT – FERRY CONNECTION

8.1 Introduction

According to Wagenborg's annual reports, there was a total number of 6278 sailings (total of both directions) in the year 2017, of which approximately 2122 delays of more than 10 minutes occurred (Wagenborg Passagiersdiensten B.V., 2018a). This is almost 34% of the sailings which are experiencing delays.

The following sections include details of the navigation channel, sedimentation processes and the increased volume of dredging associated with the dynamic morphology of the basin as introduced in Section 0.

8.2 Channel Dimensions

The ferry terminal at Holwerd is situated about 2 km seaward of the dike, with the navigation channel to Ameland starting in the Kikkertgat channel section. The ferry navigation channel connecting the mainland at Holwerd to the village of Nes on Ameland, as was shown in Figure 3-6, has a total length of 12 km, an increase of approximately 1 km over the span of approximately an 8-year period (Jager & de Kleuver, 2016). The channel is required to have a bottom width of 50 to 60 m and a minimum depth of 3.8 m (maximum 4 m).

The ferry navigation channel can be subdivided into two major sections. The first is the 8 km section from Nes to the point A, which lies in the meandering Kikkertgat channel and is shown in Figure 8-1. This 8 km long channel section is relatively wide, deep and sandy where dredging is minimum. The second section is that of the 4 km trajectory AC to the Holwerd ferry terminal. It is in this section, which runs partly parallel to the salt marshlands, where most dredging activities are required. This channel section is further described as being relatively narrow and shallow, and consists of a silty bed.

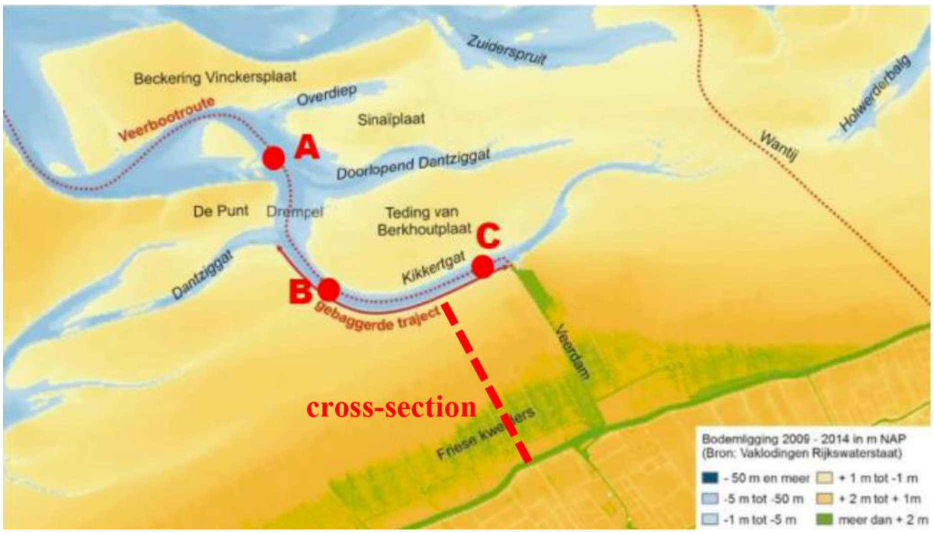


Figure 8-1: Navigation channel sections (Leovanrijn-sediment.com, 2017)

The natural bed level along the channel gradually increases in landward direction from about - 4 m NAP (dredged depth) just seaward of location A to about -1 m NAP near the ferry terminal. Figure 8-2 shows the corresponding cross-section, from the dike to the navigation channel in trajectory AC. The upper edge of landward channel side is at -0.5 m (below) NAP at a distance of 1.8 km from the dike. The marshland zone consists of a pioneer zone with a slope of 1:700 between -0.5 m NAP and +1 m NAP over a distance of about 1 km and a high zone at approximately +1.5 m NAP. The natural sedimentation in the marshland's pioneer zone in the period 1999-2004 was about 10 to 20 mm/year, equivalent to 10 to 20 m^3/m over a distance of about 1 km (Leovanrijn-sediment.com, 2017).

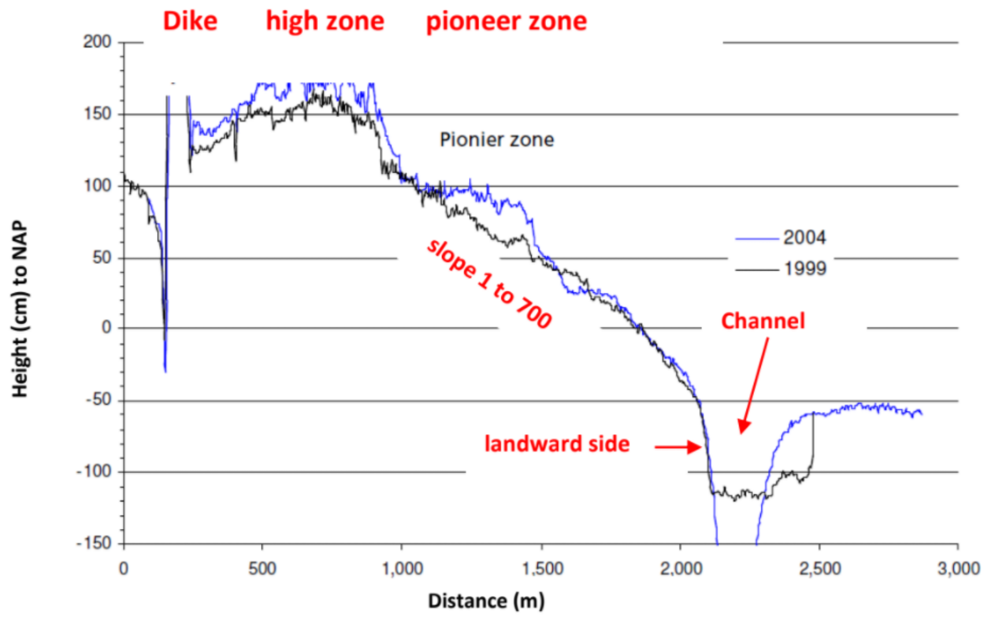


Figure 8-2: Cross-section perpendicular to Holwerd's coast (Leovanrijn-sediment.com, 2017)

8.3 Observations Regarding Sedimentation and Channel Morphology

Measurements were taken for the cross-sectional area below low water at various locations of trajectory AC from 1988 to 2011 (Arcadis, 2012). Results showed that there was a reduction in the cross-sectional areas of the channel over the 20 years for the trajectory AC, including a reduction of up to 40% in channel trajectory BC.

Noticeable developments in the navigation channel have been observed during the period 1989-2016, such as:

- Landward migration of tidal flats in period 1989 to 2005; about 3 m/year;
- Channel sides are stable after 2005 due to dredging;
- Marshland sedimentation of about 10 mm/year; and
- Thin layers of fluid mud (0.1 to 0.2 m) have been observed in the ferry channel occasionally; particularly near the ferry terminal due to agitation by ferry boat movements.

8.4 Sediment Origin and Composition

Deposition in the Holwerd-Ameland navigation channel comes from different sediment sources, namely:

- Natural deposition of mud and fine sand by landward asymmetrical tidal flow velocities (mud supplied by flood flow).
- Fine sand and mud from tidal flats on both sides of the channel stirred up by wind waves and ship waves at the shallow tidal flats; lateral supply of sediment is about 10 to 20 m3/m/year.
- Supply of mud from lower zone of marshlands stirred up by wind waves and ship waves; natural deposition of marshland zone is about 10 to 20 m3/m/year; marshland zone near the ferry

terminal shows no deposition over about 1 km which is indication of local supply of 10 to 20 m3/m/year towards channel due to cross-shore transport from the marshlands into the channel.

- Recirculation of mud due to dredging. Dredged material, disposed of during ebb flow, will move seaward over a distance of approximately 3 to 5 km during the ebb period but the mud cloud may return partly during flood flow. Soft freshly deposited mud at location A (after disposal) will be eroded during flood.

These sediment sources are illustrated in Figure 8-3 below.

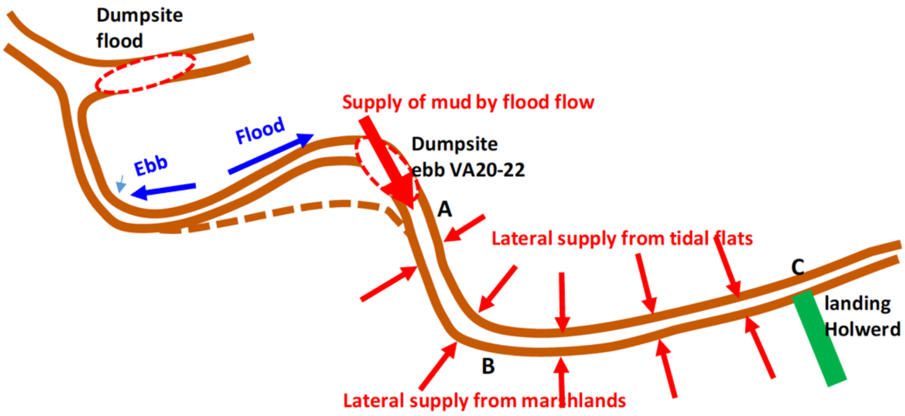


Figure 8-3: Mud sources and dumping sites along the channel (Leovanrijn-sediment.com, 2017)

The sandy channel bed is comprised of roughly 10% clay, 45% silt and 45% sand, whereas the silty channel bed (trajectory AC where dredging takes place) has 15% clay, 60% silt and 20% sand. The dry bulk densities of the dredged materials vary in the range of 250 to 650 kg/m^3. The dredged material consists of very muddy materials with a mean particle size of approximately 10 μm.

8.5 Dredging Operations

As previously mentioned, over the years there has been a significant increase in the dredging volume within the Holwerd-Ameland navigation channel. This is related to the sedimentation problems discussed above and the related changing morphology in the tidal basin (refer to Section 0), which calls for dredging operations to maintain the required channel depth of approximately -4 m NAP and channel width of 50 to 60 m for safe navigation. Safety during transit is of importance as more than 1.3 million passengers are transported via the ferry every year (Jager & de Kleuver, 2016).

The graph shown in Figure 8-4 shows that relatively no or little dredging occurred in the early 1990’s, but thereafter an exponential growth in the volume dredged occurs. The annual dredging volume of mud has increased to approximately 1.8 million m^3 in 2015. The seasonal variation in dredging volumes is not very large; with only slightly larger values during the winter period.

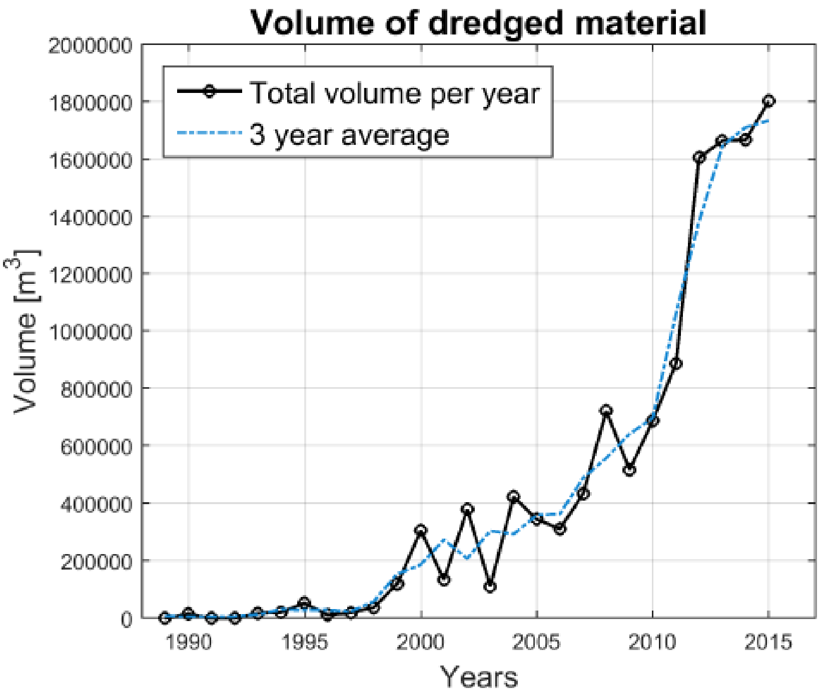


Figure 8-4: Growth in dredged volume (van Til, 2017)

Most of the dredging operations takes place in the narrow tidal channel trajectory AC which is 4 km in length. Consequently, the total thickness of the annual deposition volume spread out as a uniform layer in the channel, assuming the minimum channel width, can be estimated as 1.8 x 10^6 / (50 x 4000) = 9 m. This is more than twice the required channel depth which is too expensive and interferes with the ferry vessel's navigation, adding to the delays, i.e. 45 to 50 minute travel times instead of 30 minutes.

Since 2007, most of the dredged material, approximately 65% thereof, is pumped from the trailing suction hopper dredger at low tide into the ebb flow just seaward of location A, as demarcated in Figure 8-3 near the start of channel trajectory AC. During flood, the remainder of the muddy dredged material (35%) is dumped further away in the Zuiderspruit channel, by opening the bottom doors of the hopper vessel.

Possible and main causes of the increased channel deposition are the gradual growth of the marshland zone reducing the tidal velocities through the channel which results in less erosion capacity during ebb flow, instead enhancing flood dominance. The dredging disposal strategy may also enhance deposition as location A is still very close to the dredging site. Therefore, during flood tide sediments are stirred up and transported back into the channel where they have previously been dredged. And with the ebb flow having lower flow velocities, erosion of these sediments cannot occur.

9. ALTERNATIVE OPTIONS DEVELOPMENT

9.1 Concepts and First Elimination Round

The team held a brainstorming workshop to identify and develop alternatives at a conceptual level for both the dike for flood safety, and for the ferry navigation. These concepts were further assessed and then based on initial research, a first-order analysis was conducted to eliminate a number of the options before progressing to the preliminary design phase which follows in Sections 10 and 11. Summaries of this first elimination round are tabulated here below, with supporting information included in Appendix E for all concepts.

Alternative interventions to dike heightening, for ensuring long-term flood safety and accounting for climate change, are listed in Table 9-1. Each concept is briefly described (refer to Appendix E for further details) and the main reasons for either eliminating an option (red) or not (green) are included based on the functional requirements defined by the stakeholders' interests as listed in Section 6.2.

Table 9-1: Concept alternative measures to ensure flood safety

Flood safety alternative		Description	Elimination
1.	Traditional dike widening	Creating a storm surge berm on the outer slope to significantly reduce wave run-up and overtopping.	Sufficiently increases dike's safety. Most commonly constructed for dike strengthening.
2.	Wide green dike	Realise a shallower outer slope (1:7) covered with only grass, which would break the surf more efficiently.	Sufficiently increases dike's safety. Environmentally-friendly dike concept.
3.	Revetment change	Changing of dike cover from asphalt to concrete blocks or rip-rap blocks to increase the permeability of the cover and absorb more wave energy.	Most robust option.
4.	Multiple line of defence	Utilize natural and manmade features to reduce coastal flooding.	Lack of space. Ecological impact on existing salt marshes.
5.	Dike relocation	Moving the dike further towards the land.	Spatial restrictions, lose agriculture land. Significant costs for relocation.
6.	Sandy dike	Change inner slope of dike and place sandy layer that can reshape during a storm.	Innovative dike concept Easy to construct, low cost.
7.	Oyster/Mussel Reef	Placing artificial oyster reefs to reduce wave height.	Morphological impact worsening the sedimentation in navigation channel.

Similarly, the alternative concepts which could potentially alleviate or improve the current ferry connection problems are presented in Table 9-2 below, with two of them eliminated prior to further assessment.

Table 9-2: Concept alternatives to improve ferry navigation

Ferry connection alternative		Description	Elimination
1.	Do nothing alternative	Current ferry transport and dredging operations	Base case to compare alternatives to.
2.	Adjust vessel fleet and	Invest in a new ferry vessel, either smaller in size or faster sailing speed.	Potential to decrease annual dredging volume if smaller vessel. Potential for more reliable service, reduce operational downtime.
3.	Bend cuts	Dredge new straight channels and close meandering sections to shorten the overall length of the navigation channel.	Benefit in reducing channel length and sailing time. Potential for decrease in dredging volume.
4.	Extension of the ferry pier at current location	Build additional length of pier towards the deeper water from the existing location.	Significantly affect morphological behaviour of tidal basin.
5.	Relocation of the ferry terminal to the west	Moving the current location of the ferry terminal towards the deeper water in the west.	Guaranteed deeper water depth. Limit/no dredging required.
6.	Closure dam	Road across the tidal basin to connect Holwerd and Ameland.	Severe impact on tidal basin morphology. Negative impact to surrounding ecosystems.

Table 9-3 presents concepts that integrate Holwerd's sea dike and elements of the tidal basin, which affect the ferry's navigation, in one design. A corresponding discussion is included below Table 9-3.

Table 9-3: Concept alternatives for integrated designs

Integrated design alternatives		Description	Elimination
1.	Holwerd aan Zee	Breach the sea dike to create a tidal lake around Holwerd. Water flow flushes away sediments in navigation channel. Project proposed by residents of Holwerd (Holwerd aan Zee , 2018).	Not meet key objectives of this particular study. Spatial restrictions, lose agriculture land/out of scope. Morphological impact unknown. Flushing not guaranteed. Would increase risk of flooding.
2.	Use dredged material for strengthening of dike	Use dredged clay as material for dike reinforcement, whilst also reducing the sedimentation issue in the ferry channel by creating a sediment sink. Similar to clay ripening pilot project (EcoShape, 2018a)	Not a stand-alone solution.
3.	Alternative disposal scheme for dredged material for development of salt marshes	Dispose of dredged material elsewhere in basin so that sediments can be trapped and enhance salt marsh growth. This concept is based on idea of the current Mud Motor pilot project in Harlingen (TU Delft, 2018)	Not a stand-alone solution.

Alternative no.1 termed 'Holwerd aan Zee' is an innovative project proposal initiated by the local community of Holwerd. However, it aims to achieve objectives that are of lessor importance in this current study, such as tourism and economic growth instead of addressing the principal issue of flood safety. Although eliminated, it is an interesting concept which still requires detailed engineering studies to determine the feasibility thereof. Refer to Appendix E for more information.

The options of using the dredged sediments from the navigation channel in a beneficial way, either for reinforcing the dike directly or for salt marsh development, originates from a 'Building with Nature' approach. Both options are not deemed feasible as stand-alone alternatives, therefore they are not eliminated completely, but will be readdressed later in further analyses for inclusion and integration in the preferred solutions.

10. PRELIMINARY DESIGN – FLOOD SAFETY ALTERNATIVES

This section presents a more detailed design and analysis, including high level cost estimates, of each of the flood safety alternatives which were deemed feasible in the previous elimination stage.

10.1 Traditional Dike Widening

10.1.1 Concept definition

Widening the dike consists of creating a storm surge berm that reduces wave run-up and overtopping. A berm is a part of a dike profile in which the slope varies from horizontal to 1:15. The maximum effect can be realised with a berm height at the design water level and a width of five times the design wave height (Pullen, et al., 2007). In Figure 10-1 below, a cross-section of the dike with berm is shown.

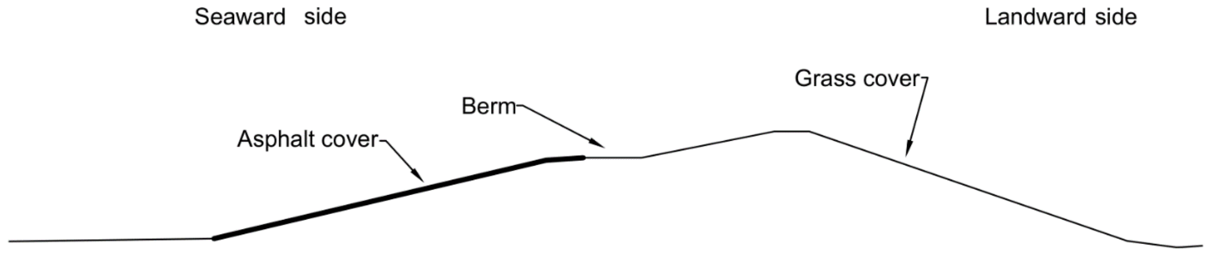


Figure 10-1: Traditional wide dike cross section

10.1.2 Technical aspects

The berm effect is taken into account in the Van der Meer formula with a berm reduction factor Υ_b given as:

$$\gamma_b = 1 - \frac{B_B}{L_B} \cdot (0.5 + 0{,}5 \cdot \cos\left(\pi \cdot \frac{h_b}{x}\right))$$

Where B_B is the width of the berm itself, L_B is the length over which the berm has an effect on the wave attack, h_b is the distance between the berm level and the water level and x is the 2% wave run-up.

By varying the length of the berm in the formula, it is possible to calculate a minimum berm length of approximately 4 m, which will reduce the overtopping to 3.8 $l/(s \cdot m)$, compared to the status quo of 14.3 $l/(s \cdot m)$ as calculated in Section 7.2 Calculations are included in Appendix F. With this reduced discharge value below the safety limit of 5 $l/(s \cdot m)$, the dike would be reliable and considered safe against sea level rise (SLR).

To build a berm 4 m long at the design water level (5.5 m), the cross-sectional area of the dike has to increase approximately 20 m^2 per meter length of the dike. Furthermore, the current asphalt cover would have to be removed and a new one replaced, adding additional costs. The berm would again need to be covered by asphalt as this would be the zone of major wave impact.

10.1.3 Impact assessment: Positive and negative consequences

Among the positive aspects of this solution is the fact that its reliability can be proven by the success of many other such engineering constructions around the world and it has been sufficiently studied.

However, this option could have a major environmental impact. Seaward land reclamation would be required, reducing the extension of salt marshes. For such a construction, legal permits under the Natura

2000 legislation are required, which may involve a somewhat rigorous application due to the protection regulations of salt marshes. The aesthetic value could be negatively perceived by the community, as most of the outer slopes are covered by asphalt. This could also reduce tourism, thus resulting in a low stakeholders' acceptance.

10.1.4 Cost estimate

The cost for materials and transport were provided by Wetterskip Fryslân. These costs are provided in Table 10-1.

Table 10-1: Costs for materials and transport (Wetterskip Fryslân[3])

Element	Cost	Units
Clay delivery	15	€/m^3
Profiling clay + compacting clay + soil top layer	10	€/m^2
Sand (by vessel)	10	€/m^2
Revetment Delivery	60	€/m^2
Revetment Installation	15	€/m^2
Granular filter layer + clay under layer + geotextile	20	€/m^2

Therefore, given the material requirements for this alternative, the total costs were calculated and are summarised in Table 10-2 below. This rough order of magnitude (ROM) cost estimate excludes operation and maintenance costs. The total capital cost for construction of a Traditional Wide Dike along the 5.5 km stretch of Holwerd's sea dike is approximately € 14.3 million.

Table 10-2: Cost estimate for traditional dike design

Material required	Quantity
New section surface extra (m^2)	19
New clay required (m^3)	106 480
New outer slope length (m)	34
New outer slope surface (m^2)	188 900
Concrete surface (m^2)	144 380
Element	**Cost**
Clay delivery	€ 1 600 000
Profiling + compact + top layer	€ 1 900 000
Concrete costs (delivery + installation)	€ 10 800 000
Total costs	**€ 14 300 000**

10.2 Wide Green Dike

10.2.1 Concept definition

A Wide Green Dike, such as the example shown in Figure 10-2, consists of a mildly sloping seaward face (with a of slope of 1:7) that merges smoothly into the adjacent tidal flats. Waves do not reach the dike during normal conditions and are damped by the foreshore. The gentle outer slope has the role of

[3] Information received by email from Paul Buring (PBuring@wetterskipfryslan.nl) on 10/5/2018

reducing wave impact during design conditions. In comparison to the Traditional Dike design, wave energy dispersion along the slope is more distributed, allowing a thick clay layer covered in grass to be sufficient to protect the dike against erosion (Loon Steensma & Schelfhout, 2016).

Additionally, a milder slope would break the waves more efficiently, reducing wave run-up and consequently decreasing overtopping rates. A Wide Green Dike, having a larger volume, may also be more robust than a Traditional Dike and have more residual strength if the top layer of the landward slope is damaged (Loon Steensma & Schelfhout, 2016).

Figure 10-2: A Wide Green Dike in Germany

Sedimentation in the adjacent salt marsh area could provide the clay for the construction of the dike and thus reducing the material costs. The maintenance system for Wide Green Dikes consists mainly in regular grazing for grass quality. In general, it has been proven that such an alternative can have economic advantages as the initial costs could be lower than a Traditional Dike (Loon Steensma & Schelfhout, 2016).

Various studies have showed the feasibility of the Wide Green Dike in the Wadden Sea area. Its ability to adapt to sea level rises rather than a dike with a stone or asphalt cover has also been highlighted (Loon Steensma & Schelfhout, 2016), (van Loon-Steensma, et al., 2014).

10.2.2 Technical aspects

To realise an outer slope of 1:7, the dike would need to be extended 15.5 m seaward which requires 68 m^2 of clay per meter length of the dike. Saltmarshes in the intertidal area just in front of the dike have a big wave damping effect that is not taken into account in the current flood defence system. Potentially, if the saltmarshes' good quality is maintained they could play a major role in preventing overtopping and dike failure. Specific to Holwerd's site conditions, salt marshes could be beneficially integrated into the Wide Green Dike design concept, as schematised in Figure 10-3.

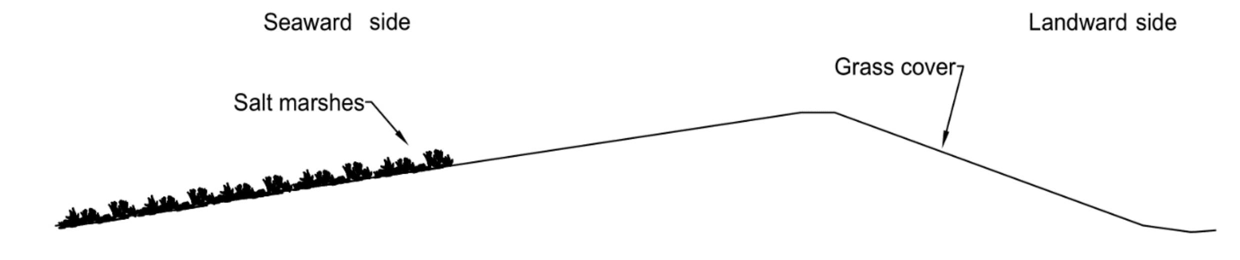


Figure 10-3: Wide green dike cross section

The overtopping assessment was done using the computer online program PC OVERTOPPING. The program is available from the EurOtop Overtopping Manual website. This program was chosen as it was based on dike structures (Pullen, et al., 2008) and has been used in many research articles on wide green dikes (Loon Steensma & Schelfhout, 2016). Implementing the wide green dike section in the program, gives an overtopping rate of approximately 2.5 l/s/m, which is well below the limit of 5 l/s/m. Therefore, the Wide Green Dike would be considered of satisfactory safety standard.

10.2.3 Impact assessment: Positive and negative consequences

This type of intervention requires a larger area on the seaward side, which could be a limiting factor. The construction of the Wide Green Dike would result in land reclaimed from the salt marshes adjacent to the dike, damaging the ecological value of the area. This reclamation for dike expansion would require legal permits. A possible solution is balancing this loss with an environmental benefit somewhere else.

The wide green dike could potentially have many environmental benefits. First, it guarantees an increase in biodiversity and allows for saltmarshes to grow on the lower part of the outer slope in the intertidal zone. This would be perceived positively both by the community and tourists, thus possibly increasing the area's income from tourism. Moreover, it has, as highlighted before, the potential to grow with sea level rise, making this alternative more flexible and adaptable to climate change. A concern is that this design has rarely been implemented in the Netherlands. However, it has in Germany and there are currently many studies and research being done on this topic, but since the implementation in reality is still low, its reliability is not very high.

10.2.4 Cost estimate

Table 10-3 summarises dimensions and preliminary costs for the proposed wide green dike design.

Table 10-3: Cost estimate for wide green dike design

Element	**Quantity**
Original section surface (m^2)	97
New section surface (m^2)	165
New clay required (m^3)	374 110
New extension (m)	45
New outer slope length (m)	45.5
New outer slope surface (m^2)	249 679
Element	**Cost**
Clay delivery	€ 5 600 000
Profiling clay + compacting clay + soil top layer (grass)	€ 2 500 000
Total costs	**€ 8 100 000**

10.3 Revetment Change

10.3.1 Concept definition

The main function of revetments is to prevent the soil body of the levee from coming into direct contact with the erosive forces of the waves, currents or other objects. Dikes typically have a clay and grass cover layer if the grass cover can provide sufficient erosion resistance. If this is not the case, a hard-protective layer must be placed instead, for which there are different options ranging from natural stone pitchings, to concrete elements or asphalt covers (Jonkman, et al., 2017). In the current situation, the dike has an asphalt cover on the lower part of the outer slope (refer to Section 7.1), which will be submerged in extreme conditions and loaded by the largest wave impacts during a storm.

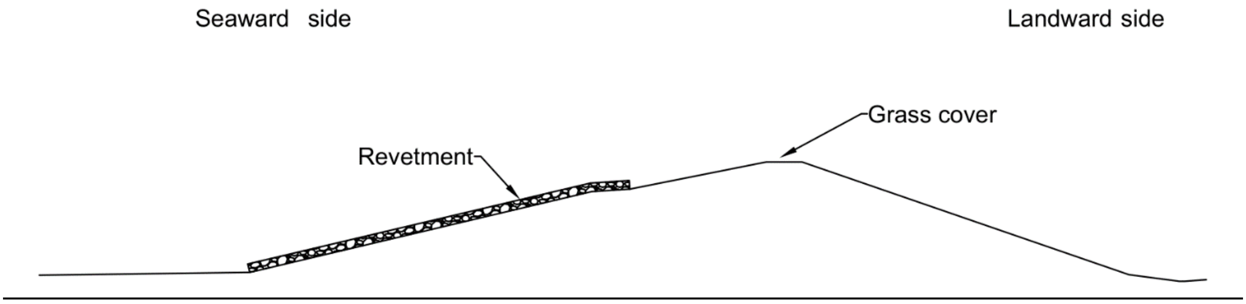


Figure 10-4: Revetment change cross section

An alternative to the asphalt cover is stone pitchings or ripraps, Figure 10-4. The difference between these two alternatives and the asphalt cover is that they have a higher permeability and allow water to partially wash through the cover, therefore losing more energy (Jonkman, et al., 2017). Riprap consists of a revetment of dumped natural rocks, which are mined in mountain areas, and transport costs to this project site may be an issue. Block pitchings can be used either from natural stones or concrete elements. The pitching itself consists of individual, loose blocks that are placed tightly together (Jonkman, et al., 2017).

10.3.2 Technical aspects

To assess the effect of these two methods on the dike's safety, roughness values of 0.90 and 0.70 for stone pitchings and a layer of riprap respectively (Pullen, et al., 2007), were used in the overtopping formula showed in Section 7.2. Since only the lower half of the outer slope would be covered with the revetment and the other half with grass, an average of the roughness value between the two covers was used in the formula. Both the two alternative revetments reduce the overtopping discharge below the 5 $l/(s \cdot m)$ safety and design limit.

To estimate the dimensions for the revetment units, the Rock Manual was used (CIRIA, et al., 2007). This manual was chosen as it is the most used for choice of revetments in Europe. The D_{n50} value was computed to be equal to 0.25 m. This is the diameter that is exceeded by 50% of the total revetment units. The thickness of the revetment is 0.5 m and a filter layer is also required. Its role is to prevent erosion of the dike core and reduce the unit diameter gradient in the cross section. The filter layer has a D_{n50} of 0.05 m and a thickness of 0.125 m. All these values come from the use of formulas in the rock manual and were later used for the cost estimate.

10.3.3 Impact assessment: Positive and negative consequences

The utilisation of revetments for dike safety is widely distributed in the Netherlands, this gives a positive value to the alternative for its reliability and practical implementation. Indeed, also the research conducted on different revetment types is quite high. For this solution, maintenance is required scarcely, as only during big storms the revetment could be affected.

Although, this solution does not have much adaptability to future scenario changes as it is a robust and rigid alternative. It would however, have a negative impact on the flora and fauna of the Wadden Sea, as rock blocks are not traditionally part of the ecosystem, thus reducing biodiversity. The aesthetic value is also believed to decrease, resulting in a negative touristic value and public acceptance.

10.3.4 Cost estimate

Using the values for materials costs as listed in Table 10-1 and the above technical requirements for this design, the total costs were calculated as follows in Table 10-4.

Table 10-4: Cost estimate for revetment change design

Element	Quantity
Dn_{50} (m)	0.25
Armour layer thickness (m)	0.5
Filter layer thickness (m)	0.125
Armour surface (m^2)	129 250
Filter surface (m^2)	129 250
Element	**Cost**
Armour transport	€ 7 800 000
Armour installations	€ 1 900 00
Filter costs	€ 2 600 000
Total costs	**€ 12 300 000**

10.4 Sandy Dike

10.4.1 Concept definition

An Overtopping Resistance Dike or simply Sandy Dike is an alternative to adapt the Holwerd sea-dike in such a way that it can withstand overtopping rates higher than the allowable design overtopping criterion. This is achieved by changing the inner slope of the dike.

The new Sandy Dike concept consists of placing a layer of sand on top of the landward slope. This layer is sufficiently thick to keep the dike stable during and after extreme overtopping events. In these cases, the sand is washed away and reshaped, as seen in Figure 10-5. Since these events rarely occur, the maintenance costs to replace the sand are expected to be very limited.

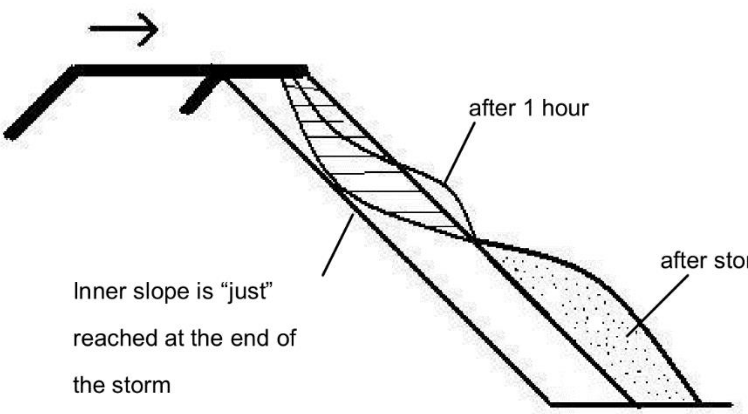


Figure 10-5: Expected reshaping in the sandy dike after extreme storms (Koopal & Onderwater, 2005)

10.4.2 Technical aspects

A 2 m layer of sand is suggested to reinforce the dike on the landward side. Drains may be placed at the lower end in order to protect the toe of the sand layer. Figure 10-6 is a scaled down drawing to represent this solution applied to the current traditional dike in Holwerd.

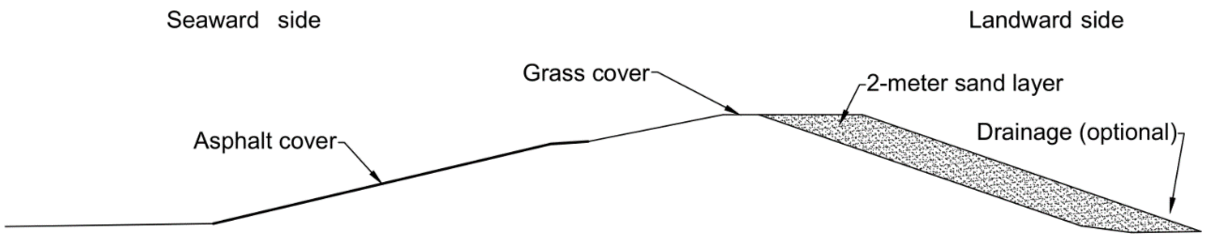


Figure 10-6: Sandy Dike profile in Holwerd

The most important failure mechanism of this alternative is the erosion in the adjacent boarder between the sand layer and the present structure. But the probability of failure due to severe rainfall and wind conditions is minimal. The sand is able to move and easily change its shape, as long as its sand volume remains the same. The present asphalt layer on the seaward side of the dike and the grass cover at the crest of the dike represent an additional protection against sand erosion on the landward side.

As an example, a 2 m layer thickness has been suggested by the engineering company Arcadis for the dike Westkapelle with an average overtopping volume of 8 l/m/s for a sea level rise scenario in 2100 (Koopal & Onderwater, 2005). To determine if this sand layer thickness is also enough for Holwerd, calculations have been made using a simple sediment transport model for sand in steep slopes in Appendix F. The results show that a 2-m thick layer is safe enough to withstand the design storm with 1000-year return period for longer than 2 hours.

A drainage system is necessary if sliding of the sand cover occurs due to high pressure when this layer is wet from heavy rainfall or wave overtopping. A further geotechnical investigation needs to be performed to check if it is the case. Since sand is very permeable, this tension build-up is not likely to occur. The application of drainage pipes might also reduce the need of regular maintenance. Compared to clay dikes, sand reduces runoff, which is positive to the local water system.

10.4.3 Impacts: Positive and negative consequences

Vegetation can grow freely in this type of solution and may increase the ecological quality of the area by functioning as a bypass for certain species in the nearby ecological zones. The sand cover resembles a natural dune instead of an artificial structure that would break the landscape. The placement of a sand layer has been done in the past for landscaping purposes in the Flaauwe Werk sea dike on the north-western coast of Goeree, in the Netherlands (Veendorp, et al., 2005).

Stimulating vegetation growth also contributes to the stability of the sand, decreasing its sand losses. Protected birds could be attracted to plant species like the sea buckthorn or dune roses. The planting of these species is therefore encouraged.

Figure 10-7: Sea buckthorn in sand dunes (K.U.Leuven Campus Kortrijk, 2018) (Brooks, 2015)

No legislative risks are expected regarding the environmental permits necessary to perform this type of dike reinforcement.

People might be attracted to the dune atmosphere created by the Sandy Dike concept. This landscape creates a comfortable environment for activities such as walking and cycling, adding recreational value to the sea dike.

10.4.4 Cost estimate

The sand as a construction material has an infinite lifetime. Its maintenance necessity is similar to sand dunes. Sand is easier to work as a construction material than clay, since the transportation of clay create lumps that need to be compacted (Jonkman, et al., 2017). But human interaction might cause disturbances that increase the frequency of maintenance. Also, the road located near the dike might be affected by sand spray that needs to be wiped, increasing the maintenance costs of the road. For this reason, maintenance costs for the Sandy Dike cannot be neglected.

An initial cost estimate was done for the Sandy Dike concept, considering a 50-year lifetime of the structure, as it is shown in Table 10-5 below. These values were mostly obtained from an engineering report written by Arcadis in 2005 and corrected for inflation (Koopal & Onderwater, 2005).

Table 10-5: Cost estimate for sandy dike design

Element	Quantity	Cost
Length of the dike	5 500 m	
Cover area	150 000 m^2	
Removing current cover	2 €/m^2	€ 300 000
Eliminate current cover	4 €/m^2	€ 600 000
Placing the drains	10 €/m	€ 55 000
Placing the sand layer	10 €/m^2	€ 1 500 000
Maintenance	9.5 €/m/year	€ 2 600 000
Transportation	10 €/m^2	€ 1 500 000
	Total costs	**€ 6 500 000**

11. PRELIMINARY DESIGN – FERRY CONNECTION ALTERNATIVES

This section presents the preliminary designs and high-level cost estimates of the alternatives developed for improving the ferry connection service between Holwerd and Ameland.

11.1 Base Case

11.1.1 Concept definition

The base case option relates to a 'do-nothing' approach which will be used to compare the current ferry service and dredging operations to the proposed alternative ferry connection options in a multi-criteria analysis (MCA). Therefore, this option considers continuing to dredge the Holwerd-Ameland navigation channel, following the same dredging and disposal scheme as what is currently undertaken.

To use the current dredging scheme as comparison to the alternative suggestions, the dredging volumes, time required to dredge and potential impacts, as well as associated costs, need to be understood. Dredging operations of the current situation were introduced in Section 8.5; here follows additional details and analysis thereof.

11.1.2 Technical aspects

Based on 2015 measurements, a sediment volume of approximately 1.8 miilion m^3 is dredged annually in the navigation channel (van Til, 2017). Sediments on the seabed and channel edges need to be dredged on average every 9 days (i.e. return period), sometimes more regularly, throughout the whole year in order to provide the required safe navigational depth of -4 m NAP and channel width of 50 – 60 m for the ferry (Leovanrijn-sediment.com, 2017).

Disposal locations of the dredged material from the 4 km channel bend nearest to Holwerd, are illustrated in Figure 11-1. Most of the silty dredged material (±65%) is discharged by pumping, into the ebb flow near the dredged area, demarcated as "Ebstort VA20-22". In recent years, this order amounts to approximately 1.1 million m^3 of mainly sludge deposited per year (Deltares, 2018). The remainder is dumped further away during flood at the channel Zuiderspruit ("Vloedstort Zuiderspruit").

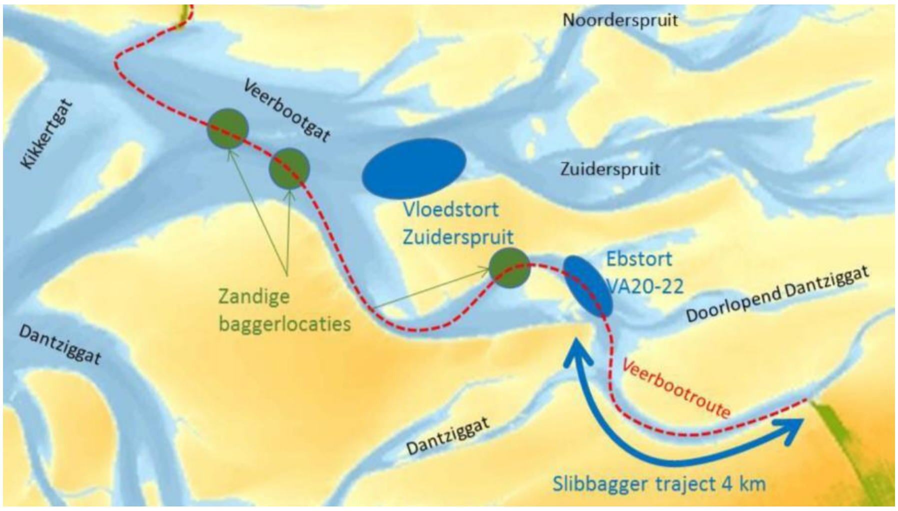


Figure 11-1: Dredging and dumping sites near Holwerd (Deltares, 2018)

Assuming that sedimentation has reached a maximum and so the amount of dredging is more or less constant per year, i.e. annual volume of 1.8 million m^3, a total volume of 54 million m^3 would need to be dredged until 2050, considering the year 2020 as a base year.

11.1.3 Impacts: Positive and negative consequences

Dredging is common practice in the Wadden Sea due to the sedimentation processes and requirement to provide safe navigable waterways to the Dutch Wadden islands, not only to Ameland. However, as previously discussed, the increasing volume of sediments to be dredged annually in the Holwerd-Ameland channel is of growing concern.

The potential environmental effects of maintenance dredging are generally two-fold, as a result of the dredging process itself and the disposal of the dredged material as well. Dredging may cause the removal or smothering of subtidal benthic organisms (IADC/CEDA, 1997). A temporary increase in the level of suspended sediment causes turbidity, changing the water quality which can affect marine flora and fauna unfavourably. This includes negative effects on primary production, on the ecological food chain of the system and the overall biodiversity.

Specific to the Holwerd-Ameland case, it is possible that the volume of dredged mud recirculates many times over the year by dredging; disposal in the ebb flow of the channel and the return of mud clouds during flood adds to the sedimentation problem (Leovanrijn-sediment.com, 2017).

Dredging and disposal may also cause changes to the hydrodynamic regime and geomorphology. This is believed to be the case here, due to the channel adapting by decreasing in width and depth through sedimentation to reach the state of equilibrium again (refer to Section 3.5).

Some benefits include that dredging should in general be adaptable to any change of scenarios and equipment is mobile. However, a negative impact of this particular dredging scheme is that dredging activities are required so often that it interferes with the ferry schedule, adding to the apparent delays.

11.1.4 Cost estimate

The cost for dredging and disposal of sediment within the Wadden Sea is assumed to lie within the range of € 2 to € 6.5 per m^3 (Boskalis.nl). For preliminary cost estimates, 75% of the above range is adopted. Therefore, assuming a more or less constant sediment volume of 1.8 million m^3 is to be dredged annually, total dredging costs can be roughly estimated to € 290 million over a period of 30 years form 2020. For more details, the dredging volumes and costs are tabulated in Appendix G, alternative 1.

11.2 Adjust vessel fleet

11.2.1 Concept definition

A suggested solution is to look into the possibility for the ferry operator company to commission new, more suitable ferry vessels. Therefore, this option looks into addressing the current ferry delays by means of a more operational approach, with the aim to also reduce the dredging costs if possible. The current vessel has a maximum speed of 10.8 knots (=20 km/hr) and so just making use of a faster vessel alone would decrease the sailing time between Holwerd and Nes, therefore better accommodating the passengers. Transport by a smaller-sized ferry could also result in a reduction of channel dimensions required for safe navigation, hence this has the potential to reduce the volume of sediments to be dredged from the channel annually.

Wagenborg Passenger services are said to have a concession agreement as the Holwerd-Ameland ferry operators until 2029 (Jager & de Kleuver, 2016). This alternative is therefore more applicable as a long-term solution, when either Wagenborg or a potential new ferry operator company can purchase the new ferries; it is considered unlikely that Wagenborg would purchase replacement ferries in the next few years prior to 2029 when their concession ends and they would need to reapply for a renewed contract.

11.2.2 Technical aspects

In the pursuit of minimizing the amount and cost of dredging in the future by reducing the depth required for safe navigation, smaller vessels with reduced drafts were first considered. However, with the current vessels, MS Sier and MS Oerd, both having a maximum laden draft of only 1.7 m, acquiring a suitable ferry with a much smaller draft, such that the minimum required channel depth reduces significantly, is assumed not possible. Faster and smaller vessels in terms of beam size, was therefore considered next.

Two ferry vessels are selected to represent example ferries having sizes which could potentially allow for the adjust vessel fleet alternative to be successful. Ship parameters of the two selected vessels are presented in Table 11-1. The Damen Fast Ferry 4212 (Damen Shipyards Group, 2018) is selected as an example ferry, based on its limited beam dimension of 11.6 m which is much smaller than the current ferries' beam of 15.9 m (refer to vessel parameters in Table 6-1). This reduction in width of the vessel can greatly improve the navigational safety of the vessel within the channel as well as allow for a reduction in required channel width. The other vessel, MS Rottum is in fact also owned by Wagenborg Passenger Services and is currently used for the Lauwersoog – Schiermonnikoog route, the island directly east of Ameland (Wagenborg Passagiersdiensten B.V., 2018d). The MS Rottum has a width only slightly smaller than that of the current ferries in operation, however this 2 m reduction could still have a significant effect on the minimum channel dimensions required for navigational safety. Photos of both ferries are shown in Figure 11-2.

Table 11-1: Design ship particulars for adjust vessel fleet alternative

Ship particular	Dimensions – Damen Fast Ferry 4212	Dimensions – MS Rottum
Length (Lpp)	42.20 m	58.00 m
Beam (B)	11.6 m	13.82 m
Draft (max)	1.5 m	1.7 m
Vessel speed	40 kn	11.9 kn
Number of passengers	450	1000
Number of passenger cars	0	48

Figure 11-2: Example ferries for adjust ferry vessel fleet alternative. *(Left)* Damen Fast Ferry 4212. *(Right)* MS Rottum

Through additional research it has become apparent that Wagenborg and the Municipality of Ameland argue that the current width of the navigational channel is not sufficient and should be expanded to 67 m, according to independent international PIANC guidelines. Rijkswaterstaat who manages the dredging operations however disagrees (Royal Wagenborg, 2016). Included in Appendix G are calculations for the channel width following the standard approach followed by PIANC (2014). For the base case, assuming the 15.9 m beam of the MS Sier or MS Oerd, a channel width of 67 m is indeed calculated. However, it is important to note that these calculations are based on channel calculations for two-way traffic, whereas the entire Holwerd-Ameland channel is not assumed to be classified as two-way traffic channel. Therefore, these calculations can be seen as somewhat conservative for the specific case of the tidal channel between Holwerd and Nes. Additionally, due to Rijkswaterstaat being a key stakeholder in this study, the dimensions they see fit are adhered to, i.e. 50 – 60 m (±18% reduction). To obtain the minimum channel width required for the smaller-sized ferry vessels, the PIANC calculations are carried out and reduced relative to the base case. The smaller-sized ferries result in a smaller channel width requirement assuming the same ±18% reduction from the PIANC calculation. These dimensions are summarised in Table 11-2 and details can be referred to in Appendix G.

Table 11-2: Summary of safe channel width calculations

Parameter	**Ferry vessel alternative**		
	Base case – MS Sier, MS Oerd	**Damen Fast Ferry 4212**	**MS Rottum**
Channel width based on PIANC (2014)	67.0 m	53.4 m	58.0 m
Channel width reduction compared to base case	-	20.4 %	13.4 %
Average actual width required (-18%)	55 m	45 m	48 m

Figure 11-3 illustrates a schematization of this width reduction for the Damen Fast Ferry 4212.

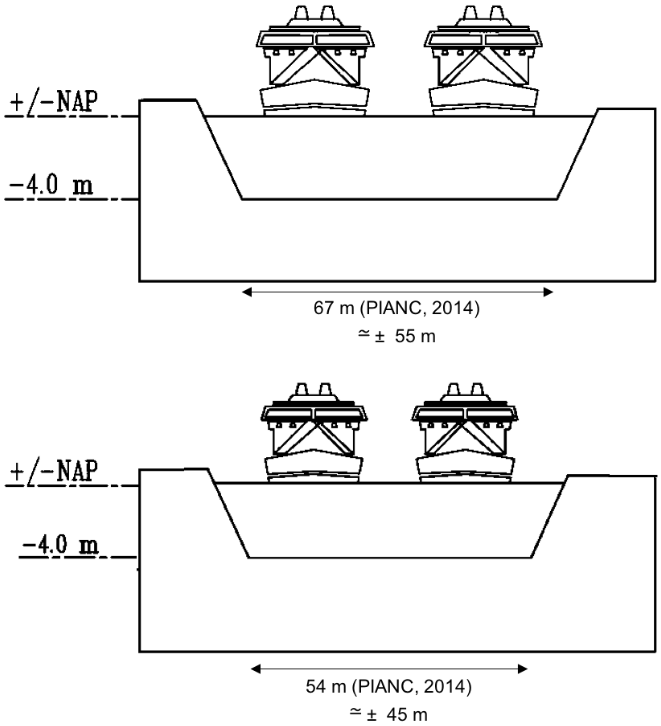


Figure 11-3: Reduction in width of navigation channel

It terms of the volume of sediments to be dredged in the navigation channel, a reduction relative to the width reduction is assumed due to a narrower channel being required to be maintained by dredging. Therefore, with a ferry the size of the Damen Fast Ferry 4212, a total of 1.43 million m^3 (-20.4%) would need to be dredged annually instead of 1.8 million m^3. Similarly, a reduced sediment volume of 1.56 million m^3 (-13.4%) would be required to be dredged for operation of the MS Rottum.

Regarding the speed of vessels, it was found that a faster vessel could decrease sailing time and consequently result in a more reliable ferry service. For the Wadden Sea, a maximum vessel speed of 15 knots (27.8 km/hr) is assumed. This is quite fast for a large ferry vessel, considering the meandering bends in the navigation channel and a need for the vessel to slow down to ensure safety. Therefore, a vessel speed faster than 15 knots is not recommended as this would again increase the channel width safety requirement. Assuming a maximum speed of 15 knots for the Damen Fast Ferry 4212, the sailing time is reduced to approximately 32 minutes instead of the 45 minutes that MS Sier and MS Oerd take. This calculation takes into account an additional 25% as a safety margin due to slowing down, especially when navigating the channel bends. MS Rottum has a lower maximum speed and hence results in a total sailing time of approximately 40 minutes.

Noticeable in the ship parameters, particular to the Damen Fast Ferry 4212, is that this ferry only has capacity for 450 passengers, a significant decrease compared to the capacity of 1200 passengers which Wagenborg's vessels can currently accommodate. However, analysis of the current ferry operation shows that with approximately 1.3 million passengers transported annually and a total number of 6278 sailings in 2017 (Wagenborg Passagiersdiensten B.V., 2018a), an average of only 207 passengers are on board each ferry trip to/from Ameland. Wagenborg Passenger Services publish that they provide sufficient capacity and so it is not necessary nor possible to pre-book your passenger ferry tickets online if not traveling with a car. The vessel MS Sier and MS Oerd can both transport 1200 passengers. This is considered over capacity in light of the above calculations of average persons transported per day. This is not assuming higher traffic volumes during peak holiday periods, however the average of 207 people transported per day still gives a good indication that the two ferries currently in use have excess capacity on an everyday basis.

11.2.3 Impacts: Positive and negative consequences

Positive impacts of adjusting the ferry vessel fleet to two vessels of smaller size is that the dredging volume and hence costs incurred by Rijkswaterstaat, should decrease. With that the negative impacts caused by dredging operations as discussed for the base case should also relatively decrease. Concerning morphological impacts, it is also possible that making the channel narrower, helps reduce the sedimentation rates in the channel as this cross-section would create a more stable equilibrium for the tidal basin. However, due to the dynamic response of the Wadden Sea tidal basins, there still lies uncertainties in this assumption.

As discussed in the technical aspects section, if the ferry has a higher maximum sailing speed, the total sailing time could decrease which is a benefit to passengers. The ferry operators could also adjust the schedule to maximise these benefits. Moreover, the entire travelling time would decrease due to shorter loading and unloading times if the ferry has no capacity for cars.

However, a major drawback and point of concern of such a new ferry vessel like the Damen Fast Ferry 4212 is that it has capacity for only passengers and not cars. This could have a significant effect on the tourism and cause dispute from the Ameland residents. On the positive side though, this alternative would open opportunities for more public transport initiatives on both Holwerd and Ameland, and an option would be to make Ameland 'car-free' for non-inhabitants like Vlieland is, another Dutch Wadden island (Vlieland.org, 2018). This new strategy would initiate the use of environmentally friendly means of transport on Ameland, such as bikes. Moreover, building additional parking areas near Holwerd could add to the socio-economic status of the town as tourists will start visiting Holwerd as well. However, additional costs will arise for the design and construction of additional parking spaces and realizing the public transport initiative. This would affect the municipality and residents of Ameland more than this study's scope allows for.

11.2.4 Cost estimate

Preliminary cost estimates are carried out for both example ferry vessels. Cost calculations are included in Appendix G. For the Damen Fast Ferry 4212, it is assumed that normal dredging operations would continue up to 2029 as Wagenborg would still be operating MS Sier and MS Oerd during this time, so there would be no reduction in dredging costs. From 2030 when the new concession starts, it is assumed that the new ferries will be purchased and a relative reduction of 20.4% is taken into account for the reduced dredging costs over the next 20 years. Purchasing of two ferry vessels are included at a price of € 4.5 million each, assuming a range between € 2 million and € 5 million (Maritime Sales, Inc., 1999). The total cost for this alternative is approximately € 258 million; this is assuming the same dredging cost of approximately € 5.4/m^3 as what is considered in the base case.

For MS Rottum, different assumptions are made. This is based on the fact that Wagenborg already owns this vessel and could possibly exchange their fleet between the two island routes by 2020, without additional costs. Therefore, without the need for purchasing of new vessels and assuming Wagenborg's contract is extended beyond 2029, this option results in a total preliminary cost of € 251 million.

For the purposes of the MCA, the option of purchasing the Damen-type ferry vessels are considered, as it is unlikely that Wagenborg would be able to exchange their vessel fleet between the two island routes.

11.3 Bend Cuts

11.3.1 Concept definition

Bend cut-offs are proposed in two sections of the navigation channel, in effect to create a new channel as shown in Figure 11-4, with the aim to shorten the sailing distance and time between Holwerd and Nes, and decrease the dredging amount. Therefore, this intervention would improve accessibility to Ameland and contribute to an improved maintenance regime for the navigation channel (Deltares, 2015a).

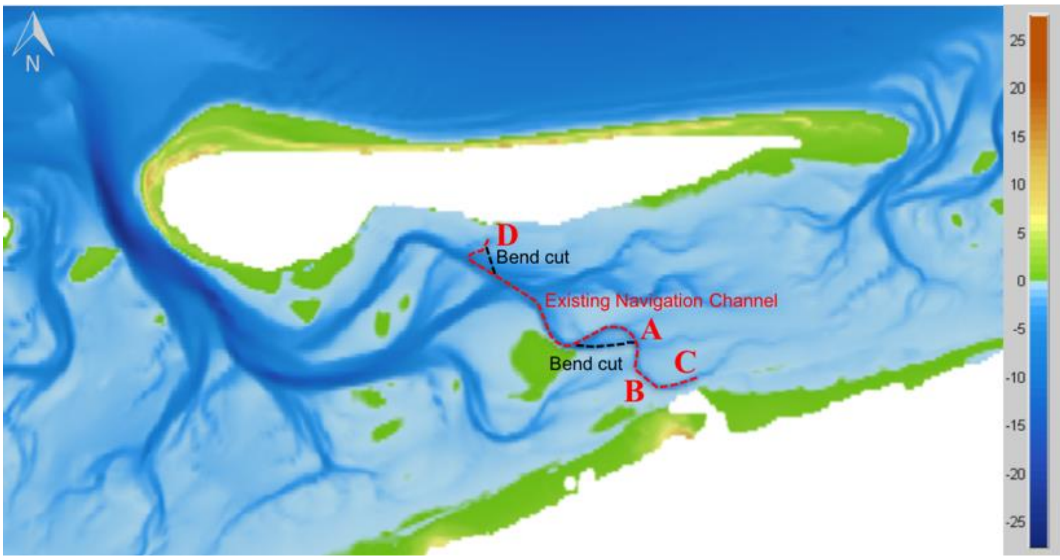


Figure 11-4: Bend cut-off concept

This proposed option includes shifting the first leg of the navigation channel from the ebb to the flood channel (Herman, et al., 2016). Thereby the longer meandering bend, Kikkertgat channel bend, will be bypassed. This section is termed 'Bochtafsnijding vloedgeul'. The second bend cut-off, 'Reegeul Oost', would be to the east of the current channel section near the Ameland ferry terminal. The locations of both these alternate routes are shown in Figure 11-5.

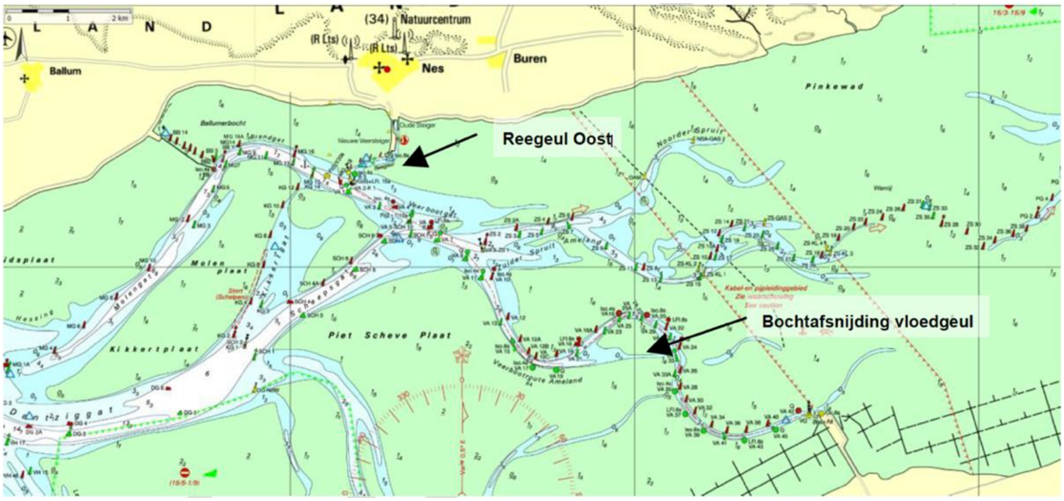


Figure 11-5: Bend cut-off locations (Deltares, 2018)

11.3.2 Technical aspects

The two proposed bend cut-off constructions allow for the following reduction in sailing distance and time. 'Bochtafsnijding vloedgeul' makes the sailing distance approximately 850 m shorter (Deltares, 2015a) and 'Reegeul Oost' results in a further shortening of 700 m (Jager & de Kleuver, 2016). The navigation channel will therefore ultimately be straighter and shorten to a length of approximately 10.45 km if both of these bend cuts are realized. This is a 13% reduction from the current channel length of 12 km. Assuming a maximum speed of 10.8 knots for the ferry vessel (same as current operations), the total sailing time will decrease by approximately 10 minutes. This calculation takes into account a safety margin of 15% for slowing down, instead of 25% as in the previous alternative due to less extreme bends to navigate. These calculations are presented in Table 11-3.

Table 11-3: Maximum reduced sailing distance and time due to bed cuts

Navigation channel dimensions	**Measurement**	**Units**
Current navigation channel length	12	km
Distance shortened by Bochtafsnijding vloedgeul	0.85	km
Distance shortened by Reegeul Oost	0.7	km
Total navigation channel length after bend cuts	**10.45**	**km**
Sailing time calculation	**Measurement**	**Units**
Vessel speed (max)	10.8	kn
Vessel speed (max)	20.0	km/hr
Reduced sailing time	**36**	**min**

In recent studies by Deltares (2015a) (2018), different scenarios of the bend cut-off alternatives were modelled to determine the effects of the modified bathymetry on the changing morphology and the amount of dredging required. The preferred variant to reduce the dredging issue was determined to be 'Bochtafsnijding vloedgeul', where the channel is changed from ebb to flood. This is compared to other variants also considered and the current situation.

For the 'Reegeul Oost' bend cut, there are still major uncertainties regarding the effects of the intervention (Jager & de Kleuver, 2016). These uncertainties include that the position may be unfavourable in relation to current flow patterns and it may actually increase the dredging amount. For these reasons, further analysis only considers the bend cut to realize 'Bochtafsnijding vloedgeul'.

'Bochtafsnijding vloedgeul' shows the strongest decrease in sedimentation of the sludge. This phenomenon is explained as follows: With the channel section changed into a flood channel by means of the bend cut, flow velocities through this section would increase. Sediment is deposited and settles when speeds of tidal flows decrease, i.e. in the ebb channel. Therefore, the bend cut results in less sediment being able to flow back to the shipping channel.

Initial analysis of 'Bochtafsnijding vloedgeul' shows that during the immediate stage, before the old channel is completely blocked off, there would be an increase of up to 31% in dredging volume. In the year after construction the reduction would be less, approximately a reduction of 9%. Over time, the decrease in sedimentation of sludge is estimated at approximately 13% (with band width 8% - 18%) (Deltares, 2018).

The dredged sludge could also be used to fill up the current navigation channel section, thus cutting off the meandering bend completely. This would make the sediment available again more slowly and reduce the dredging volume in the short-term. Using the ebb channel for storage of the dredge spoil also depends on the rate of siltation and changing morphology of the basin.

It is still uncertain of how the tidal basin would adapt morphologically, but it is estimated that the bend cuts are only guaranteed to reduce the dredging volume over a period of 10 years. This is because over time the mudflats continue to increase. Storage space becomes smaller and flow velocities reduce further again, increasing the tendency of siltation and flood dominance.

In terms of realization/implementation, it is estimated that realizing this bend cut would take almost two years. This includes further planning and preparation of one year for drawings up reports and documents to comply with various Water and Nature Protection Acts. Contract and tendering would take another year. Should permits be required, this could run in parallel with the tendering process. However, it is envisaged that the 'Bochtafsnijding vloedgeul' bend cut alternative would be allowed to occur within the regulations of the current dredging permit. Therefore, no new permit would need to be issued, but proof of compliance will still need to be registered through application and permission is to be granted by authorities.

11.3.3 Impact: Positive and negative consequences

By structurally shortening the sailing time, the negative environmental effects of the current ferry operation would reduce proportionally. This includes a reduction in CO_2 emissions during the ferry vessels voyage as a result of the short sailing time. In terms of the functioning of the ecosystem, bend cuts are seen as a potential improvement to the current morphological situation as it would become a more stable deposition regime which prevents high return of mud clouds and sedimentation of the channel by dredged material.

The bend cut alternative is expected to have a similar influence as base case has on benthic animals, including mussel or oyster beds.

There are some logistical issues that exist, such as using the dredged material to close-off the existing channel section, whilst not affecting ferry operations and navigational safety during implementation. This could result in additional downtime or delays during realization.

11.3.4 Cost estimate

The estimate for realizing the 'Bochtafsnijding vloedgeul' bend trench is equal to approximately an investment of € 2 million to € 2.4 million. Taking into account the relative reduction in dredging volume per year due to construction of the bend cut and it being guaranteed for more or less only 10 years, the total estimated cost of dredging up to 2050 is calculated to approximately €252 million. A summary of these calculations is included at the end of Appendix G.

11.4 Relocation of the Ferry Terminal to the West

11.4.1 Concept definition

Relocation of the ferry terminal is another alternative development suggested to overcome the present ferry connection problem which has been described. Speculation suggests that the present location of the ferry terminal is too near to the tidal watershed (refer to Figure 3-6). This is considering the possibility that the meandering of channels and increased sedimentation is also attributed to the movement of the tidal watershed. However, as previously stated in Section 0, no uniform conclusion has been drawn up regarding this theory (van Til, 2017). Nevertheless, relocating the ferry terminal towards an area further away from the tidal watershed, where the meandering tendency and sedimentation is not as pronounced, forms an alternative to the current situation (Jager & de Kleuver, 2016). Therefore, this alternative looks into the development and construction of a new ferry terminal towards the west, approximately 6 km from the current location, as illustrated in Figure 11-6.

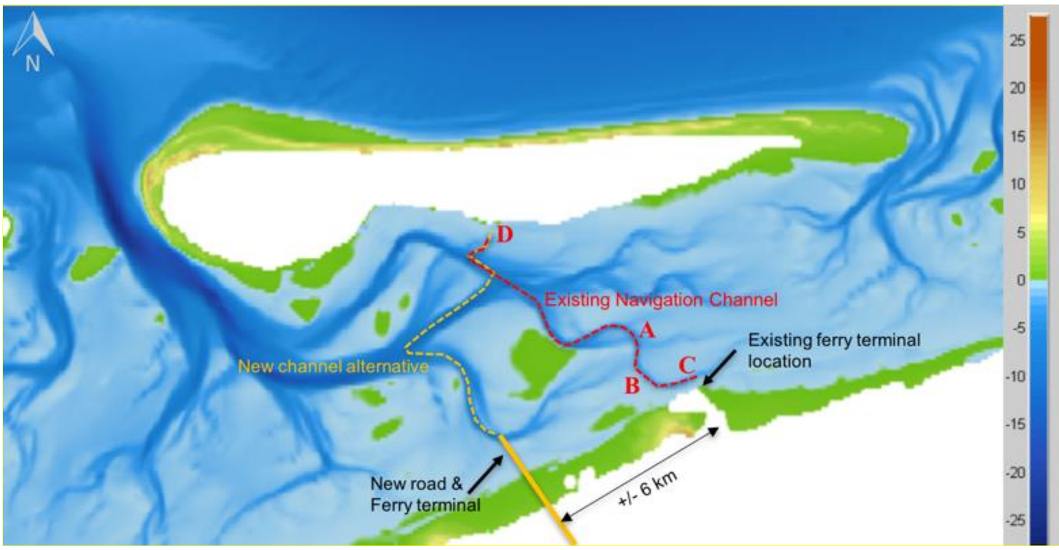


Figure 11-6: Ferry relocation concept

With a terminal at this proposed located, navigational safety issues due to restricted depth of the channel can effectively be eliminated. The alternative ferry route to Nes follows a tidal channel which is in more open and stable water with larger guaranteed channel depths of around 5 m- 10 m. This reduces, or potentially eliminates completely, the need for continuous maintenance dredging such as what is required in the existing navigation channel.

Further, the new location of the ferry terminal would result in a shorter sailing distance of approximately 9 km, 3 km less than the current sailing distance. If the speed of the ferry operating the new designated channel is assumed to be the same as that of the existing ferry vessel, i.e. 10.8 knots, this shorter sailing distance results in only 35 minutes sailing time (includes 25% safety margin) instead of 45 minutes.

11.4.2 Technical aspects

For the purpose of a high-level cost analysis, a preliminary design was developed for the new ferry terminal as sketched in Figure G-1 included in Appendix G. Dimensions of the new terminal were taken as the same length and width of the current terminal. It was assumed that the existing area of the *current* terminal has enough capacity to satisfy the peak demand for vehicle storage during the holiday seasons. However, for the *new* terminal design, it was assumed that the same parking space area would satisfy future off-seasonal demands only, and not necessarily increased seasonal demands.

Assuming vehicular growth is to follow population growth, the potential increased demand for the next 50 years was calculated (design life of the marine structure is 50 years). As the current car holding capacity of the terminal was approximately estimated as 1640 AEU (Auto mobile Equivalent Units), the increased demand was obtained as 350 AEU for the next five decades, assuming 3.9% growth rate per decade (World population review, 2018). However, this increased future seasonal demand cannot be handled with the above dimensions of the new ferry terminal. And, increasing the terminal area in order to satisfy the future demand may cause significant negative consequences. For instance, increasing dimensions of the marine structure may result in an exponential increase in costs. Not only that, but also severity of the impacts due to morphological changes also depends on the size of the intervention. Therefore, it was recommended to introduce additional parking space outside the terminal area (Close to the main entrance) and adopt alternative methods, such as shuttle services, to transport passengers to the terminal during peak demand periods (season).

For the preliminary design, lowest elevation of the vehicle holding compound was set as 2.0 m higher than the predicted 200 YRP water level (refer to Figure B-3 in Appendix B). As the predicted water level for 200 YRP is 410 cm, the lowest elevation was calculated as 6.1 m. This will minimize the possibility of wave run-up onto the vehicle holding compound during storm periods. Even though a higher return period would ensure increased safety, it also results in higher costs. Therefore, the 200 YRP was chosen as it will only result in 25% probability of failure during the 50-year life time of the structure.

Additionally, it would be required to build a new access way from the main road to the new terminal location. To minimize the interaction between the existing saltmarshes and the proposed structure it was decided to construct an approximately 3 km long pier bridge with a width of 10 m, instead of a new road which may require a very large land fill for the entire 3 km stretch (from main road to the terminal location) and cause more damage than necessary to the salt marshes in the region. Also, it was decided that the pier bridge would be constructed with a concrete deck and steel box girder as this type has much less self-weight than pure concrete bridges (SteelConstruction.info, 2017). Hence, it requires less bearing capacity of soil compared to that of concrete bridges. Figure 11-7 shows the expected three-dimensional view of the new ferry terminal after construction.

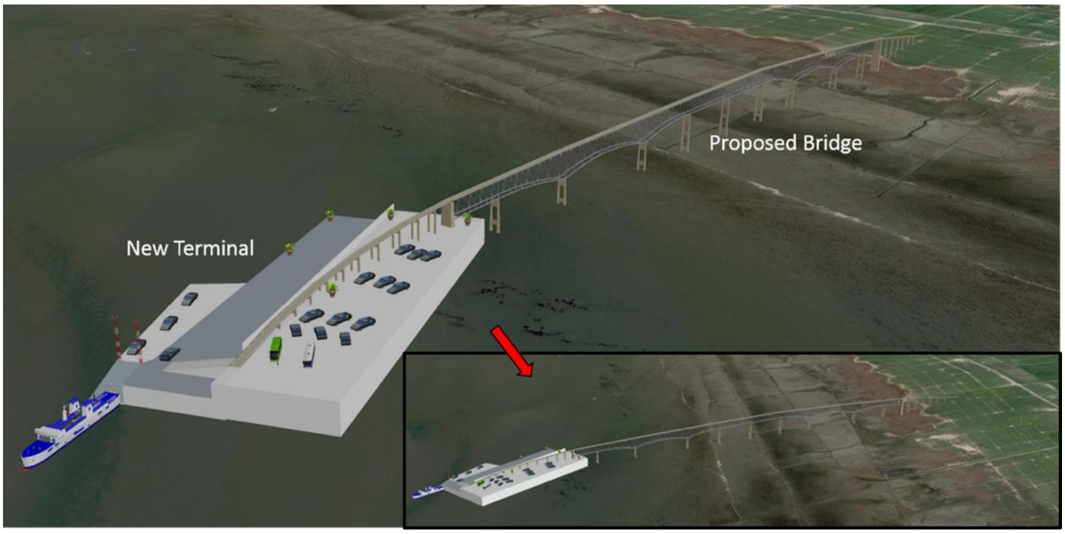


Figure 11-7: Expected view of proposed new terminal

Figure 11-8 shows the main components of the ferry terminal (with all required accessories), considered in the preliminary design for cost purposes. However, it should be noted that the design of these components and accessories are to be carried out in the detailed design stage.

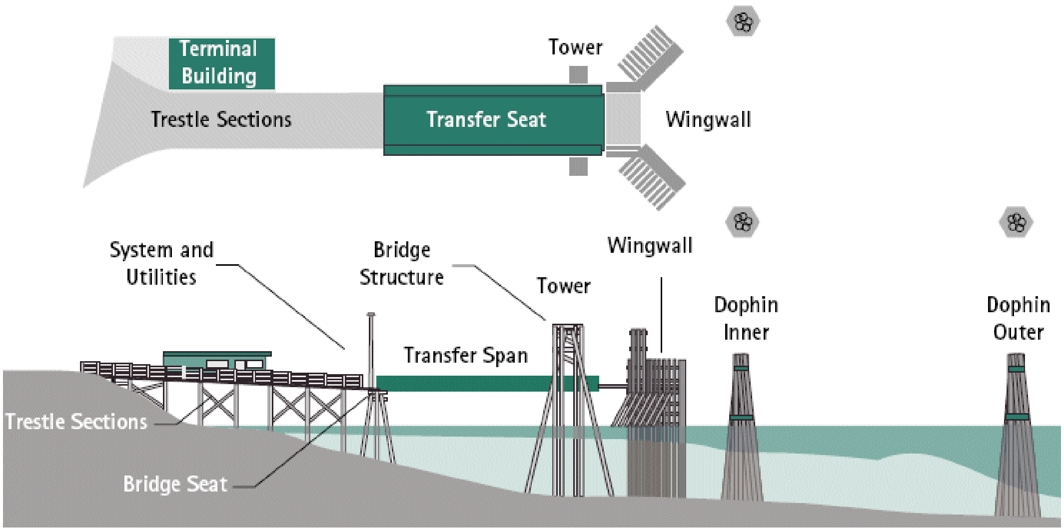


Figure 11-8: Typical ferry terminal structure

11.4.3 Impacts: Positive and negative consequences

As a completely new construction development in the ecologically sensitive area, this alternative has many impacts, discussed below.

One of the major positive impacts of the relocation of the ferry terminal to the west is that it can effectively reduce all negative impacts directly related to the excessive dredging problem. Due to the channel depth requirement for the current ferry being -4 m NAP, it is predicted that very little to no dredging would be required in the new location as the channel has sufficient depth to accommodate the vessel. Consequently, the increasing dredging volumes and associated high dredging costs, as described in the base case scenario in Section 11.1 can be well avoided.

As described in Section 3.3, salt marshes, one of the unique features of the Wadden Sea ecosystems and specifically the area of Holwerd, have very high environmental and ecological value and so are protected under Natura 2000. As seen in Figure 11-9, the entire upper intertidal area of the proposed new location of the ferry terminal consists of saltmarshes.

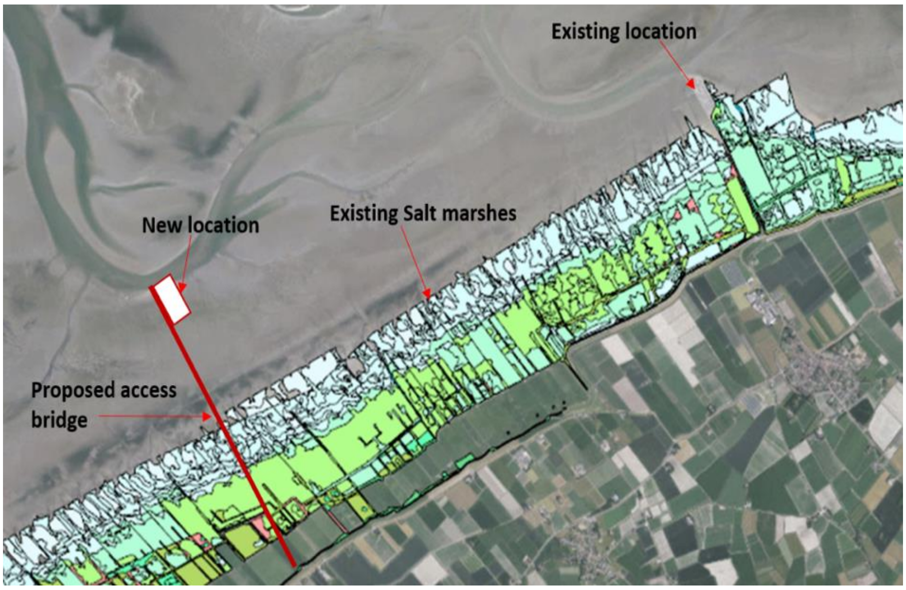


Figure 11-9: Map of existing salt marshes in area of new ferry terminal (Rijkswaterstaat, 2018c)

As illustrated in the above figure, building an access way over the salt marshes is inevitable as there is no other possible way to provide access to the new terminal. Therefore, destruction of part of the existing salt marshes is unavoidable. This can lead to massive negative impacts on the Wadden Sea ecosystems. Hence, carrying out an Environmental Impact Assessment (EIA) is vital to assess the severity of impacts before implementing such a development.

Furthermore, this alternative is introduced as a hard solution to prevent the current sedimentation problem in the navigation channel. On one hand, hard solutions are good as it has long life time expectancy. On the other hand, hard solutions always act as an interference which alter the natural coastal processes. In addition, the Wadden Sea tidal basins have especially very dynamic behaviour. Therefore, a small change in the system can eventually cause significant changes in coastal morphology, hydrodynamic conditions and suspended sediment concentrations. Understanding the system is very important to be able to mitigate the potential negative impacts. Hence, it is also essential to perform proper morphological assessments with the use of numerical models to assess the change or disturbance to processes due to the presence of the terminal structure. Also, once implemented, further expansion is regarded as not possible. Hence, this option is less adaptable being a hard solution.

As already stated, the Wadden Sea is listed as a UNESCO World Heritage Site and any new developments are restricted by legislature (Section 3.2). Because of the protected status of this area, obtaining authorizations and permits from the relevant authorities is mandatory to the implementation.

Another issue related to this is that relocation of the terminal moves it further away from Holwerd and to its neighbouring municipality, which is in fact governed by a different administrative division. This can cause several political issues especially in terms of obtaining authorizations.

The relocation could result in a significant increase of traffic during both the construction and operational phases. Hence, infrastructure improvement might be required. During the construction phase, there is a possibility of queuing due to increased traffic as materials have to be transported from outside and dredged materials have to be taken away to the disposal location. The effect can be minimized avoiding peak hours during construction. Nonetheless, during the operational phase, it is to be expected that there would be a significant increase in traffic during peak periods in the new area, which implies a potential for local community oppositions unless remedial measures are provided. Therefore, this option requires a good communication with stakeholders.

Existing access roads towards the new terminal location may require widening to accommodate this increase in traffic. If widening of the road is required, there can again be some objections from the local community if private properties are to be affected. Therefore, it is strongly recommended to do a proper traffic survey considering future traffic demand before implementation.

In terms of socio- economic impacts, this alternative results in several positive impacts. The key benefit being that the new location of the ferry terminal would result in a reduction of 10 minutes in the sailing time compared to the current situation and also the avoidance of delays. This allows for the level of service to be productively increased, providing a sound solution to the current issue of delays. Therefore, by increasing the efficiency of the service, a higher demand can be expected which eventually results in increased revenue. Also, navigational safety is better ensured due to the guaranteed larger channel depth.

Moreover, new relocation project can emerge several job opportunities during all phases of the project. During the construction phase, the local community can benefit from working in several disciplines involved with the project. During the operational phase, new business opportunities, like restaurants and transportation facilities can emerge. Therefore, this would enhance the financial status of the local community due to the positive impact on the local economy. However, this does not benefit the community of Holwerd itself as tourists would no longer drive by or stop in Holwerd. In fact, it could lead to an income loss for the local community of Holwerd who are involved in the tourism industry, by relocating the ferry terminal and there some oppositions can arise from local transport facility providers who currently provide transport services for the passengers of the ferry. This issue can be negotiated if they are allowed to relocate their business again to the vicinity nearer to the new location of the ferry terminal. Regular passengers from the Holwerd area would then also have to travel a few extra miles to reach the new location, but this issue is overwhelmed by benefits like shorter ferry travel duration.

The future use and/or demolition of the existing ferry terminal in Holwerd is not addressed. However, it is suggested that instead of demolition, it can be utilized to develop a research centre and facilities elated to mud flats and salt marshes. This would help to improve knowledge of the new generation on these areas which can be used to develop more economic and nature friendly solutions within the morphodynamically changing Dutch Wadden Sea.

Owing to highly dynamic morphological behaviour in tidal basins, there is a potential risk of causing the same sedimentation problem in the new ferry terminal location as well. However, this won't cause extreme level of dredging problems like the current situation as the depth of new navigation channel is well below the required minimum depth. Also, as these kinds of morphological changes evolve over large time scales it will take a long time to cause severe problems. Despite the potential negative consequences of this alternative, the overall reliability of this alternative is deemed sufficient.

11.4.4 Cost estimate

A high-level cost estimation for the ferry relocation was based on the preliminary design described above, together with several assumptions made. All rates were based on previous projects which have similar order of magnitudes in terms of design ships and dimensions of the terminal: (RH2 Engineering, 2009), (SNC-Lavalin Inc, 2016), (Dougla & Playter, 2003).

All rates have been converted to the present values using 2% inflation rate. Lump sum amounts were included for the items that are not quantified during preliminary design stage. It was assumed that all the components like wingwalls, dolphins, towers, transfer span are newly designed without utilizing anything from existing pier. Further, in order account for safety margins 10% and 20% of respective subtotals were added for mobilization and contingencies. Operational costs are excluded as the other alternatives also don't take into account operational costs of the ferry terminal itself, only dredging costs. For the new ferry terminal, capital dredging is accounted for and a 5% allowance is added to account for potential maintenance dredging of the channel.

The high cost involved with the relocation can be considered as one of the major issues. As the new ferry terminal and required facilities have to be constructed from scratch, it requires a huge capital cost for the installation. However, after construction it may not require large costs in terms of maintenance and operation as this location is not expected to cause problems like excessive sedimentation. Further, if the terminal is properly designed to minimize potential negative impacts as much as possible, the initial high capital cost could be a good investment as this solution provides a more efficient long-term solution to reaching Ameland and facilitates passengers in a better way. A detailed cost-benefit analysis would therefore be required to determine whether the benefits of this alternative outweigh the high costs and potential negative impacts. The preliminary cost analysis is summarised in Table 11-4 and accumulates to a total estimated cost of € 270 000 000. Abbreviations 'Ea' stand for 'each', i.e. cost per unit, and 'LS' refers to 'Lump Sum'.

Table 11-4: Preliminary cost estimate for ferry terminal relocation

Item	Unit	Quantity	Costs
Marine Terminal			
Pier Section	m^2	60000	€ 108 500 000
Bridge seat	Ea	1	€ 226 000
Transfer span	Ea	1	€ 622 000
Electrical and mechanical systems for transfer span	Ea	1	€ 900 000
Towers, Headframe and foundations	Ea	1	€ 565 000
Wing walls	Ea	2	€ 2 260 000
Inner dolphins	Ea	2	€ 1 000 000
Outer dolphins	Ea	2	€ 1 400 000
toll booths	Ea	1	€ 57 000
Terminal building	m^2	300	€ 1 000 000
Storage building	m^2	50	€ 42 000
Car park_Additional	LS	1	€ 3 000 000
Capital Dredging	LS	1	€ 25 000 000
Utilities			
Water supply system	LS	1	€ 110 000
Sanitary Sewer System	LS	1	€ 80 000
Communication system	LS	1	€ 110 000
Electrical supply and distribution	LS	1	€ 565 000
Access Bridge	LS	1	€ 60 000 000
Total			€ 210 000 000
Maintenance dredging 5%			€ 10 000 000
Sub with maintenance			€ 220 000 000
Contingency 10%			€ 20 000 000
Sub with contingency			€ 240 000 000
EIA 12%			€ 30 000 000
		Total cost	**€ 270 000 000**

12. EVALUATION

12.1 Criteria for MCA

From the preliminary designs of the proposed alternatives, which are presented and discussed in the previous sections, the different intervention options are evaluated by means of a multi-criteria analysis (MCA) method. The MCA is a decision tool for objectively weighing options on a number of criteria; this allows for a relative comparison of numerous alternatives. Therefore, the MCA is carried out for each alternative through the process of relative scoring and ranking, based on weightings assigned to carefully selected criteria. Criteria relevant to both flood safety and the ferry connection were selected as follows:

- Environmental impact
- Practical implementation
- Socio-economic impact
- Safety risk
- Reliability

This is so that the two parts within the project are analysed consistently. Table 12-1 presents these criteria and weightings used to rank the different design options. The description column summarises the key aspects which may need to be considered within each criterion; some are related to both the dike and ferry alternatives, while others are option dependent.

Environmental impact and *safety risk* are regarded as the most important criteria, both given a weighting of 30%. Firstly, environmental impact has a relatively high weighting because of the particular site location. Given the environmental and ecological value of the region, with the Wadden Sea being a UNESCO World Heritage Site, and the salt marshes in the area of Holwerd having to be protected and conserved, any intervention should strive to have no/minimal negative environmental impact.

The salt marshes and associated biodiversity is relevant to dike reinforcement alternatives due to the present foreshore in this area near the dike being vegetated with salt marshes. They are also relevant to the ferry connection alternatives as it is the natural sediment processes within the tidal basin which aid in salt marsh growth. More specific to the ferry connection alternatives, is that interventions should not worsen the sedimentation issue.

The *safety criteria* include risk of flooding. This is more specifically aimed at the design of the flood defence alternatives to ensure a robust design is selected which will adequately prevent overtopping and dike failure. For the ferry connection alternatives, the safety criteria include the safety of vessels whilst sailing, i.e. minimum depth and channel widths should be provided to prevent collision or other marine traffic risks.

Of the remaining criteria, *socio-economic impact* is weighted 20%. This is to ensure that stakeholder interests, including that of the local community of Holwerd and passengers using the ferry service, who may be affected by the interventions or oppose specific developments, are accounted for. However, this is not as important as environmental impact or safety as those two criteria specifically form part of the functional design requirements. On the other hand, in the stakeholder analysis, some stakeholders were classified to only be kept informed, hence the lower weighting for socio-economic impacts.

Practical implementation and *reliability* both have a weighting of 10% to complete the criteria. These criteria are related to the engineering and realisation of the interventions, such as difficulty in construction thereof and methods required, or whether the design is based on experience and guaranteed results or only research and expert opinion so far.

Table 12-1: Criteria for MCE

Criteria	Description	Weighting
Environmental impact	• Conservation or destruction of salt marshes • Impact on flora and fauna • Preserving biodiversity • Morphological changes in the tidal basin • Disposal scheme and location of dredged material • Water quality, i.e. due to turbidity or pollution	30%
Practical Implementation	• Constructability and/or method of realisation of intervention • Duration of realisation thereof • Compliance to legislation, permit approvals. • Availability of materials and equipment, including transport. • Expansion and adaptability	10%
Socio-economic impact	• Stakeholder impact • Funding opportunities • Public acceptance • Aesthetics • Impact on local community • Job creation (direct – construction/maintenance labour, indirect – local business opportunities) • Local economy • Economic risk reduction • Agriculture - loss of land • Recreational value/utility • Tourism enhancement	20%
Safety Risk	• Probability of flood damage, i.e. dike failure • Resilience • Severity of damage should flooding occur • Safe navigation for ferry service, i.e. passing distance of vessels, minimum depth for sailing	30%
Reliability	• Experimental/testing • Research conducted • Level at which results can be guaranteed	10%
	Total	**100%**

The results of the MCA are presented in the following sections. It should be noted that costs are excluded from the criteria. Instead, costs are taken into account separately by dividing the alternatives' ranked value in the MCA by the preliminary cost per alternative (Refer to Sections 10 and 11) to determine the value-cost ratios for each. Selection of the preferred alternatives are based on the highest value-cost ratios.

12.2 MCA for alternative dike designs

12.2.1 MCA scores for alternative dike designs

The four alternative designs for reinforcement of the dike at Holwerd were scored according to the criteria defined in the previous section. The results of the MCA are presented in Table 12-2, which also indicates the evaluated criteria and the weighting applied to each criterion. The first part of Table 12-2 shows only the individual scores per criterion, given out of 100%, for each intervention option. Tables in Appendix H can be referred to for details of how these scores were obtained. These appended tables summarise the key positive and negative impacts within each criterion and the alternative options were then compared relative to one another to define a sensitivity score for each intervention per criterion.

The second part of the MCA takes into account the weighting applied to each criterion by multiplying the sensitivity scores by the weighting percentages. When added for each alternative, a total score and rank is allocated for each intervention.

Table 12-2: MCA for flood safety alternatives

Sensitivity scores					
Interventions		**Traditional dike widening**	**Wide green dike**	**Revetment change**	**Sandy Dike**
Criteria	**Weighting**				
Environmental Impact	30%	35%	80%	50%	65%
Practical Implementation	10%	40%	45%	60%	70%
Socio-economic impact	20%	40%	75%	45%	60%
Safety Risk	30%	75%	70%	85%	35%
Reliability	10%	55%	65%	90%	30%
Total	100%				
Overall scores					
Interventions		**Traditional dike widening**	**Wide green dike**	**Revetment change**	**Sandy Dike**
Total		**51%**	**71%**	**65%**	**52%**
Rank		**4**	**1**	**2**	**3**
Criteria	**Weighting**				
Environmental Impact	30%	11%	24%	15%	20%
Practical Implementation	10%	4%	5%	6%	7%
Socio-economic impact	20%	8%	15%	9%	12%
Safety Risk	30%	23%	21%	26%	11%
Reliability	10%	6%	7%	9%	3%
Total	100%				

The MCA results show that the Wide green dike alternative, with an overall score of 71%, scores much higher than the other three alternative interventions. This is mainly due to its high ecological and cultural value, which led to relatively high scores in the environmental and socio-economic impact categories. Revetment change, since it is more commonly applied and offers high resistance to overtopping, is considered to be the most reliable and safe alternative for flood defences, but its lack of recreational and aesthetic values was responsible for undesired socio-economic impacts, which mostly resulted on this alternative becoming the second highest scoring.

12.2.2 Value-cost ratio for alternative dike designs

Table 12-3 include the total estimated costs previously calculated for the preliminary designs. Value-cost ratios are calculated and results shown in Table 12-3. As seen in the table, when costs are considered, the Sandy dike now ranks second for it being the cheapest solution. However, the Wide green dike still remains the highest scored alternative.

Table 12-3: Value-cost ratios for flood safety alternatives

Alternatives final scores	Traditional dike widening	Wide green dike	Revetment change	Sandy Dike
Scores without costs	51%	71%	65%	52%
Costs estimate (million €)	14.3	8.1	12.3	6.5
Value-cost ratio	3.53	8.77	5.24	8.00
Ranks	**4**	**1**	**3**	**2**

12.3 MCA for ferry connection alternatives

12.3.1 MCA scores for alternatives addressing ferry connection

Similarly, the three alternative interventions which are suggested to improve the ferry connection problem, were scored and ranked relative to the base case scenario. The results of this MCA are presented in Table 12-4. Refer to the tables in Appendix H for the summarised assessment of impacts per criterion for each intervention option.

The MCA for the ferry connection alternative shows an improvement from the current situation, although it is not considered a major improvement as the overall scores are all still below 60%. Relocating the ferry terminal has the highest score, however by a slim margin. This is due to the relocation option offering a better guaranteed safety for navigation as the channel is located in more open and stable water. The channel with greater depths alleviates the major issue of sedimentation, therefore requiring minimal to no maintenance dredging. None of the alternatives score high in terms of reliability; this is because of the dynamic hydrodynamic and morphological systems within the tidal basin and associated long-term uncertainties.

Table 12-4: MCA for ferry connection alternatives

Sensitivity scores					
Interventions		Base case - "Do-nothing"	Adjust vessel fleet	Bend cuts	Relocation of ferry terminal to west
Criteria	**Weighting**				
Environmental Impact	30%	50%	65%	60%	40%
Practical Implementation	10%	50%	40%	70%	20%
Socio-economic impact	20%	25%	60%	40%	75%
Safety Risk	30%	45%	60%	60%	80%
Reliability	10%	20%	35%	45%	45%
Total	100%				
Overall scores					
Interventions		Base case - "Do-nothing"	Adjust vessel fleet	Bend cuts	Relocation of ferry terminal to west
Total		**41%**	**57%**	**56%**	**58%**
Rank		**4**	**2**	**3**	**1**
Criteria	**Weighting**				
Environmental Impact	30%	15%	20%	18%	12%
Practical Implementation	10%	5%	4%	7%	2%
Socio-economic impact	20%	5%	12%	8%	15%
Safety Risk	30%	14%	18%	18%	24%
Reliability	10%	2%	4%	5%	5%
Total	100%				

12.3.2 Value-cost ratio for ferry connection alternatives

Costs have a major influence on the scores of the ferry connection alternatives. As seen in Table 12-5, the relocation of ferry terminal option goes from being ranked as option 1 to option 3. This is due to the high capital cost for such a development. The adjust vessel fleet and bend cut alternatives consider long-term dredging costs; these options show a reduction in total costs compared to the event in which nothing is done (base case), but are still very costly options. Adjusting the vessel fleet becomes the highest scored option, given that the vessels can be purchased for less than € 5 million each.

Table 12-5: Value-cost ratios for ferry connection alternatives

Alternatives final scores	Base case - "Do-nothing"	Adjust vessel fleet	Bend cuts	Relocation of ferry terminal to west
Scores without costs	41%	57%	56%	58%
Costs estimate (million €)	290	258	252	270
Value-cost ratio	1.40	2.21	2.20	2.13
Ranks	**4**	**1**	**2**	**3**

12.4 Results

The MCA indicated that the preferred alternative for the reinforcement of the dike would be to modify the outer slope of the current dike to that of a wide green dike design. A wide green dike would provide sufficient safety against flooding considering the future scenario of climate change.

Another advantage is that it is a more environmentally-friendly engineering dike design, which can be integrated with the salt marshes and help conserve the biodiversity of the area. With a grass-only seaward slope, instead of an asphalt cover, the dike will also look more natural in its surroundings and the local community will be pleased.

Also based only on the MCA results, adjusting the ferry vessel fleet is ranked as the preferred alternative. With this alternative, there is the potential to adjust the ferry's schedule or make up the delayed time as the vessels can sail faster. Ideally there would also be a reduction in the volume of sediments that need to be dredged from the channel due to a change in required channel dimensions for the smaller-sized ferries.

However, this alternative is only a long-term solution and so bend cuts becomes the preferred short-term solution which will result in a shorter sailing distance and time, as well as reduce the dredging requirements.

It is important to note that these results are dependent on the particular weightings applied to the criteria for this MCA. Further input or objections from stakeholders could significantly influence this decision.

13. PREFERRED SOLUTIONS

The preferred solutions as identified by the MCA in Section 12 can either be further enhanced prior to the detail design phase or combined with elements of other alternatives. The selected solutions drive the development of a new flood safety and coastal zone management plan for the area of Holwerd. The sections that follow provide details on the preferred alternatives and associated recommendations for further consideration and design.

13.1 Wide Green Dike

13.1.1 Introduction

As concluded from the evaluation using a multi-criteria analysis (MCA), the wide green dike is selected as the preferred solution to ensure the sea dike at Holwerd meets the required flood safety standard of 1/1000 per year, also in future years considering the effects of climate change and sea level rise (SLR).

The gentle seaward slope of the wide green dike reduces wave impact (Refer to Section 10.2) and therefore a thick clay layer covered in grass is sufficient to protect the dike against erosion during extreme events; no stone or asphalt revetment is required (Loon Steensma & Schelfhout, 2016). The gentle outer slope will allow for additional space for grassland vegetation. This gives extra natural benefits for the area, such as increasing biodiversity and enhancing natural development.

13.1.2 Technical requirements

The required seaward expansion for the wide green dike is approximately 15.5 m to 16 m. A detailed cross-section of the wide green dike is shown in Figure 13-1 and a larger image thereof included in Appendix I.

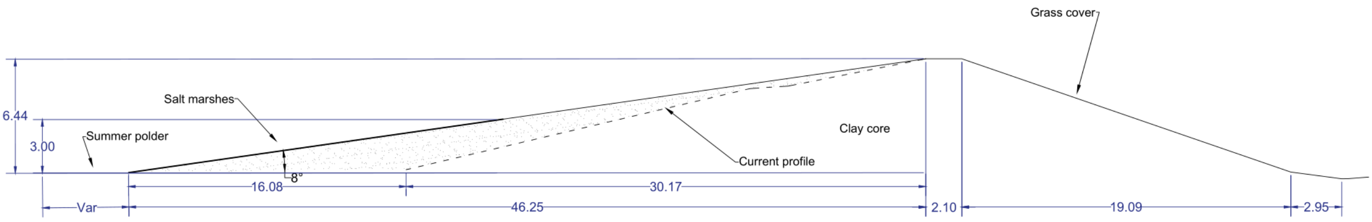


Figure 13-1: Detailed cross-section of wide green dike

The extra volume of clay to construct the dike is 375 000 m^3. Using this value, and the increased outer slope surface that has to be compacted (250 000 m^2), the costs for the material and transport were calculated. The preliminary material costs for construction are shown in Table 13-1 below.

Table 13-1: Cost estimate for wide green dike design

Element	Quantity
Original section surface (m^2)	97
New section surface (m^2)	165
New clay required (m^3)	375 000
New extension (m)	45
New outer slope length (m)	45.5
New outer slope surface (m^2)	250 000
Element	**Cost**
Clay delivery	€ 5 600 000
Profiling clay + compacting clay + soil top layer	€ 2 500 000
Total costs	**€ 8 100 000**

As stated before, the overtopping assessment was done using the computer online program PC OVERTOPPING. The program is available from the EurOtop Overtopping Manual website. The program was set up so that almost every sloping structure can be modelled. The input parameters are the ones used in the Van der Meer formula described in Section 7.2.

In Table 13-2 below, the results are shown. The wide green dike gives an overtopping of approximately 2.5 l/s/m, which is well below the limit of 5 l/s/m, ensuring no dike failure due to overtopping.

Table 13-2 PC OVERTOPPING result for the Wide Green Dike

Interim results of calculation	
Calculation results	
Ru2PERC	2.525 [m]
Ru2PERC+SWL	9.025 [m]
Overtopping	2.406 [l/s/m]
V max	289/wave/[l/wave/m]
Comment	De 2 ploonfoploop isjk r dan de dijk
Calculation of cross section	
Ru2PERC	2.525 [m]
Overtopping	2.406 [l/s/m]
Hm0	2.000 [m]
Tm0	4.000 [s]
Ksio	0.765 [-]
L0	56.188 [m]
GammaB	1.000 [-]
GammaF	1.000 [-]
GBeta run up	1.000 [-]
GBeta overtopping	1.000 [-]
Waterlevel	4.568 [m]
TanAlpha	0.144
Iterations	3

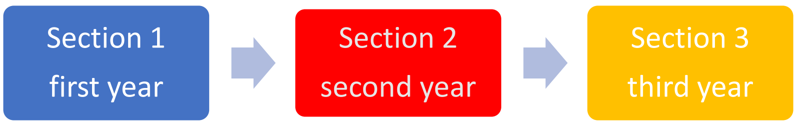
13.1.3 Maintenance

Along the toe of the wide green dike, a maintenance road would have to be built. This can consist of a path of grass paving blocks (Loon Steensma & Schelfhout, 2016). Maintenance costs could be a drawback of this alternative. Indeed, after every storm the deposited debris has to be removed within a few days. This is done to prevent the decaying of the organic matter that could damage the grass cover.

Ordinary maintenance would require periodical cattle grazing to control the growth of grass of the cover, nevertheless, grazing cannot occur too often to not excessively decrease the grass density and height (Loon Steensma & Schelfhout, 2016).

13.1.4 Time-plan:

The clay for the dike will be transported from another location. After transport, the construction operations can begin, which, according to a ''wide green dike'' project of the same magnitude conducted by the local water board Wetterskip Frysland, are expected to last for 3 years. The wide green dike can only be built during the summer months, from the 1st of April to the 30th of September. This is because working on flood defences during the winter storm season is not allowed. Therefore, the whole 5.5 km dike section, has been divided in three parts, each one of them will be built during one of the three years of the project.



In Figure 13-2, the three dike sections can be seen. The colours represent the chronological construction order as highlighted in the timeline above.

Figure 13-2: Dike construction sections

13.1.5 Construction alternatives

<u>Use of dredged material for dike reinforcement</u>

An alternative solution within the construction of the Wide Green Dike is to source the clay material needed from the clay dredged from the ferry channel to reinforce the sea dike and save material costs. This new approach has been proved attainable under certain circumstances and it is explored under the Building with Nature (BwN) concept. For instance, in Germany and Poland, flume experiments and field investigations under the project DredgDikes determined that dredged material from the South Baltic Sea region is suitable for construction purposes (Cantre & Saathoff, 2013).

Fine-grained dredged material as the one found in the Wadden Sea inlets has to be processed before re-usage. First, the material has to be dried to separate it from water, through a process called dewatering (Cantre & Saathoff, 2013). The least expensive way to dewater is to dispose the dredged material in a settling basin so that the solids fall to the bottom and clear water flows over a weir. It takes a long amount of time until the material is dry. Mechanical dewatering and geotextile tubes are other dewatering methods that are faster but more expensive than settling basins.

Figure 13-3: Example of settling sediment basin (JND Thomas Company, 2012)

The material also has to be ripened to become suitable for sea defence purposes. Ripening consists of the transformation of sediment into soil and can be divided into physical, chemical and biological ripening (Vermeulen, et al., 2003). This process can take from several months up to years.

In the Wadden Sea, Ecoshape is investigating the feasibility of such a clay ripening process. In this pilot project, 70000 m^3 of dredged material collected from the Zeehaven Canal and Breebaart polder will be used to strengthen a 1 km section of the local Dollard dike, also for a Wide Green Dike concept (EcoShape, 2018b). The project will begin in 2018 and it is expected to have the material ripened by 2021, when it could become suitable for construction (EcoShape, 2018b). The objective is to answer whether this is a cost-effective solution, best ripening methods and clay quality, along with the ecosystem services involved. If the project is successful, the remaining 10.5 km stretch of the dike is also planned to be strengthened this way. Knowledge gained from this pilot study about transforming dredged material into usual clay soil, could be very valuable elsewhere in the Netherlands. There lies potential for such a study and its implementation for the strengthening of the Holwerd dike.

For Holwerd's Wide Green Dike, roughly 375 000 m^3 of clay is necessary to reinforce the sea dike. As mentioned in Section 8.5, the dry bulk density of the dredged material is, on average, 450 kg/m^3. Using an average mixture density of 1200 kg/m^3 for a trailing suction hopper dredger (Vlasboom, 2005), the resultant sediment content in the dredged material is 38%. Consequently, 1 million m^3 of dredged material is necessary to produce the required volume for construction. In this plan, the dredged mixture would be placed in a settling basin, a potential area identified as shown in Figure 13-4.

By dividing the required dredging volume by the basin area, a total operational basin depth of 2.5 m is obtained at the end of the operations. In practice, however, this depth would be greatly reduced by the water evaporation and absorption by the land.

Figure 13-4: Sediment settling basin location

Clay ripening operations and time plan

The transport of dredged material would be done by land, using trucks loaded by the dredger using pumps. Table 13-3 shows the productivity calculations to estimate the total duration and number of trucks, considering the current dredging rate.

Table 13-3: Transport productivity calculations

Transport Productivity Parameter	Value	Units
Dredging volume	1000000	m^3
Trailing suction hopper dredger production	42000	m^3/week
Truck capacity	20	m^3
Filling time (1 truck)	0.12	hours
Average truck velocity (empty)	50	km/h
Average truck velocity (full)	40	km/h
Travel distance	2.4	km
Dumping time (1 truck)	0.17	hours
Efficiency	80	%
Cycle time (1 truck)	0.50	hours
Work Time (12 hours per day, 7 days per week)	84	hours/week
Number of cycles (1 truck)	169	cycles/week
Productivity (1 truck)	3377	m^3/week
Required number of trucks	12	trucks
Total duration of operation	24	weeks

A sample of a project timeline is provided in Figure 13-5. This considers 3 years to complete the ripening process, as in EcoShape's pilot project (EcoShape, 2018b). The time for construction of the dike was considered to be 3 years, as explained in the Technical Requirements Section.

The time for construction of the dike was considered to be 3 years, as explained in the technical requirements section.

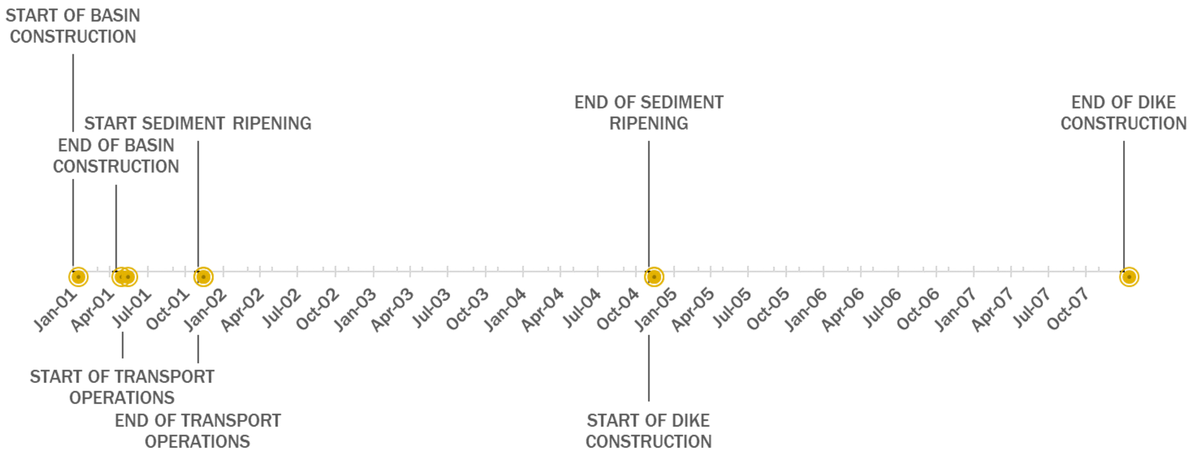


Figure 13-5: Ripening project timeline example

The total cost estimation for the dredged material ripening operation is shown in Table 13-4. The transportation costs consist of the rental of a dump truck such as the Caterpillar 740 (Rental Yard, 2018), plus labour and fuel costs. The basin construction and land costs estimates were based from a technical survey (Minton, 2003) and a Dutch statistical institution (Centraal Bureau voor de Statistiek, 2003), respectively. The costs were corrected for inflation.

Table 13-4: Estimation of dredged material ripening costs

Estimated Ripening Costs	Cost	Units
Transportation costs (1 truck)	5000	€/week
Transportation costs (12 trucks)	60000	€/week
Total duration of operation	24	weeks
Total transportation costs	1440000	€
Basin construction costs	500000	€
Land rental costs (8 years)	1680000	€
Total costs	3620000	€

This results in approximately 10 €/m^3 of material available for construction, compared to the price of 15 €/m^3 to buy clay from external sources, as discussed in Section 0. Total savings of € 2 million are expected for the Wide Green Dike reinforcement using dredged material. Extra transportation savings are obtained when considering the local availability of the materials, as opposed to ordering from other sources.

The ripened material would consist of a mixture of clay, sand and silt. Further investigations are necessary to assess whether the geotechnical characteristics of this material are appropriate for dike construction. In addition, how the removal for this dredged material from the tidal basin system, creating a sediment sink, would affect the morphodynamics and sedimentation processes, directly affecting the issues related to the ferry connection.

13.2 Vegetated foreshore damping

Salt marshes can play a big role in flood protection if proper assessment of their quality and impact is conducted. In general, vegetated foreshores reduce wave energy and height with three different processes: depth induced wave breaking, bottom friction and waves performing work on vegetation. Reducing wave energy, vegetated foreshores decrease the values of run-up and overtopping on the dike and consequently the probability of a dike breach. In the research conducted by Vincent Vuik et al (Vuik, et al., 2016), it is shown how the efficiency of wave damping by vegetated foreshores depends on the relative water depth. For shallow waters there is not much of a difference between vegetated and bare shores. For larger water depths, the influence of vegetation becomes more distinct. The characteristics and dimensions influence the impact of salt marshes on wave height and some trends were discerned. For foreshores with a small width, depth induced wave breaking dominates the total wave energy dissipation. Bottom friction and wave attenuation by vegetation gain relative importance with increasing width (Vuik, et al., 2016).

In the project location, a very wide and good quality salt marshes area is present (see section 4.3). The salt marshes extent reaches from 1.5 km westward of the ferry terminal, and decreases until a complete retreat eastward of the terminal. Figure 13-6 shows the effects of wave height reduction in percentage of bare (left) and vegetated foreshores (right). As can be seen on the y-axis, the reduction depends on the depth as well.

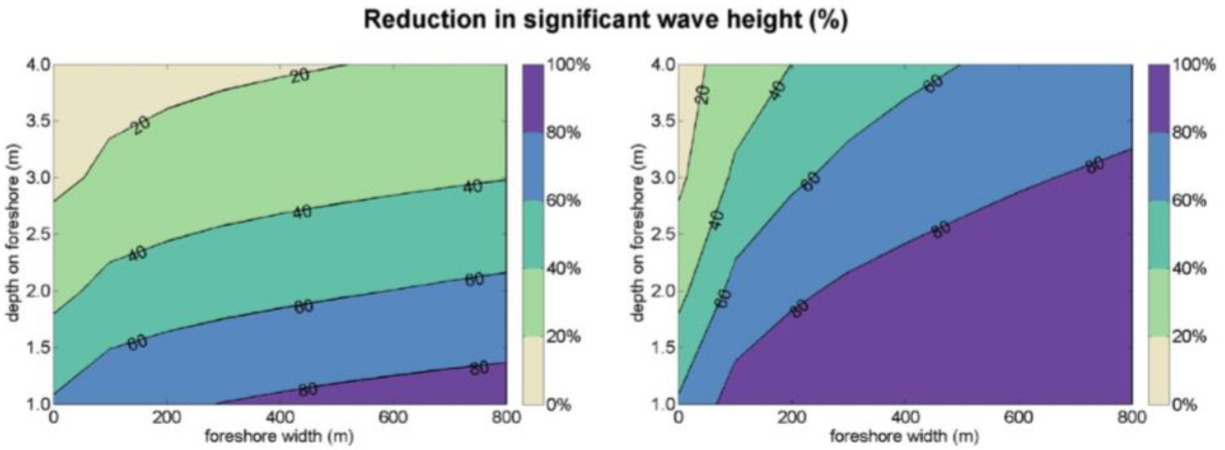


Figure 13-6: Reduction in significant wave height (%) due to bare *(left)* and vegetated *(right)* foreshores (Vuik, et al., 2016)

As aforementioned, a reduction in significant wave height results in a reduction of wave overtopping. Figure 13-7 shows changes in the reduced overtopping rates.

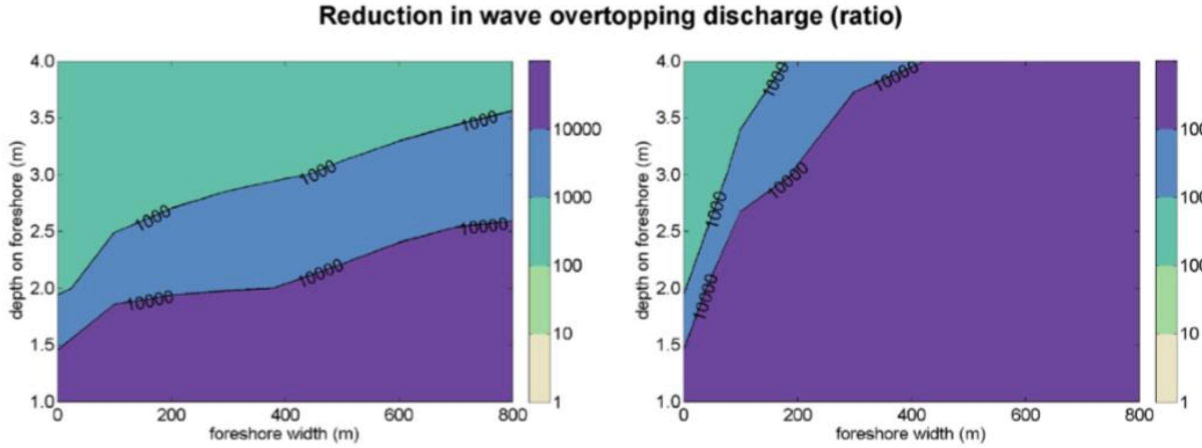


Figure 13-7: Reduction in wave overtopping discharge (ratio) due to bare *(left)* and vegetated *(right)* foreshores (Vuik, et al., 2016)

The reduction increases with decreasing water depth and increasing foreshore width (fig xx right panel).

Salt marshes show the highest stems during summer whereas in winter they are at the shortest. Therefore, the wave height reduction varies over the seasons (Vuik, et al., 2018) as a consequence of vegetation stems changes. Wave attenuation will be largest in summer, when the vegetation growth is at its seasonal maximum. The minimum is expected to occur during winter, around February or March (Vuik, et al., 2018). In spring, new shoots start growing, leading to a rapid increase in wave attenuation from March to May. Big winter storms may break or lean stems and produce a seasonality in the ratio of broken and standing stems. Figure 13-8 includes different months and their broken-standing stems ratio. This further reduces the salt marshes wave damping potential. This effect, has to be taken into account when implementing salt marshes in a flood defence system.

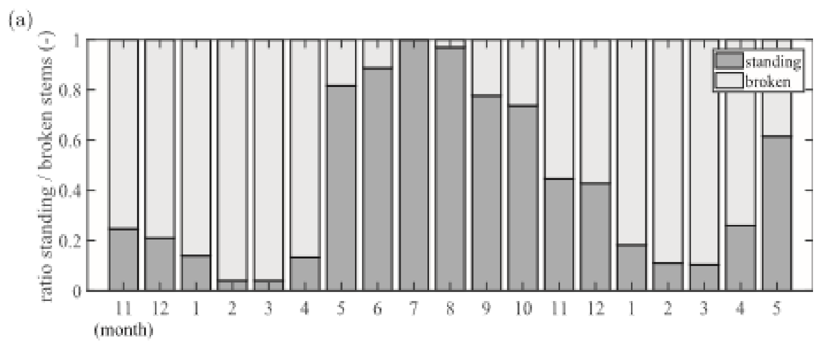


Figure 13-8: Standing and broken stems in different months (Vuik, et al., 2016)

Considering the recent research conducted by Vincent Vuik (2018), a decrease of 20% of wave height due to the presence of salt marshes is to be expected at the project location, where the salt marsh extension is at the maximum. In order to have the same impact on wave heights by the foreshore of the whole project, salt marsh implementation would be required on the eastward side of the ferry terminal.

13.3 Multifunctional Design

Extra measures are proposed to enhance the functions of the Wide Green Dike. The reasoning behind these measures is to make use of the opportunity of the dike reinforcement to create recreational, ecological and economic value to the local community and tourists in Holwerd.

The crest of the sea dike is 2.10 m wide, which is enough to accommodate a 2-way cycling lane as envisioned in Figure 13-9 and Figure 13-10. For the entire dike stretch this means an additional investment of approximately € 115 500, considering 10 €/m^2 of asphalt cover (Zwammerdam Group, 2018).

Since salt marshes grow on the seaward side slope of the dike, cattle, horse and sheep grazing is recommended for economic reasons. Previous research indicates that grazing can be beneficial for salt marshes, as long as proper management practices are applied (PUCCIMAR, 2013).

To stimulate cultural awareness, the installation of educational signs along the dike crest is proposed. These signs could contain information about the local history of flood protection and land reclamation, as well as the most relevant fauna and flora species in the region.

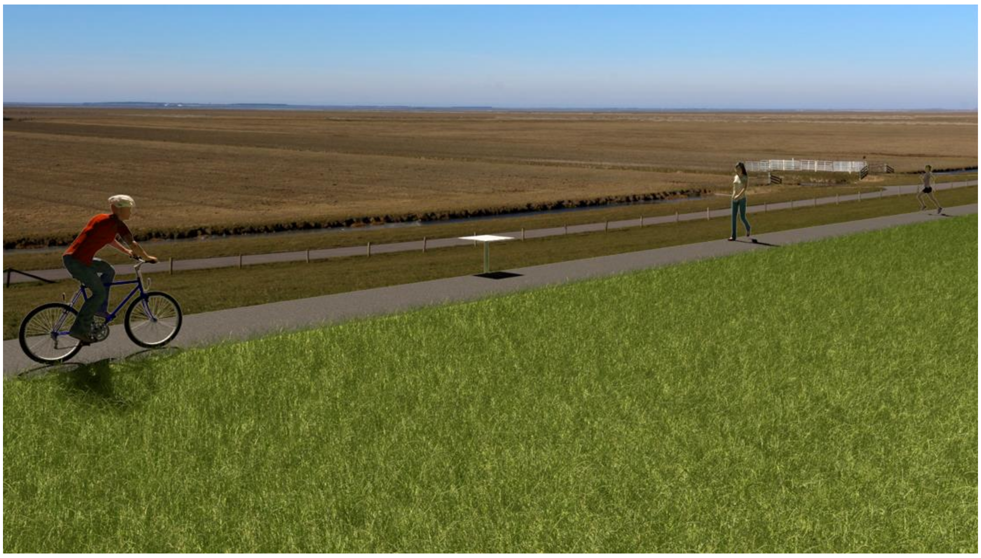


Figure 13-9: Artistic impression of a multifunctional Wide Green Dike in Holwerd (1)

Figure 13-10: Artistic impression of a multifunctional Wide Green Dike in Holwerd (2)

13.4 Ferry Connection

13.4.1 Comparing alternatives

Although the results of the MCA in Section 12.3 show that the Adjust ferry vessel fleet is the preferred alternative based on the highest value-cost ratio, there are various uncertainties and scenarios which may significantly influence this decision and need to be considered in further assessments. This is especially so as the MCA results show that there is not a big difference in the overall scores for the alternatives. Some aspects that may affect the scoring and change in decision are highlighted below:

- Difference in time scales and implementation of the interventions:
  - It should be noted that the Adjust ferry vessel alternative is likely to only be considered as a long-term solution due to Wagenborg's contract only ending in 2029.
  - In contrast, the Bend cuts alterative is foreseen only as a short-term solution. This is because of uncertainties regarding the dynamic morphology of the tidal basin over the long-term, hence the reduced sedimentation rates can only be guaranteed for a maximum of 10 years.
- Difference on responsibility to funding:
  - Purchasing new ferries would be a cost to the ferry operator company who may not be prepared to commit to this investment. Consideration needs to be given to what the company does with their existing fleet.
  - All options result in reduced dredging costs, funding of which is the responsibility of Rijkswaterstaat.
  - Relocation of the ferry terminal has the biggest potential in reducing the frequent maintenance dredging costs, but comes at a significant capital cost. Funding opportunities for this development would need to be defined and a cost-benefit analysis executed.
- Stakeholder interests and spatial scales:
  - Adjusting the vessel fleet concerns more stakeholders, including the Municipality of Ameland as key stakeholder, due to the secondary effects this solution may have on travelling to Ameland.
  - Relocation of the ferry terminal affects the neighbouring town's municipality and residents more so than Holwerd.

13.4.2 Short-term solution

The bend cuts alternative is proposed as the preferred short-term solution. This is because of uncertainties regarding the dynamic morphology of the tidal basin over the long-term. Using processed-based numerical models available today, it is still computationally difficult to perform analyses to make accurate morphological predications. Sources of uncertainty related to quantification of morphological predictions include input uncertainty, model limitations and calibration uncertainty. Therefore, it is understandable that there lies uncertainty in determining morphological behaviour on a time scale of several decades. Such is the case for quantifying the effects of implementing bend cuts in the already morphologically dynamic Ameland tidal basin. Thus, morphological predictions regarding the reduced sedimentation rates as a result of bend cuts in the Holwerd-Ameland navigation channel can only be guaranteed for a maximum of 10 years.

The bend cuts solution involves realizing the 'Bochtafsnijding vloedgeul' by means of shifting the first leg of the navigation channel from the ebb to the flood channel (Herman, et al., 2016). Thereby the longer meandering bend, Kikkertgat channel bend, will be bypassed and the navigational channel shortened by approximately 850 m. This new channel section is illustrated in Figure 13-11 below (Deltares, 2018).

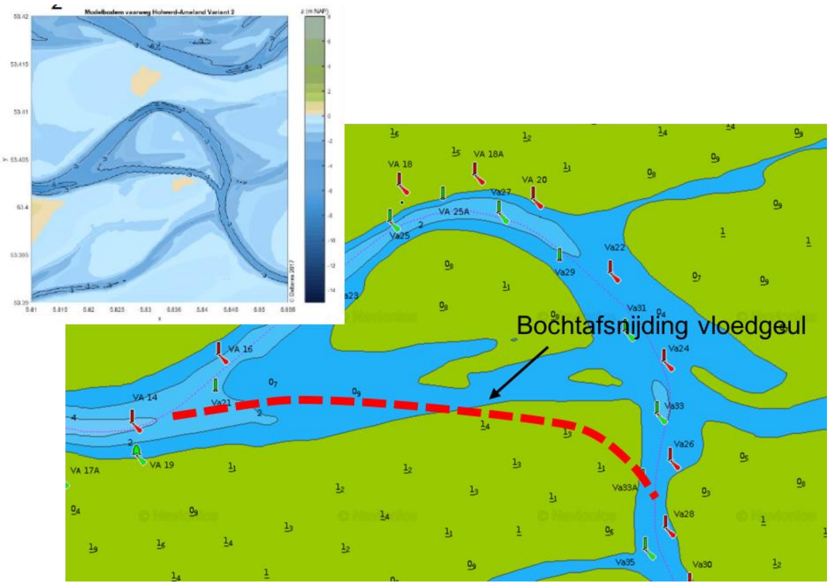


Figure 13-11: Realization of 'Bochtafsnijding vloedgeul' (Adapted from Navionics.com)

The shorter sailing distance therefore also results in a reduced sailing time of approximately 39 minutes, as calculated in Table 13-5, instead of the current time of 45 to 50 minutes.

Table 13-5: Reduced sailing distance and time for preferred 'Bochtafsnijding vloedgeul' solution

Navigation channel dimensions	Measurement	Units
Current navigation channel length	12	km
Distance shortened by Bochtafsnijding vloedgeul	0.85	km
Total navigation channel length after bend cuts	**11.15**	**km**
Sailing time calculation	**Measurement**	**Units**
Vessel speed (max)	10.8	kn
Vessel speed (max)	20.0	km/hr
Reduced sailing time	**38.5**	**min**

In terms of realization of this intervention, it is estimated that approximately 570 000 m^3 of material would need to be removed to create the new channel section. This is estimated to a capital cost of between € 2 million to 2.4 million (Jager & de Kleuver, 2016). Optimization of this design is still required and so with further assessments and planning, as well as an additional 1 year for dredging the new channel, it may take another two years to realize this solution.

Considering the approximated decrease in sedimentation rates as discussed in Section 11.3, for a period of 10 years, maintenance dredging costs are estimated to a value of € 85 million. This is more than € 10 million less than what it would cost if no bend cuts are implemented, thus a considerable saving. It is expected that the ebb channel can be used to store the dredged material for several years, depending on the rate of siltation.

A logistical and safety issue raised is using the dredged material to close-off the existing channel section whilst not interfering with the sailing of the ferry. A suggestion to limit this risk is to divide the realization of the 'Bochtafsnijding vloedgeul' bend trench into two phases as follows:

1. Construction phase: Dredge the bend cut and dispose of the dredged material in the deeper parts of the ebb channel. The ferry should still be able to sail through the ebb channel.
2. Maintenance phase: The ferry sails through the newly constructed flood channel once sufficient depth is acquired. Dredged material will be deposited in the ebb channel to start closing it off.

During phase one, once dredging of the flood channel commences, it is expected that currents will be stronger through the flood channel and less so through the ebb channel. During the second phase, tidal flow rates in the flood channel will continue to increase which helps to keep the flood channel open, while those in the ebb channel further decrease, which allows for the disposed dredged material to settle. Therefore, less sediment will flow back to the navigation channel enabling a reduction in the dredging issue.

It's important to note again that this bend cut solution is not a structural and sustainable solution for the long-term (after 2030) and so adjusting the vessel fleet is also given consideration, due to it being ranked as the preferred solution in the MCA.

13.4.3 Long-term solution

From the MCA, the Adjust ferry vessel fleet option is selected as the preferred solution. Considering that Wagenborg's contract would end in 2029, this gives opportunity for the new ferry operator company (or Wagenborg, should they reapply) to purchase smaller-sized ferry vessels which may be better suited for the sailing through the navigation channel.

With a smaller, faster vessel, with a restricted speed of up to 15 knots (27.8 km/hr), the sailing time could be reduced to approximately 32 minutes. With shorter loading and unloading times as well, the overall travel times decrease and allows for an adjustment to the ferry departure schedule to maximize benefits and prevent delays. This would be considered a more reliable ferry service than than the current situation.

Considering the example Damen Fast Ferry 4212 as a suitably sized ferry, the smaller beam of 11.6m allows for a narrower channel width requirement. Narrowing the channel, as shown in Figure 13-12, may result in a relative decrease in the dredging volume that is required on an annual basis.

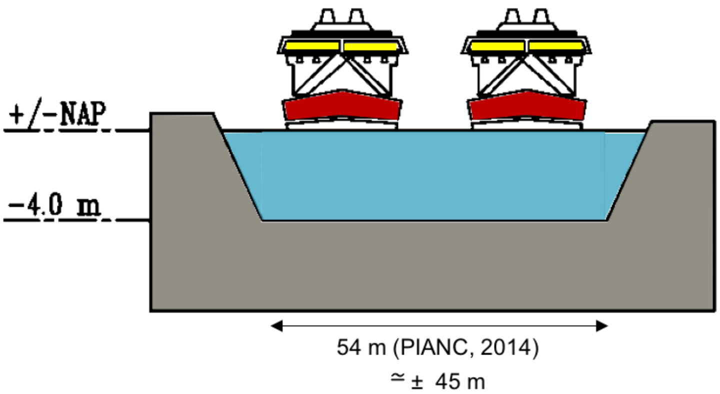


Figure 13-12: Reduced width of navigation channel for preferred alternative

Instead of 1.8 m^3 million m^3, it is estimated that future dredging will be in the order of 1.4 million m^3. This is approximately a 20% reduction. Considering the dynamic morphological behaviour of the Holwerd-Ameland channel and Wadden Sea as a whole, this relative reduction is not guaranteed. Should further studies show that it may work, this solution would cost roughly € 258 million over the next 30 years (assuming that bend cuts do not take place). The cost of purchasing the two ferries would however be the ferry operator company's cost and not Rijkswaterstaat's.

As previously highlighted, one of the major concerns of having a fleet with smaller-sized vessels is that is the ferry may have a reduced capacity for passengers and no or limited capacity for cars. Regarding the smaller capacity for passengers, this is not foreseen as a major issue due to the current vessels providing overcapacity on a daily basis. A recommended change to the operations is however that passengers should be able to book their tickets online to be guaranteed a ticket so that they can plan their trip accordingly. However, during peak summer and holiday seasons, alternative measures would need to be taken. Further assessment is required to define the future demand, and whether a 3rd ferry would need to be purchased for summer months.

Regarding the limited capacity of cars, some benefits that lie within this solution, is that public transport initiatives can be improved and should an additional parking area be required in Holwerd, this would draw more tourists to the town and could help improve their socio-economic status. Further studies, such as a traffic impact study and analysis of demand forecast would first need to be executed before this option is considered feasible. Also, very important for this solution, is involvement and communication with the Municipality of Ameland and its residents.

Considering that this solution is a long-term one, there are additional factors to consider such as:

- Future sailing route post 2030: a shorter, straighter navigation channel would result if bend cuts are implemented.
- Future transport demand: If the number of passengers travelling to Ameland continue to increase, ferries offering larger capacities would need to be supplied.
- Types of ships available in 2030 and thereafter: This influences any potential modification made to the ferry fleet.

13.5 Integrated Building with Nature Design

13.5.1 Salt marsh growth as a pilot project

The idea of utilising the dredged material for the restoration and development of salt marshes comes from the Mud Motor Pilot Project currently being researched near Harlingen, also along the Dutch Wadden Sea coast. The Mud Motor consists of the utilisation of dredged material from the Port of Harlinegen, transported by tidal currents, to restore a salt marsh area to the north of Harlingen. By making use of natural processes such as the tidal currents to transport dredged material, and using the dredged material in a beneficial way to provide ecosystem services forms part of a Building with Nature (BwN) approach. More information on ecosystem services is included in Appendix K. For the Holwerd case, a similar concept is given as a recommendation for further studies and a solution that could potentially reduce the high rate of sedimentation in the ferry channel and work in conjunction with the wide green dike. On the eastern side of the ferry, salt marsh development is possible, although it may require considerable effort. This is indicated in Figure 13-13. In this map, the area of interest is at the margin of the green line where salt marshes are already present, and the yellow line indicated as an area where there is potential for salt marsh development, but which requires larger efforts.

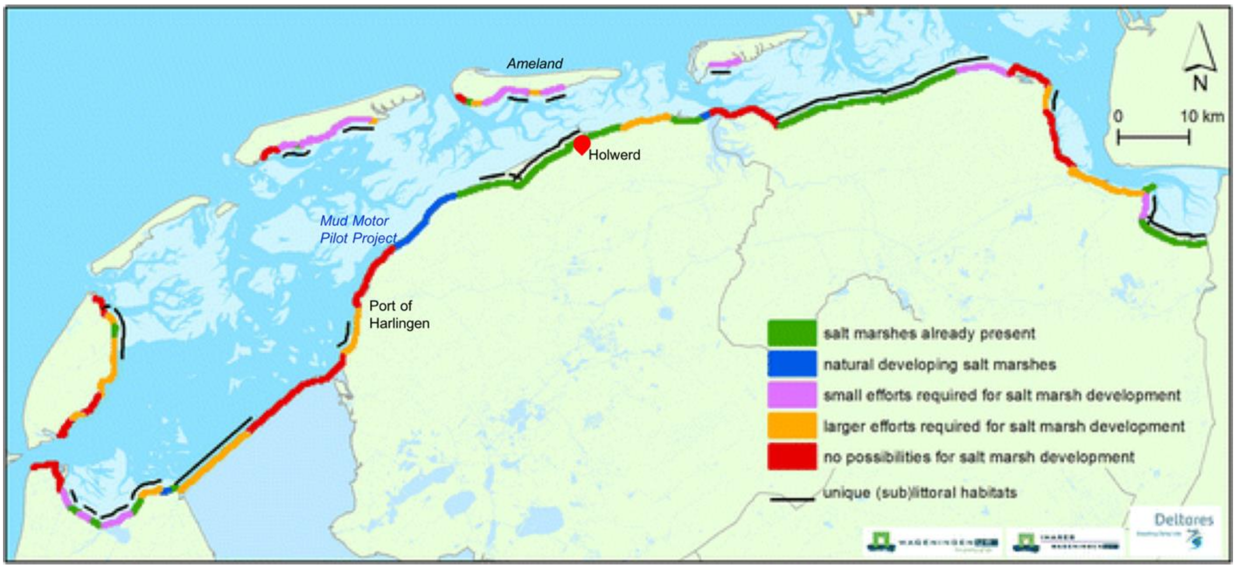


Figure 13-13: Salt marsh potential map (Loon-Steensma, 2015)

If the dredged material from the Holwerd-Ameland ferry channel is to be used for salt marshes restoration, a proper assessment of the feasibility of the project has to be done. It would be important to quantify the effect of disposing dredged material elsewhere (and to be used for salt marsh growth) and how this disposal scheme influences the dynamic morphology of the tidal basin and sedimentation processes affecting the ferry service. In order to develop salt marshes, the natural system, hydrodynamic and ecological processes have to firstly be understood.

13.5.2 Concept definition

An ecosystem is defined as a community of organisms and abiotic factors that have interactions with each other. Therefore, the existence of a certain ecosystem strongly depends on the abiotic conditions that are present. Some abiotic factors in a water-land environment are: temperature, pH of water, salinity, sunlight, turbidity and many others. In order to establish a strong and stable marshland, the aforementioned parameters need to be in the correct range Salt marshes develop through feedbacks between hydrodynamics, sediment and vegetation, and are dynamic by definition (Groot & Duin, 2013).

An important parameter is surface elevation, which, together with the tidal range, determines the flooding frequency and hydro period of the salt marshes.

If, consequently to the disposal of dredged material, mud flats will develop, and initially pioneer species could grow, using the seeds made available by the adjacent salt marshes in the Holwerd area. Pioneer species reduce water flow and trap sediments, rendering the environment suitable for the establishment for species that need more stable sediment. This is regarded as a positive feedback, in which the presence of the vegetation increases the rate of soil accretion and plant growth. A distinction of the different salt marsh zones can be seen in Figure 13-14. Note that there is a slight gradient in the ground from pioneer species to high salt marshes, which is exaggerated in the picture. The most biodiverse part is the zone that is regularly, but not daily, flooded. In zones that are only occasionally flooded, vegetation diversity decreases with ongoing succession.

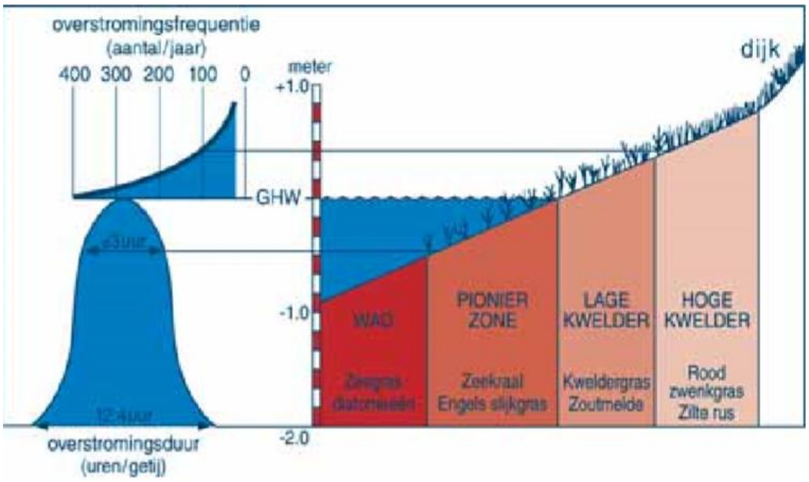


Figure 13-14: Salt marsh zonation and flooding period (It Fryske Gea, 2007)

13.5.3 Target Species

The salt marshes target species and habitats are those that are presently predominant in the Wadden Sea. This project will seek to establish the following habitats:

• Salicornia – 1310: this habitat periodically colonizes inundated mud flats and its typical species are Glasswort (Salicornia procumbens), Annual Glasswort (Salicornia europaea), and Seepweeds (Suaeda maritima). According to measured data (Deltares, 2015b), this type occurs between the mean low water line level and the mean high water line.

• Spartina swards – 1320: it consists of perennial pioneer grassland. Typical species are Small Cordgrass (Spartinetum maritimae) and Common Cordgrass (Spartinetum townsendii). It occurs in the same range of 1310, but has a lower resistance to high hydrodynamics.

• Atlantic salt meadows – 1330: including Sea lavender (Limonium vulgare), Common salt marsh grass (Puccinellia maritima), Sea-purslane (Atriplex portulacoides) and Couch grass (Elytrigia atherica). This habitat type can be found in a zone near the mean high water level up to the foot of low dunes and dikes, with a regular to incidental flooding frequency.

In terms of the zonation, habitat types 1310 and 1320 can develop in the pioneer zone and low salt marsh zone, and species of the Altantic salt meadows can grow in the high salt marsh zone (Deltares, 2015b).

Figure 13-15 shows a map of the local salt marshes near Holwerd. They are classified in pioneer zone, low salt marsh, middle salt marsh and high salt marsh. In Appendix I, the complete map containing all legends is available.

Figure 13-15: Salt marsh zones (Rijkswaterstaat, 2018)

13.5.4 Suggested plan

As a suggestion for salt marsh restoration on the eastern side of the ferry terminal, the proposed area for the disposal location is shown in Figure 13-16. This area measures approximately 580 500 m2. The bathymetric data was obtained from the Vaklodingen dataset from Rijkswaterstaat. The average elevation in the shaded area is -0.25 m NAP. To fill up with sediment such an area up to +1 m NAP, a total volume of 725 600 m3 of sediment is required. It is suggested to raise the soil level up to +1 m NAP as this is the height for the development of low and middle salt marshes (see Figure 13-14).

Figure 13-16: Proposed area for the disposal of dredged material to restore salt marshes

Currently there are summer polders in the frontward area of the dike, and since seawater floodings are too infrequent, saltmarshes cannot grow properly. De-embankment of summer polders in Holwerd is therefore recommended to enhance the development of wide salt marshes in the area (Common Wadden Sea Secretariat, 2018).

13.5.5 Concerns and uncertainties

When considering a project in a natural and dynamic system, there are many uncertainties and risks to be dealt with. Especially in the Wadden Sea, changes to the tidal prism can produce unexpected and undesired outcomes. The exact behaviour of the system to the disposal of dredged material for salt marshes implementation cannot be exactly predicted. This solution could, indeed, reduce the required dredging amount from the channel as predicted for the current Mud Motor pilot project. Although, specific to the Holwerd case, it could be that the creation of mud flats close to the ferry navigational channel may actually further decrease the tidal prism, which would in turn increase the sedimentation rates even more in the channel (Stive & Bosboom, 2015). To reduce the potential negative consequences, if this option was to be selected, the volumes of disposed material for salt marshes should not be too large at the beginning. This would allow time to study the response of the system and better plan the future strategy.

Therefore, if implemented, it is recommended to also be done as a pilot project in order to further develop knowledge within this field. It would be required to closely monitor the functioning of such an intervention, to determine whether it works and if it could be implemented elsewhere where similar abiotic and biotic conditions exist.

14. EIA AND RISK ASSESSMENT

14.1 Introduction

An Environmental Impact Assessment (EIA) can broadly be defined as a study of the effects of a proposed project on the environment (Achieng, 2007). EIA is a procedure used to examine the environmental consequences or impacts, both beneficial and adverse, of a proposed development project and to ensure that these effects are taken into account in project design. The EIA is therefore based on predictions. These impacts can include all relevant aspects of the natural, social, economic and human environment (Achieng, 2007).

Potential impacts have been identified for both construction and operation phases of a project and have been classified in to three different categories as shown below.

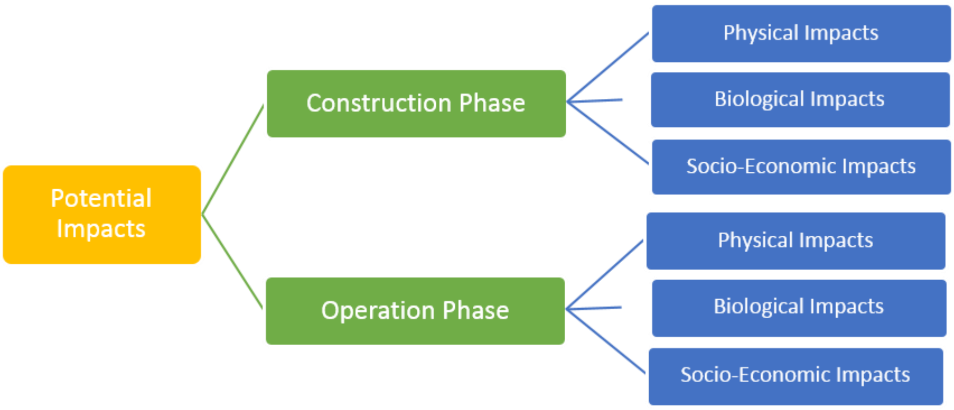


Figure 14-1: Classification of potential impacts

14.2 Quantification

In order to quantify the significance of impacts, an Environment Impact Significance Assessment (EISA) is performed using simplified form of widely adopted general method introduced by Conesa 2006 (Zuluet, et al., 2016); (Javier Toro, et al., 2013). Table 14-1 defines the Conesa 2006 criteria adopted in EISA (Javier Toro, et al., 2013). Corresponding scale values for each criterion are included in Appendix L.

Table 14-1: Conesa Criteria (2006)

Criteria		Meaning
Overall impact type	+	Positive: those that improve the environment
	-	Negative: those that cause degradation or harm the natural area
Intensity	IN	It refers to the incidence of the action over the environmental factor
Extension	EX	It reflects the extent of the specific component of the environment that is affected by the implementation of the project
Persistence	PE	It refers to the term that the effect lasts over the environment
Reversibility	RV	This criterion denotes the suitability of reconstruction the affecting factor has by itself, once the project stops acting over the environment
Recoverability	RC	This criterion refers to the suitability of recovering its original state after a given impact, through human intervention

Based on the criteria, the environmental importance (I) can be calculated by applying the following algorithm: I= (3IN+2EX+PE+RV+RC).

Regarding the environmental importance, impacts can be classified as follow.

Impact	I		
Compatible	8	to	15
Moderate	15	to	35
Severe	35	to	50
Critical	>	50	

An EIA was implemented for the chosen alternatives as described in Section 13 and is presented below. The EISA was adopted using Conesa method to identify the level of significance of each impact (Geovanna, et al., 2017); (Javier Toro, et al., 2013).

14.3 Wide Green Dike with Dredged Materials

14.3.1 Identification and evaluation of the potential impacts

Table 14-2 on the next page presents both direct and indirect anticipated impacts and respective significance levels during the construction phase as well as operational phase for the wide green dike solution, also assuming the possibility that dredged material could be used for either salt marsh development or in a clay ripening pilot project (refer to suggested integrated BwN designs in Section 13.5). Detailed evaluation of the EISA can be found in Appendix L.

14.3.2 Mitigation measures

As shown in Table 14-2, the overall positive and negative impacts lie in the moderate level of significance. Severe negative impacts during construction phase can be expected due to morphological changes and destruction of salt marshes. Therefore, it is recommended to study the system behaviour and understand it to come up with a proper design which can minimize the alteration of natural coastal processes. It is important to note that the possibility of using the dredged material in an integrated flood defence design, requires further assessment and knowledge through research.

Further, effects due to destruction of salt marshes can be restored during operation phase as the wide green dike enhances the ecosystem values. A detailed description of mitigation measures can be found in the Appendix L.

Table 14-2: Potential impact and significance levels for wide green dike solution

Impacts		Description	Sign	Impact
Construction phase				
Physical	Noise	Noise invasion due to construction equipment and traffic	-	Compatible
	Ambient air quality	Flume emission from construction equipment	-	Moderate
		Dust from material handling and other construction activities	-	Compatible
	Vibration	Vibration caused by the construction equipment	-	Compatible
	Water quality	Increased turbidity caused by the dredging	-	Moderate
		Discharge of pollutants on the water	-	Moderate
		Oil/ Fuel spill from construction equipment/storages	-	Moderate
	Soil quality	Discharge of pollutant on the soil	-	Moderate
	Morphology	Alteration of natural morphodynamic processes due to the construction	-	Severe
Biological	Flora	Destruction of the salt marshes and disturbances to the other vegetation present in the area	-	Severe
	Fauna	Damage and alteration to the present biodiversity	-	Moderate
Socio-Economic	Employment	Creation of new job opportunities for the local community	+	Moderate
	Traffic	Traffic congestion may be caused by trucks when materials are transported to the ripening location	-	Moderate
	Solid waste	Solid waste generation within the area of construction site and campsite will be increased	-	Moderate
Operation phase				
Biological	Flora	Guarantees an increase of biodiversity and allows for saltmarshes to grow on the lower part of the outer slope	+	Severe
	Fauna	Creation of new habitats after development of mudflats and saltmarshes	+	Severe
Socio-Economic	Employment	Creation of new business opportunities for the local community	+	Moderate
	Tourism	Possibility of increasing the area's income from tourism	+	Moderate
	Infrastructure development	With the possibility of the increasing the recreational value of the area infrastructure development can be occurred	+	Moderate
	Aesthetic and Land scaping	Higher aesthetic value	+	Moderate
	Solid waste	Solid waste generation within the area will be increased with the increased recreational activities	-	Moderate
		Overall	+	Moderate
			-	Moderate

14.4 Adjust Ferry Vessel Fleet

14.4.1 Identification and evaluation of the potential impacts

Table 14-3 shows the potential positive and negative impacts of the adjust vessel fleet alternative. Generally, impacts on the biological system will be positive, as smaller vessels will use less fuel and require less dredging. With less dredging, the water turbidity and disturbance to the fauna will also decrease. Negative impacts include the effect of a smaller vessel capacity, which could be problematic in the peak touristic season. The scores for each impact are shown in the Appendix L.

Table 14-3: Potential impact and significance levels for adjust ferry vessel fleet

Impacts		Description	Sign	Impact
Operation phase				
Biological	Flora	Reduced amount of dredging will result in less turbidity and disturbance to sea bed (benthic) plants	+	Moderate
	Fauna	Less dredging will result in less turbidity and disturbance of benthic organisms	+	Moderate
Physical	Ambient air quality	Less air pollution, since the smaller vessel with use less fuel and dredging vessel will operate less.	+	Moderate
	Water	Less water pollution, since the smaller vessel with use less fuel and dredging vessel will operate less.	+	Severe
Socio-Economic	Travel experience	A better and faster travel experience as the vessels can complete the route in a shorter time	+	Compatible
	Tourism	Tourists will be more attracted to utilise the service with a shorter travelling time	+	Moderate
	Employment	Less crew required on the vessel, less job opportunities	-	Moderate
	Ferry capacity	Smaller passenger capacity which is problematic for the peak season in Summer	-	Moderate
	Car transport	Less/no cars can be transported by the vessel, resulting in Ameland's inhabitants' discontent	-	Moderate
		Overall	+	Moderate
			-	Moderate

14.4.2 Mitigation measures

Also for this alternative, as can be seen in Table 14-3 above, the overall positive and negative effects lie in the moderate level of significance. To mitigate the effect of the reduced car transport, a car park could be built in the proximity of the ferry terminal and adequate public transport services can be provided by both Ameland and Holwerd. Moreover, an appropriate ferry schedule in the peak season could reduce the impact of the reduced passengers' capacity of the vessel. Alternatively, a third smaller ferry could be purchased to provide maximum capacity. These possible mitigation measures for the negative impacts are included in Appendix L.

15. CONCLUSION AND RECOMMENDATIONS

From developing conceptual designs through to preliminary designs, and evaluating them with the use of a multi-criteria analysis (MCA), preferred solutions for reinforcing the Holwerd sea dike and addressing the Holwerd-Ameland ferry connection problems, are selected. These selected solutions drive the need for further assessments and a detailed design study, prior to development of a new flood safety and coastal zone management plan for the local area of Holwerd.

The Wide Green Dike concept was the selected preferred solution as a reinforcement design to withstand extreme wave heights and water levels with a 1000-year return period, including relative sea level rise projections for the next century. Providing a cycle path along the dike and installing educational signs could enhance the functions of the dike, by creating recreational, ecological and economic value to the local community and tourists in Holwerd.

For the ferry connection, channel bend cuts are the feasible short-term solution to alter the route of the navigation channel, shortening the sailing distance and thereby reducing the sailing time by 5 to 10 minutes. As the morphological impact of bend cuts reducing the dredging amount can only be guaranteed for approximately 10 years, it is concluded there is no long-term structural, sustainable solution for reducing the dredging issue in the navigation channel. However, in this study, adjusting the vessel fleet to make use of two smaller-sized ferries, which can result in potentially decreasing the current maintenance dredging volume by 20%, is selected as the preferred solution. This is subject to the MCA criteria and weighting applied. Stakeholder interests and their influence on decision-making could change this result. It is therefore recommended that the next design phase includes the proactive involvement and communication with all key stakeholders, including the Municipality of Ameland and the ferry operator company. It is recommended that a demand forecast and traffic impact study be done to analyse the effect of providing a ferry service with limited capacity.

Considering the high environmental and ecological value of the Wadden Sea and surrounding region of Holwerd, options to integrate a Building with Nature (BwN) approach into the design of the preferred solutions was considered. The beneficial use of the dredged material for dike reinforcement and/or salt marsh development are suggested as solutions to provide additional ecosystem services. These alternatives have the potential to help alleviate the dredging issue for the ferry connection whilst also addressing the flood safety of the region by reinforcing the dike, and in addition, it adds value and environmental benefits to the region. The effects of using the dredged material for construction or salt marsh growth instead of dumping it in nearby channels are largely unknown. Therefore, it is recommended to conduct morphological modelling studies to determine how the tidal prism and consequent sedimentation rates in the navigation channel would change and how that in turn affects the dredging scheme and implementation of bend cuts. Should these solutions be deemed feasible, it is still recommended to implement them as pilot studies in which long-term monitoring will be conducted in the form of field measurements to observe the functioning of the system and determine if it works. This will help develop knowledge within the BwN field in order to see whether the same concept can be applied along the adjacent sections of the Holwerd sea dike or elsewhere.

An Environmental Impact Assessment was conducted for the preferred solutions of the wide green dike solution, also considering the potential use of dredged material, and the long-term solution of adjusting the ferry vessel fleet. This assessment was used to identify key risks for these concept solutions so that adequate mitigation measures could be implemented and risks could be accounted for in the next design phase before implementation. Severe negative risks, applicable to all solutions, include the impact of construction or change in dredging scheme on the natural morphodynamic processes of the tidal basin. Mitigation measures are vital to ensure implementation of any development will not worsen the sedimentation issue in the navigation channel. This again emphasises the need for additional morphological assessments in the next design phase. Destruction of salt marshes is another severe negative risk identified. This should be prevented in design and construction, given that the salt marshes are protected under regulation and should therefore be conserved.

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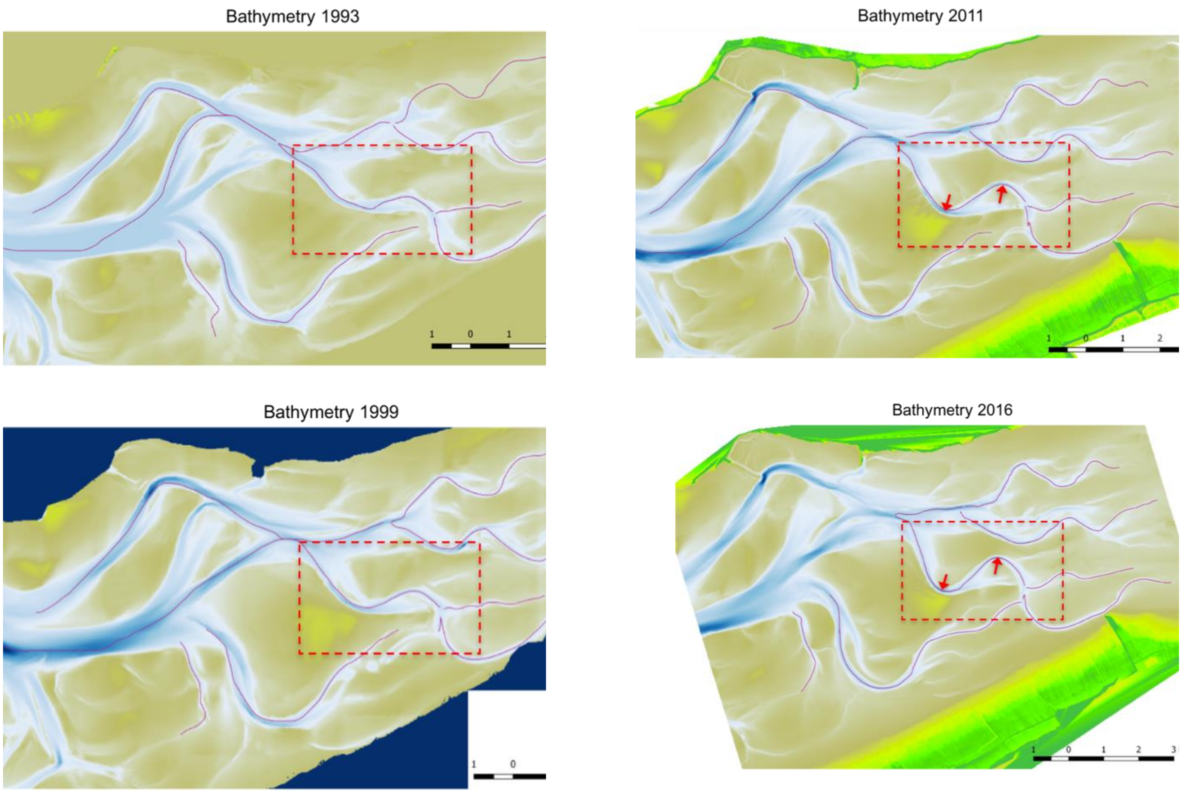
APPENDIX A: Bathymetry Maps

This appendix presents the historical bathymetry maps that are used to assess the migrating meanders of the tidal navigation channel, resulting in changes in channel geometry and dimensions, specifically in the Kikkertgat channel section as indicated. All figures are obtained and adapted from the Master thesis: *Tidal meanders in the Ameland Basin* (van Til, 2017).



APPENDIX B: Extreme Water Level Analysis

In order to determine the extreme water level in 1000-year return period (YRP), extrapolation was done by fitting annual maximum water level data to the Generalized Extreme Value Distribution (GEV). The GEV model is adopted as it can perform better than other traditional methods (Xu, 2007). Moreover, its goodness of fit with the data set under consideration is very high.

There are several statistical methods available to determine the distribution parameters. For instance, Maximum Likelihood Estimates method, Method of moments estimators, etc. Even though manual determination of these parameters using above methods requires little more computational effort, nowadays there are lot of state of the art statistical software techniques available for efficient computations. Therefore, determination of distribution parameters of the GEV model and prediction of extreme water levels were done using Mathwave EasyFit software.

Mathwave EasyFit software is one of the statistical software which is very user friendly and hence popular broadly. EasyFit allows to automatically or manually fit a large number of distributions to the data and select the best model in seconds (Mathwave Technologies, 2017). Also, respective distribution parameters are computed using maximum likelihood estimates method. It can be used as a stand-alone application or with Microsoft Excel, enabling to solve a wide range of problems with only a basic knowledge of statistics. Hence, to perform the water level analysis it was decided to use EasyFit software which is well known for fast and accurate statistical analyses.

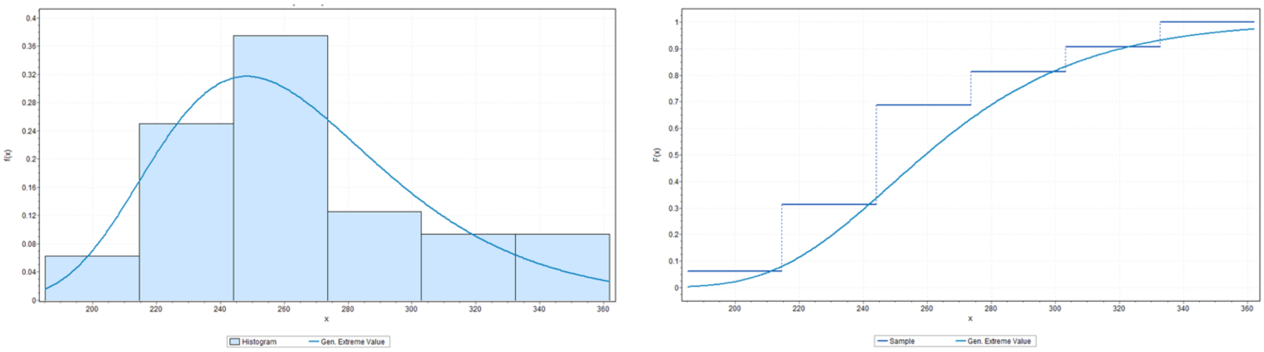


Figure B-1: GEV distributions of annual maximum water levels. (Left) PDF, (Right) CDF

According to the results obtained from the statistical analysis, the extreme water level related to the 1000 YRP is 452.96 cm NAP.

Sea level rise needs to be accounted for as discussed in Section 3.2.Hence a final design water level for 1000 YRP was calculated as 553 cm (NAP), taking both the extreme water level and 1m of SLR into account.

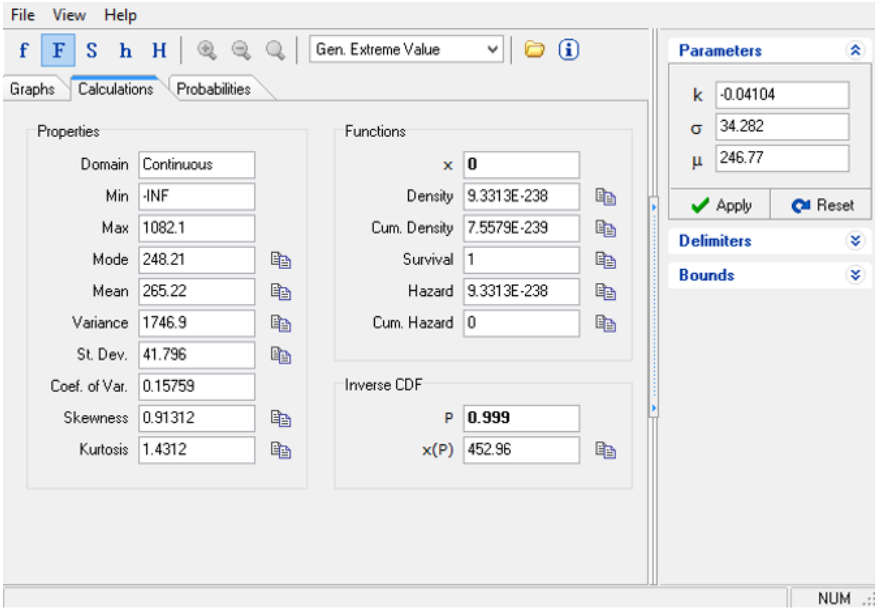


Figure B-2: Extreme water level predicted for 1000 YRP

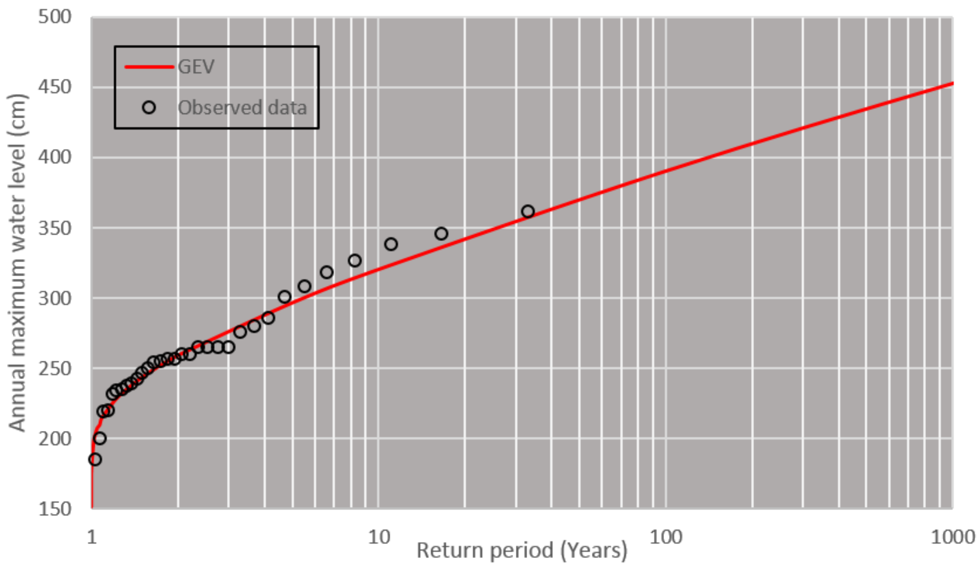


Figure B-3: Extreme water levels predicted by GEV model for different return periods

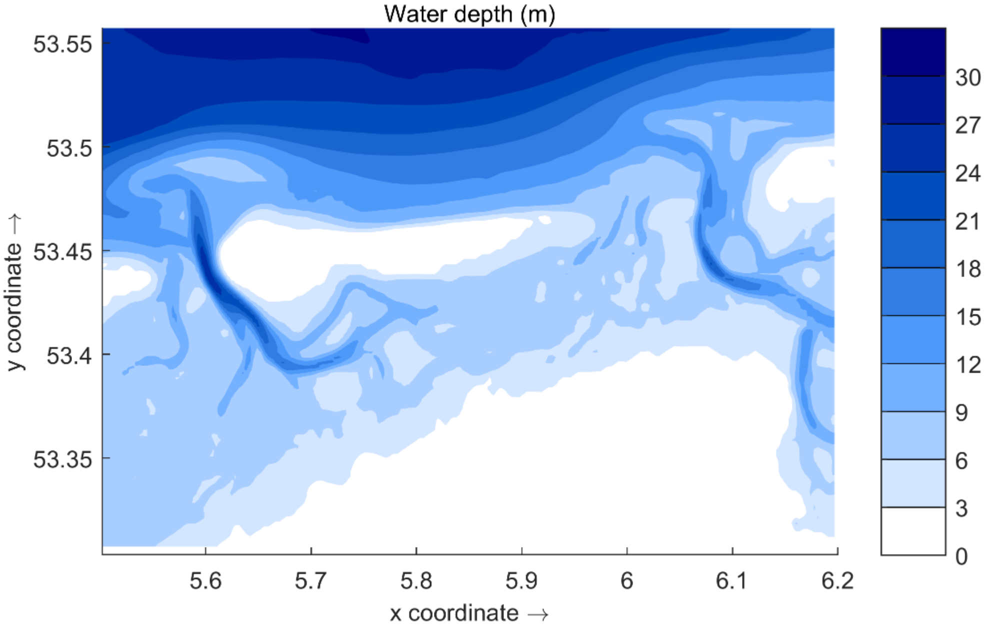


Figure B-4: Distribution of extreme water depths in the design storm with 1000 YRP

APPENDIX C: Wave Transformation

Offshore data

Figure C-1 shows a scatter plot of all wave directions measured at the offshore location (53°36' N, 6°10' E). Since there is only one peak of wave directions around 325°N, it is not necessary to filter the data on wave direction criterion.

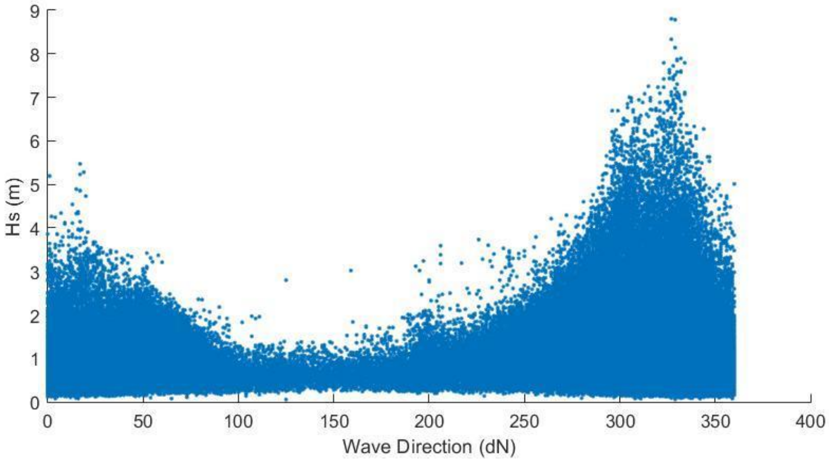


Figure C-1: Distribution of wave direction data

The plot of wave period and significant wave height in Figure C-2 demonstrates dominance of storm waves as opposed to swell waves (waves with long periods and low wave heights). Therefore, there is no need to filter data to separate between storm and swell waves. Storm waves are assumed to be dominant.

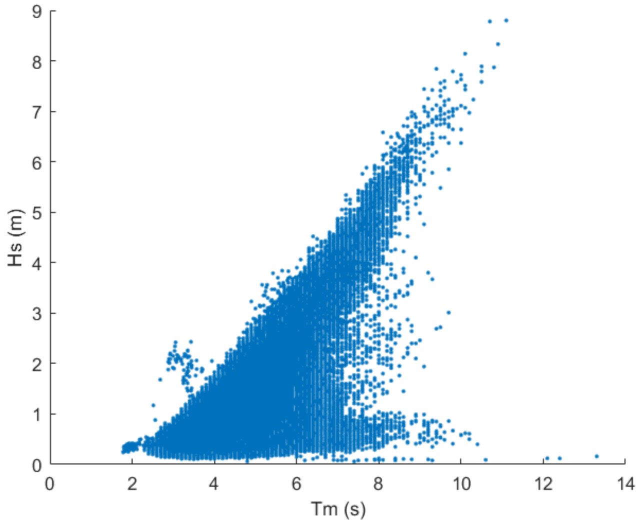


Figure C-2: Wave period and significant wave height relationship

Statistical Modelling

The Peak-Over-Threshold Method was used to select the largest storms each year to be considered in the extreme value analysis. Table C-1 shows the total number of storms and the average number of storms per year above each arbitrary threshold corresponding to a specific significant wave height.

Table C-1: Number of storms and average number of storms per year above an arbitrary threshold

Threshold (m)	Number of storms	Storms per year
8.0	3	0.1
7.0	10	0.4
6.0	35	1.2
5.0	96	3.4
4.0	233	8.2
3.75	302	10.6
3.5	370	13.0

Since, as a rule of thumb, 10 storms per year is the recommended value, the largest storms from this dataset were considered to have significant wave height peaks above 3.75 m. Table C-2 represents some samples of storms above this threshold.

Table C-2: Sample of storms with significant wave heights above 3.75 m

Date and Hour		***H_s (m)***	***Dir (°N)***	***T_m (s)***
31/07/89	7:00	4.13	318	6.9
01/08/89	17:00	3.99	323	6.9
08/10/89	0:00	4.06	333	6.8
09/11/89	11:00	4.00	294	7.3
26/01/90	0:00	4.29	272	6.3
08/02/90	18:00	4.80	294	7.2
14/02/90	9:00	5.41	295	7.6
06/07/90	16:00	5.60	311	8.0
20/08/90	12:00	3.87	295	6.7
20/09/90	5:00	5.27	315	8.3
21/09/90	16:00	5.33	316	8.2
07/10/90	5:00	6.12	297	9.3

The distribution of the largest storms was then fitted to a Weibull distribution with parameter α= 1.2. The actual significant wave heights for each return period and the fitted line can be seen in Figure C-3. Since the probability of failure P_f to be tested for the dike is once every 1000 years, the corresponding return period is $1/P_f$=1000 years. For a 1000-year return period, the offshore significant wave height H_S is 11.5 m, as shown in Table C-4. By finding a correlation of the type $T_m = a\sqrt[b]{H_s}$ (with a and b as constants), the mean wave period corresponding to the significant wave height was found to be 12 s.

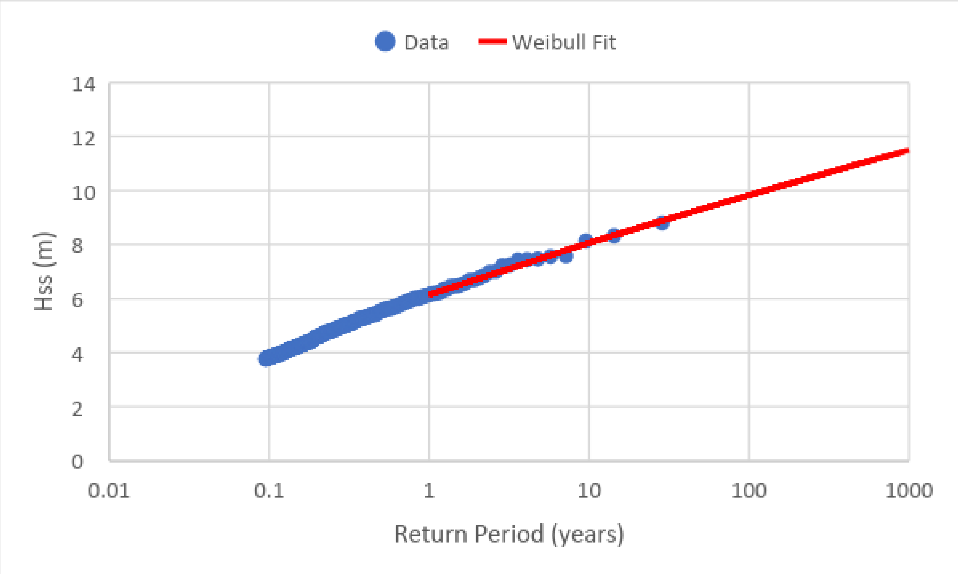


Figure C-3: Return period versus significant wave height for the Weibull distribution

Table C-3: Significant wave height predictions for the Weibull distribution

Return period (years)	Linearized Variable X	Predicted H_s (m)
1	2.04	6.15
10	3.61	8.07
20	4.05	8.61
50	4.62	9.31
100	5.04	9.83
200	5.45	10.34
500	5.99	11.01
1000	6.39	11.50

Wave Transformation

The software Delft Dashboard was used to create a model of the Ameland tidal basin and it's inlets to perform a wave transformation from offshore to nearshore conditions (near the dike at Holwerd). A rectangular grid of 200 by 100 points was generated, containing associated bathymetric data from the Vaklodingen dataset.

The following boundary conditions were placed along the north face of the grid: H_S = 11.5 m; T_m = 12 s; Wave direction = 325 °N. These conditions were directly obtained from the statistical analysis of the offshore wave dataset. Wind direction is assumed to be the same as the wave direction and a wind speed of 26. 5 m/s is accounted for.

The uniform water level used was 5.53 m, as determined from the extreme water level analysis in Section 5.3 and Appendix B, which takes into account sea level rise. Wave heights are assumed independent from the extreme water level statistical analysis. Four output locations along the dike were considered to calculate the results. Figure C-4 shows the grid with the associated bathymetry (in the present situation) and the output locations (yellow dots).

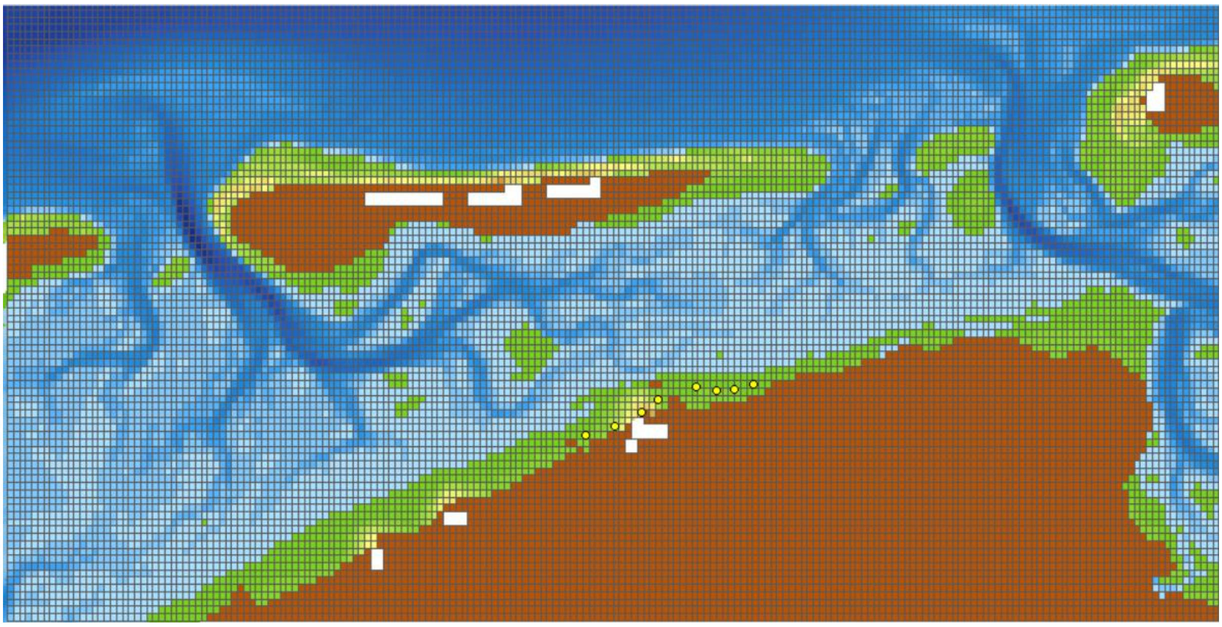


Figure C-4: Generated model used for the wave transformation

The generated model in Delft Dashboard was applied in the software Delft3D Wave, which performs the wave transformation using SWAN. The values of the wave transformation during extreme events obtained for the significant wave heights, mean wave periods and wave directions for each output location can be seen in Table C-4 below. The output locations are ordered from west to east in ascendant order.

Table C-4: Nearshore wave transformation results

Xp (°)	Yp (°)	Depth (m)	H_s (m)	T_m (s)
5.83	53.37	4.79	1.77	3.54
5.85	53.37	1.52	0.86	3.49
5.86	53.38	0	0	0
5.87	53.38	4.53	1.24	3.01
5.89	53.39	5.15	1.97	3.84
5.91	53.39	4.78	1.93	3.92
5.92	53.39	4.87	1.95	3.96
5.93	53.39	5.08	2.00	3.95

The wave heights related to the four points located to the east of the ferry terminal are all higher than the ones located to the west, due to the bathymetry of the region. The points with zero water depth, wave height and period indicate dry locations. The critical design wave height selected for the dike assessments is therefore selected as 2.00 m, i.e. the worst-case scenario corresponding to the highest predicted waves among the output locations. Figure C-5 shows the magnitude and direction of wave speeds.

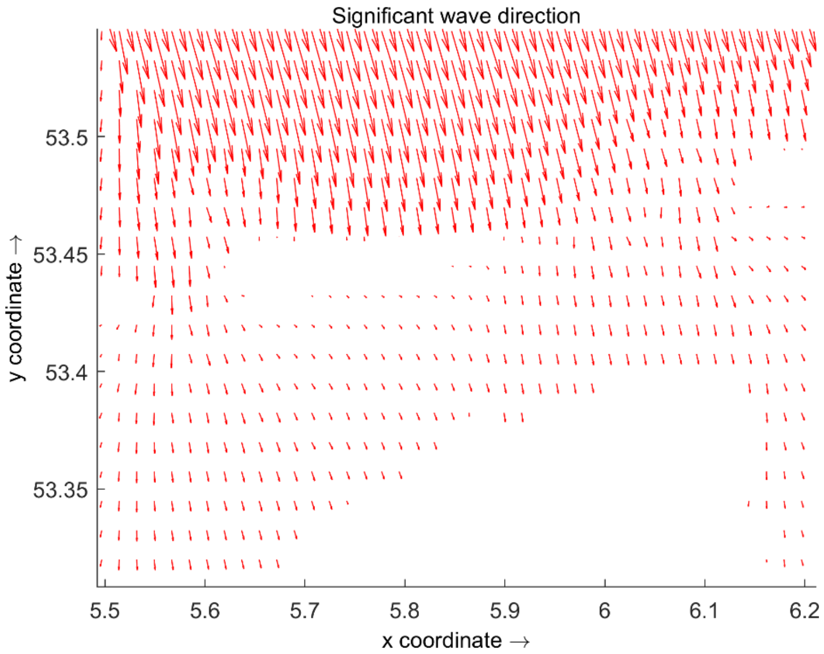


Figure C-5: Magnitude and direction of computed wave speeds

APPENDIX D: Overtopping Calculations For Present Dike

Calculations shown for the overtopping assessment of the current dike design, taking into account Sea Level Rise (SLR). For the formula's parameters A and B, characteristic values of 0.026 and 2.5 were used respectively. Table D-2 defines each parameter within the Van der Meer formula:

$$\frac{q}{\sqrt{g \cdot H_{mo}^3}} = \frac{0.026}{\sqrt{tan\alpha}} \cdot \xi_{m-1,0} \cdot \exp\{-(2.5 \cdot \frac{R_c}{\Upsilon b * \Upsilon\beta * \Upsilon f * \xi_{m-1,0} \cdot H_{mo}})^{1.3}\}$$

This is the formula used with the reduction coefficients.

Table D-1: Overtopping calculations

VAN DER MEER and BRUCE (2014)

Parameters				
H_{mo} (m)	2	q (l/s*m)	14.30	Breaking waves
α (radiants)	0.23090706			
$\xi_{m-1,0}$	1.287337064			
Rc (m)	2.85			
g (m/s²)	9.81			
β (°)	0			
T	3.95			
Reduction coefficients				
Υ_b	1			
Υ_f	1			
Υ_β	1			

According to VAN DER MEER and BRUCE [2014] the reliability of the coefficient values is as follows:

general shape $\frac{q}{\sqrt{g \cdot H^3}} = A(...)exp{-B(...)}^{1.3}$	Equation 5.5 A	Equation 5.5 B	Equation 5.6 A	Equation 5.6 B
Mean value	0.023	2.7	0.09	1.5
Standard Deviation	0.003	0.20	0.013	0.15
Characteristic value[4]	0.026	2.5	0.103	1.35

Table D-2: Definition of overtopping parameters

Hmo (m)	**Significant wave height**
α (radians)	Outer slope angle
$\xi_{m-1,0}$	Irribaren number
Rc (m)	Crest height
g (m/s²)	Gravity acceleration
β (°)	Wave angle of incidence
T (s)	Wave period
Reduction coefficients	
Υ_b	Berm coefficient
Υ_f	Roughness coefficient
Υ_β	Wave angle coefficient

APPENDIX E: Elimination Of Concept Alternatives

Flood safety concept alternatives:

Traditional dike widening: (not eliminated)

Widening the dike consists of creating a storm surge berm that reduces wave run-up and overtopping. A berm is a part of a dike profile in which the slope varies from horizontal to 1:15. The maximum effect can be realised with a berm height at the design water level and a width of five times the design wave height (Pullen, et al., 2007). Initial analysis shows that this alternative meets the functional design requirements.

Wide green dike: (not eliminated)

A Wide Green Dike consists of a mildly sloping seaward face (with a of slope of 1:7) that merges smoothly into the adjacent tidal flats. Waves do not reach the dike during normal conditions and are damped by the foreshore. The gentle outer slope has the role of reducing wave impact during design conditions. In comparison to the Traditional Dike design, wave energy dispersion along the slope is more distributed, allowing a thick clay layer covered in grass to be sufficient to protect the dike against erosion (Loon Steensma & Schelfhout, 2016). Initial analysis shows that this alternative meets the functional design requirements.

Revetment change: (not eliminated)

The main function of revetments is to prevent the soil body of the levee from coming into direct contact with the erosive forces of the waves, currents or other objects. Dikes typically have a clay and grass cover layer if the grass cover can provide sufficient erosion resistance. If this is not the case, a hard-protective layer must be placed instead, for which there are different options ranging from natural stone pitchings, to concrete elements or asphalt covers (Jonkman, et al., 2017). This is the most robust design for the reinforcement of the dike and so meets the functional design requirements.

Multiple line of defence: (eliminated)

The Multiple Lines of Defense Strategy proposes that two key elements of the coast will together sustain the coast. These elements are: Utilizing natural and manmade features which directly impede storm surge or reduce storm damage (Lines of Defense) and establishing and sustaining the wetland habitat goals (Target Habitat Types). These two, when integrated, can sustain the coast.

This strategy has been effectively implemented in few coasts around the world in order to prevent coastal flooding. However, this concept would be difficult to introduce in the present study. This is mainly due to the site-specific characteristic of the tidal basin. For instance: vast majority of the basin is covered with the flood tidal delta and hence majority of the area is covered with salt marshes. Therefore, it is difficult to introduce man made features in this natural and ecological system. And there is no room to accommodate line of defences within the system. Therefore, this alternative is eliminated based on that it does not meet the following functional requirements: limited morphological and ecological impact, spatial restrictions.

Dike relocation: (eliminated)

The main purpose of a dike relocation would be for enlargement of the tidal basin. With this measure, the tidal prism and subsequently sub channel volume could increase. The material that erodes in the channels may raise the intertidal flats and salt marshes and dampen the wave energy more effectively. On the other hand, there are several consequences of a dike relocation that would significantly affect the local community in several ways, such as loss of farm land, devaluation of property and loss of income.

Therefore, this measure is politically hardly feasible. Also, this measure would involve significant costs. Effectiveness of the measure strongly depends on the site characteristics like sediment availability, size of the tidal basin etc. Therefore, considering above drawbacks, amongst others, the dike relocation measure was eliminated.

Sandy dike: (not eliminated)

An Overtopping Resistance Dike or simply Sandy Dike is an alternative to adapt the Holwerd sea dike in such a way that it can withstand overtopping rates higher than the allowable design overtopping criterion. This is achieved by changing the inner slope of the dike.

The new Sandy Dike concept consists of placing a layer of sand on top of the landward slope. This layer is sufficiently thick to keep the dike stable during and after extreme overtopping events. In these cases, the sand is washed away and reshaped. As this is an innovative reinforcement concept, easy to construct and cheap, this alternative is not eliminated.

Oyster/Mussel Reef: (eliminated)

Oyster reefs deliver many ecosystem services and are abundant, persistent structures of marine ecosystems worldwide. Oysters form dense three-dimensional reef structures that can alter water flow and reduce wave action (Walles, et al., 2015). Reducing wave height helps against flood safety. Moreover, these organisms have a high ability in trapping sediment and enhance accretion.

These sedimentation effects however, make oyster reefs not feasible in this project, where sedimentation in the tidal basin's navigation channel is already a problem for the ferry connection.

Ferry connection concept alternatives:

Adjust vessel fleet: (not eliminated)

A suggested long-term solution is to look into the possibility for the ferry operator company to commission a new, more suitable vessel. The current vessel has a maximum speed of 10.8 knots (=5.5 m/s). A faster vessel could be used to limit the delays, however operational and safety limits for navigation across the tidal basin would need to be checked. A smaller-sized vessel could also reduce the channel dimensions required. This alternative shows potential for a more reliable ferry service reducing operational downtime and potential for decrease in the annual dredging volume if smaller vessel.

Bend cuts: (not eliminated)

Bend cut-offs are proposed in two sections of the navigation channel with the aim to:

- Shorten the sailing time between Holwerd and Nes; and
- Decrease the dredging amount.

This intervention would in effect improve accessibility to Ameland (shorter sailing time) and contribute to an improved maintenance regime for the navigation channel (less dredging) (Deltares, 2015a).

Extension of the ferry pier at current location: (eliminated)

The main purpose of the pier extension is to extend the pier so that it reaches deeper water in a channel with sufficient depth to accommodate the vessel or in which at least less dredging would be required on a continual basis. This would bypass the first channel bend where most dredging operations currently take place, therefore potentially reducing the requirement for maintenance dredging and associated costs.

This option is assessed as being not feasible in the current study area due to few key reasons. Primarily this would significantly affect the morphological behaviour of tidal basin as the system tries to adapt to the new construction. Further, as the Wadden Sea area has high environmental value it would be difficult to obtain necessary authorizations to implement this measure. Another reason, this alternative would involve high capital costs for construction of the pier, while this does not ensure complete alleviation of the current sedimentation problem.

Relocation of ferry terminal to the west: (not eliminated)

Relocation of the ferry terminal is another alternative measure suggested to overcome the present ferry connection problem. According to the recent findings of Deltares, the present location of the ferry terminal is too near to the tidal watershed. Therefore, this alternative suggests moving the ferry location more towards the west from the current location in order to take it away from the tidal divide.

Once the terminal is moved further away from the tidal divide, the problem of depth reduction of the channel due to sedimentation can be effectively eliminated. Moreover, the new location of the terminal is in more open and stable water with larger channel depth (around 5 m- 10 m). As the draft requirement for the present ferry is -4 m, no dredging would be required in the new location as it has sufficient depth to accommodate the vessel. Consequently, the current high dredging costs and the tremendously increasing dredging volumes can be well avoided.

Closure dam: (eliminated)

A closure dam, like the Hindenburg Dam (built in 1927) connecting the Sylt island in the Wadden Sea to mainland Germany, could provide a road to connect Holwerd to Ameland. This closure dam would be located in the shallower area near the tidal divide. However, this location is considered to be both a Habitat Directive and Birds Directive areas under the Natura 2000 conservation initiative, which means that construction activities of this type are restricted under the Nature Conservation Act (Department of Nature, 2005).

Even the experience in Germany showed that a closure dam is indeed very impactful to the local environment, by disturbing the equilibrium of the tidal inlet and causing erosion in the southern part of Sylt. Considering the dynamic and partly unclear morphology of the Ameland basin, especially regarding the watershed movement, a closure dam at this location would not be feasible due to the environmental regulations not being approved as a result of severe morphological impacts and too high capital costs due to construction in this location being very difficult.

Integrated concept alternatives:

Holwerd aan Zee: (eliminated)

Proposal

The 'Holwerd aan Zee' project is an innovative project proposal that was initiated (and supported) by the local community of Holwerd in 2013-2014 (Holwerd aan Zee , 2018). This project acts as an initiative to boost tourism and economic activities in the region, in effect to 'recreate' Holwerd and provide a 'sense of place'.

The core idea of this project is to breach the sea dike so that a tidal lake around the village would be created. This would restore the connection that existed between Holwerd and the Wadden Sea in the past (Alderliesten, et al., 2016). Sluice gates would be built in the sea dike to control the water levels. Figure E-1 shows the conceptual design of Holwerd aan Zee.

Figure E-1: Holwerd aan Zee conceptual design (Alderliesten, et al., 2016)

It is proposed that the new tidal lake could provide a natural landscape with extended salt marshes, fish migration using a fish ladder and additional space for bird breeding. Also, pleasure watercrafts are suggested for tourists to enjoy the Wadden Sea environment without the need to leave the mainland (Alderliesten, et al., 2016).

Agricultural activities using the formed saline water reservoir such as algae and seaweed production can be utilized as sources of food for animals or vitamin supplements. Conversion of algae into biomass might also be an option (Alderliesten, et al., 2016).

Relevant to this flood safety and ferry navigation study, Holwerd aan Zee aims to also address the current dredging issues. It has been proposed that the water flow in the channel as a result of the dike breach (it would also serve as a navigable access channel for the pleasure watercraft), could flush away sediments from the tidal basin, reducing the amount of dredging required for the navigation of the ferry (Alderliesten, et al., 2016). The project is ongoing and the feasibility thereof still under investigation.

Analysis

Although the Holwerd aan Zee project proposal has many potential benefits, especially socio-economic aspects, such as creating recreational areas and boosting tourism within Holwerd, there are also many potential drawbacks.

To breach the dike would be a very costly operation and it would create a vulnerability in the flood defence system. Additional dikes would need to be developed along the new channel leading inwards to the tidal lake (reservoir). A detailed morphological study must also be conducted to determine the impact of the created reservoir on sediment transport, since this measure could disturb the dynamic equilibrium and cause undesired environmental impacts in the salt marshes, sea dike and navigation channels, instead of the flushing of sediments as proposed.

Although the local people's needs and socio-economic situation of Holwerd is also of importance to this flood safety and ferry navigation study, it is not the first priority. Flood safety is of key concern in terms of engineering design and feasibility, with strengthening the dike as one of the objectives of the study. The concept of breaching the dike would contradict this objective.

At this stage, the Holwerd aan Zee concept proposal cannot be considered a feasible alternative for this study. Based on limited guaranteed information already available regarding the design of the Holwerd aan Zee project and this study's scope of work, it was agreed that the Holwerd aan Zee project proposal would not be analysed further for inclusion to this study's alternatives. One can refer to their website for further information on the Holwerd aan Zee project and current status thereof:
https://www.holwerdaanzee.nl/nld/.

Use dredged material for strengthening of dike

Utilizing the clay dredged from the ferry channel could potentially be used to reinforce the sea dike, whilst saving material costs and also alleviating the need for constant dredging activities in the ferry navigation channel. This approach has been proved attainable under certain circumstances and it is explored under the Building with Nature concept. For instance, in Germany and Poland, flume experiments and field investigations under the project *DredgDikes* determined that dredged material from the South Baltic Sea region is suitable for construction purposes (Cantre & Saathoff, 2013).

The clay ripening solution aims the beneficial use of dredged material by transforming the sediments into appropriate soil to be used for dike reinforcement. This solution is based on the pilot project by Ecoshape currently in progress in the Eems-Dollard area (EcoShape, 2018b). This can be incorporated in another dike reinforcement solution, however not alone.

APPENDIX F: Overtopping calculations – alternatives

Traditional Dike Widening

As introduced in Section 10.1, the effect of a berm is considered using the berm reduction coefficient, given as:

$$\gamma_b = 1 - \frac{B_B}{L_B} \cdot (0.5 + 0,5 \cdot \cos\left(\pi \cdot \frac{h_b}{x}\right))$$

Where B_B is the width of the berm itself, L_B is the length over which the berm has an effect on the wave attack, h_b is the distance between the berm level and the water level and x is the 2% wave run-up. The length of the berm, L_B was progressively increased to find at what point it would have been enough to reduce overtopping below the limit of 5 l/m/s.

In the tables below, the values of the different parameters are shown and the overtopping rates with different berm legths. L_B is equal to 15 m, h_b is equal to 1.83 m and x to 5.3m.

As highlighted in the table, a berm of 4 m long would bring the overtopping rates below the design limit.

γ_b	Berm length (B_B)	Q (l/m/s)
0.944	1	10.09
0.919	1.5	8.52
0.896	2	7.21
0.874	2.5	6.42
0.854	3	5.71
0.835	3.5	5.15
0.818	4	3.81
0.801	4.5	3.27
0.786	5	2.82
0.771	5.5	2.43
0.757	6	2.10
0.743	6.5	1.82

Revetment change

The rock manual (CIRIA, et al., 2007) *was used to estimate the dimensions of the stones that would be used for the new revetment. The following formula was used:*

$$\frac{H_s}{\Delta \cdot D_{n50}} = C_{pl} \cdot P^{0.18} \cdot \left(\frac{H_s}{H_{2\%}}\right) \cdot \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \cdot \left(\xi_{m-1,0}\right)^{0.5}$$

The results are presented in the table below, along with the definitions of the different parameters.

Parameter	Symbol	Value
Significant wave height (m)	H_s	2
Slope angle (radians)	alpha	0.2
Density parameter	Δ	1.8
Irribaren number	$\xi_{m-1,0}$	1.3
Coefficient	C_{pl}	8.4
Permeability parameter	P	0.1
Damage parameter	S_d	2.0
N° of waves during storm	N	2700
2% exceeded wave height (m)	$H_{2\%}$	2.8
Median rock unit diameter (m)	D_{n50}	0.60

Sandy dike

The safety assessment for the Sandy Dike is performed by determining if the designed sand layer thickness is enough to withstand the wave overtopping during an extreme storm. For Holwerd, a wave overtopping value of 0.014 $m^3/m/s$ is used, as calculated in Section 7.2 for a storm with a return period of once per 1000 years. The slope of the landward side is determined as $\beta=19^o$ from the dike's geometry.

From a report on wave overtopping (Van Der Meer, 2008), the following relationship is used to calculate the flow velocity over the sand:

$$u = 5.0V^{0.34} = 1.2\ m/s$$

It is assumed that the flow velocity is constant over an extreme storm with duration of 2 hours. For an averaged sand diameter D of 1 mm and the determined flow velocity, the Reynolds number is Re=1171, corresponding to a critical Shield's mobility parameter θ_{cr}=0.4 at initiation of motion. The sediment transport is then calculated using an empirical model for flows on relatively steep slopes of sand (Visser, 1995):

$$s_b = 4C^{-0.5}(g\Delta D^3)^{0.5}\left[\frac{D_{90}}{D_{30}}\right]^{0.2}(\tan\beta)^{0.6}\theta^{0.5}[\theta-\theta_{cr}] = 0.004\frac{m^3}{s\ m}$$

Where:

- Friction Coefficient: C=0.025
- Acceleration of gravity: g=9.81 m/s^2
- Specific density of sand: Δ=1.65
- Sand grading factor: $\left[\frac{D_{90}}{D_{30}}\right]^{0.2}$=1.10
- Shield's parameter: $\theta = \frac{Cu^2}{g\Delta D} = 2.12$

All these formulas and values were found in the literature (Visser, 1995). Failure of the sand layer is defined as all sand on the slope being eroded per unit length. From the sediment transport determined, approximately 30 m^3/m of sand is expected to erode after 2 hours of the extreme storm. Since this volume is less than the available volume 42 m^3/m, the 2-meter sand layer thickness is safe.

APPENDIX G: Ferry Connection Alternatives, Supporting Calculations

Alternative 1: Base case

The table below summarises the cost estimate for dredging 1.8 million m^3 annually over a 30-year period until 2050.

COST ESTIMATION:		
Alternative 1: Base case - 'do-nothing' options - Current ferry and dredging operations		
Dredging amount, V =	1.80E+06	m^3/year
Unit dredging cost, C_u =	5.4	EUR/m^3
Base year, Y_1 =	2020	years
Delivery year, Y_2 =	2050	years
Contract period, t =	30	years
Total dredging amount, V_T =	5.40E+07	m^3
Total dredging cost, C_0 =	**€ 290 250 000.00**	**EUR**

Assume 75% value of range 2-6.5 €/m3

The table below presents the safe channel width calculation according to the standard approach set out in PIANC (2014), for the ferry currently in use, the MS Sierd or MS Oerd, both with a beam of 15.9 m.

Alternative 1: Base case - 'do-nothing' options - Current ferry and dredging operations			
SAFE CHANNEL WIDTH CALCULATION (PIANC, 2014)			
INPUT:			
Channel type =	Inner channel (protected water)		
Traffic type =	Two-way		
Slope =	Gentle underwater channel slope (1:10 or less steep)		
Water depth, h =	4	m	
Vessel speed, V_s =	moderate: 8 ≤ Vs < 12		kts
Vessel length, Loa =	73.2	m	
Vessel width, B =	15.9	m	
Vessel draught ,T =	1.7	m	
Manoeuvrability, BM =	Good		
Prevailing cross wind, V_{cw} =	mild: Vcw < 15 kts (< Beaufort 4)		
Prevailing cross-current, V_{cc} =	negligible: Vcc < 0.2 kts		
Prevailing longitudinal current, V_{lC} =	low: VlC < 1.5 kts		
Beam and stern quartering wave height, H_s =	1 m < Hs < 3 m		
Aids to Navigation, AtoN =	good		
Bottom surface =	smooth and soft		
OUTPUT:			
Maneouvring Width, W_{BM} =	20.7	m	
Additional Width, $\sum W_i$ =	6.4	m	
Bank Clearance, W_{BR} = W_{BG} =	1.6	m	
Passing Width, W_P =	22.3	m	
Total Channel Width, W =	**66.8**	**m**	
Channel width, Base case (PIANC, 2014)	*67.0*	*m*	

Assume Wi is excluded

Alternative 2a: Adjust vessel fleet

The table below presents the safe channel width calculation according to the standard approach set out in PIANC (2014), for a new smaller-sized ferry, example Damen Fast Ferry 4212, which has a reduced beam of 11.6 m.

Alternative 2: Adjust vessel fleet - DAMEN Fast Ferry 4212, passengers only		
SAFE CHANNEL WIDTH CALCULATION (PIANC, 2014)		
INPUT:		
Channel type =	Inner channel (protected water)	
Traffic type =	Two-way	
Slope =	Gentle underwater channel slope (1:10 or less steep)	
Water depth, h =	4	m
Vessel speed, V_s =	fast: Vs ≥ 12	kts
Vessel length, Loa =	42.2	m
Vessel width, B =	11.6	m
Vessel draught ,T =	1.5	m
Manoeuvrability, BM =	Good	
Prevailing cross wind, V_{cw} =	mild: Vcw < 15 kts (< Beaufort 4)	
Prevailing cross-current, V_{cc} =	negligible: Vcc < 0.2 kts	
Prevailing longitudinal current, V_{lc} =	low: VlC < 1.5 kts	
Beam and stern quartering wave height, H_s =	1 m < Hs < 3 m	
Aids to Navigation, AtoN =	good	
Bottom surface =	smooth and soft	
OUTPUT:		
Maneouvring Width, W_{BM} =	15.1	m
Additional Width, $\sum W_i$ =	4.6	m (Assume Wi is excluded)
Bank Clearance, $W_{BR} = W_{BG}$ =	1.2	m
Passing Width, W_P =	20.9	m
Total Channel Width, W =	**53.4**	**m**
Channel width, Base case (PIANC, 2014)	*67.0*	*m*
Width reduction compared to Base case (PIANC, 2014)	*20.4*	*%* (Assume relative reduction based on actual safe calculated width (PIANC, 2014))

A cost estimate is shown in the table below for dredging operations over a 30-year period until 2050, should two new smaller ferries (purchase price included) be used from 2029 after a new ferry service concession begins. The annual dredged volume is assumed to reduce *relative* to the safe channel width reduction as calculated above.

COST ESTIMATION					
Alternative 2: Adjust vessel fleet - DAMEN Fast Ferry 4212, passengers only					
Present dredging amount, V =	1.80E+06	m^3/year			
Future reduction, R =	20.4	%			
Future dredging amount, V_1 =	1.43E+06	m^3/year			
Unit dredging cost, C_u =	€ 5.38	EUR/m^3			
Base year, Y_1 =	2020	years			
Delivery year, Y_2 =	2029	years			
Delivery year, Y_2 =	2050	years			
Contract period, t_1 =	9	years			
Contract period, t_2 =	21	years			
Total dredging amount, V_{T1} =	1.62E+07	m^3			
Total dredging amount, V_{T2} =	3.01E+07	m^3			
Total dredging amount, V_T =	4.63E+07	m^3			
Total dredging cost, C_{01} =	€ 87 000 000.00	EUR			
Total dredging cost, C_{02} =	€ 162 000 000.00	EUR			
Total dredging cost, C_0 =	€ 249 000 000.00	EUR			
Cost of purchasing 2 vessels, P =	€ 9 000 000.00	EUR			
Total cost rounded, C =	**€ 258 000 000.00**	**EUR**			

Alternative 2b: Adjust vessel fleet

The table below presents the safe channel width calculation according to the standard approach set out in PIANC (2014). Calculations assume that the vessel MS Rottum (owned by Wagenborg), which has a beam of 13.8 m can be used for the Holwerd-Ameland transit instead of its current operations between Lauwersoog en Schiermonnikoog, purchase price therefore excluded.

Alternative 2: Adjust vessel fleet - MS ROTTUM			
SAFE CHANNEL WIDTH CALCULATION (PIANC, 2014)			
INPUT:			
Channel type =	Inner channel (protected water)		
Traffic type =	Two-way		
Slope =	Gentle underwater channel slope (1:10 or less steep)		
Water depth, h =	4	m	
Vessel speed, V_s =	moderate: 8 ≤ Vs < 12	kts	
Vessel length, Loa =	58	m	
Vessel width, B =	13.82	m	
Vessel draught ,T =	1.7	m	
Manoeuvrability, BM =	Good		
Prevailing cross wind, V_{cw} =	mild: Vcw < 15 kts (< Beaufort 4)		
Prevailing cross-current, V_{cc} =	negligible: Vcc < 0.2 kts		
Prevailing longitudinal current, V_{lC} =	low: VlC < 1.5 kts		
Beam and stern quartering wave height, H_s =	1 m < Hs < 3 m		
Aids to Navigation, AtoN =	good		
Bottom surface =	smooth and soft		
OUTPUT:			
Maneouvring Width, W_{BM} =	18.0	m	
Additional Width, $\sum W_i$ =	2.8	m	Assume Wi is excluded
Bank Clearance, W_{BR} = W_{BG} =	1.4	m	
Passing Width, W_P =	19.3	m	
Total Channel Width, W =	**58.0**	**m**	
Channel width, Base case (PIANC, 2014)	*67.0*	*m*	
Width reduction compared to base case (PIANC, 2014)	*13.4*	*%*	Assume relative reduction based on actual safe calculated width (PIANC, 2014)

A cost estimate is shown in the table below for dredging operations over a 30-year period until 2050, should Wagenborg be able to interchange their vessels if determined suitable as soon as 2020. The annual dredged volume is assumed to *reduce* relative to the safe channel width reduction as calculated above.

COST ESTIMATION					
Alternative 2: Adjust vessel fleet - MS ROTTUM					
Present dredging amount, V =	1.80E+06	m^3/year			
Future reduction, R =	13.4	%			
Future dredging amount, V_1 =	1.56E+06	m^3/year			
Unit dredging cost, C_u =	€ 5.38	EUR/m^3			
Base year, Y_1 =	2020	years			
Delivery year, Y_2 =	2029	years			
Delivery year, Y_2 =	2050	years			
Contract period, t_1 =	9	years			
Contract period, t_2 =	21	years			
Total dredging amount, V_{T1} =	1.62E+07	m^3			
Total dredging amount, V_{T2} =	3.27E+07	m^3			
Total dredging amount, V_T =	4.89E+07	m^3			
Total dredging cost, C_{01} =	€ 75 000 000.00	EUR			
Total dredging cost, C_{02} =	€ 176 000 000.00	EUR			
Total cost rounded, C =	**€ 251 000 000.00**	**EUR**			

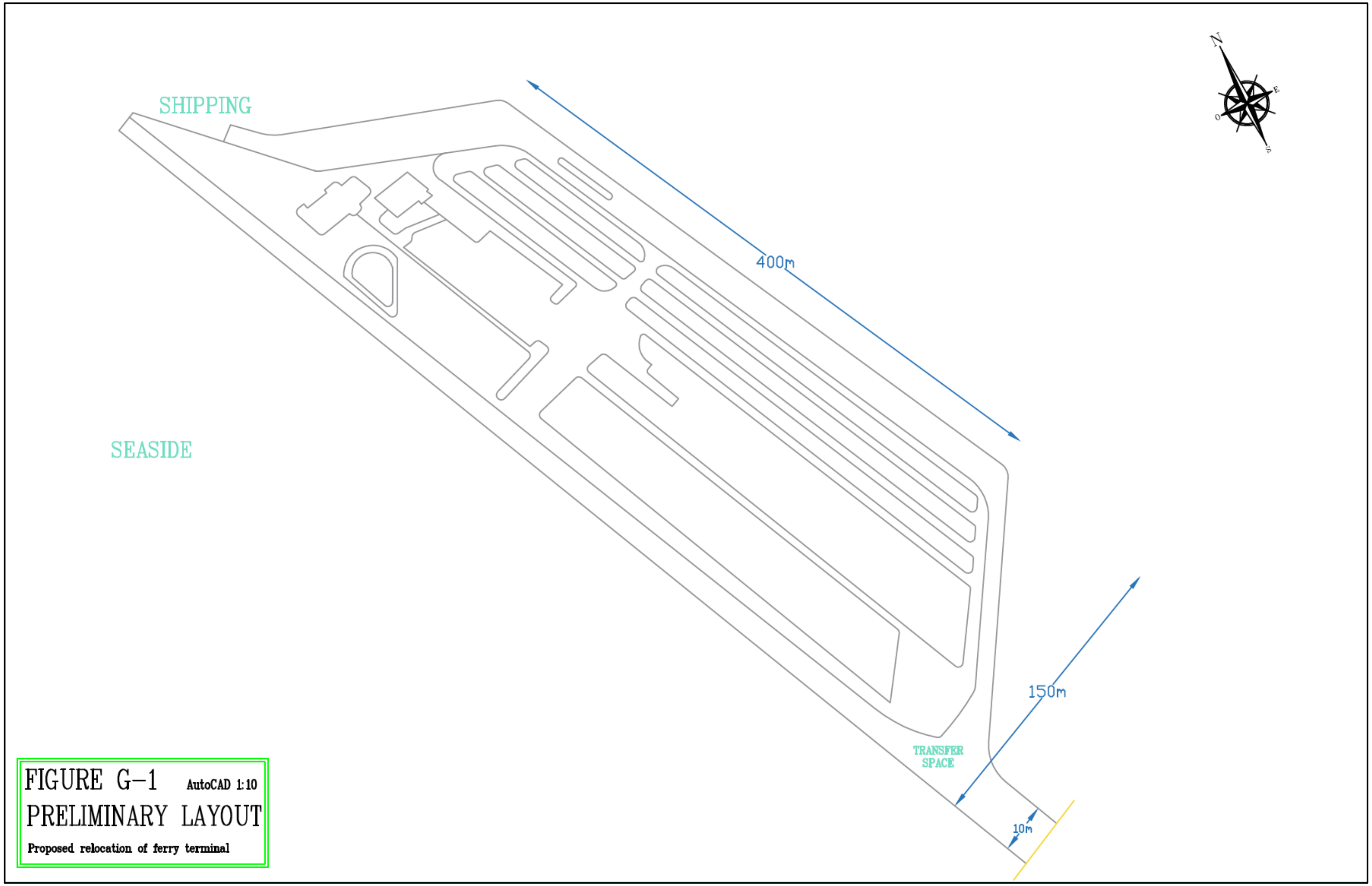
Alternative 3: Bend cuts

The table below summarises the assumptions and costs considered for the long-term cost estimate to realize and maintain the 'Bochtafsnijding vloedgeul' bend cut.

Status quo dredging operations	**Volume**	**Units**	
Annual volume of material dredged	1800000	m^3/yr	
Dredging costs			
Unit dredging cost, lower limit	2.0	EUR/m^3	
Unit dredging cost, upper limit	6.5	EUR/m^3	
Unit dredging cost, C_u =	5.4	EUR/m^3	
Dredging cost per year	**€ 9 675 000.00**		
Dredging 'Bochtafsnijding vloedgeul'	**Volume**	**Units**	**Assumptions**
Reduction in dredged vol_year 1	162000	m3/yr	9% reduction
Reduction in dredged vol_ after year 1	234000	m3/yr	13% reduction
Reduction in dredged vol_ after 10 years	180000	m3/yr	10% reduction
Cost estimate	**Cost**	**Assumptions**	
Capital dredging	€ 2 400 000.00	Dredge new channel	
Year 1 (2021)	€ 8 804 250.00	9% reduction	
Guarenteed for 10 years up to 2030	€ 75 755 250.00	13% reduction	
Long-term 2030-2050	€ 165 442 500.00	10% reduction	
Total cost	€ 252 402 000.00		
Total cost, rounded	**€ 252 000 000.00**		

Assume 75% value of range 2-65 €/m3

Plan view of relocated ferry terminal design:



APPENDIX H: MCA Weightings

Traditional Dike

Criteria	Description	Score
Environmental impact	• Land reclamation from adjacent salt marshes (-) • Impact on flora and fauna (-) • Not preserving biodiversity (-)	35%
Practical Implementation	• Creating a berm requires high construction accuracy (-) • Material transport required (-) • Possible expansion but not much more safety gained and not really practical (-) • Longer construction time as asphalt has to be removed and then replaced (-) • Governmental authorization required, Natura 2000 permit (-)	40%
Socio-economic impact	• Lower Aesthetic, touristic and recreational value (-) • Loss of land for agriculture (-) • No local job creation as construction requires precision by specialists (-/0) • Possible reduction of local economy with lover tourism (-) • Low public acceptance (-) • Stakeholder and community impact (-)	40%
Safety Risk	• Safe for overtopping limit (+) • Same severity of damage and flooded area if flooding (0) • Normal durability, maintenance required for asphalt cover (-/0)	75%
Reliability	• No testing conducted in the area (-/0) • Not too much research conducted for flooding, mainly for breakwaters (-) • Not too high reliability of results (-)	55%
Costs		€ 14.3 M

Wide Green Dike

Criteria	Description	Score
Environmental impact	• Increasing or not changing biodiversity (+/0) • Reclamation of land from adjacent salt marshes (-) • Full grass cover for outer slope (+) • Higher attractive value for fauna (+) • Higher carbon intake from grass and vegetated foreshore (+)	80%
Practical Implementation	• Possible expansion and adaptability, can grow with SLR (+) • Material transport is required (- /0) • Large availability of material in the NL (+) • Governmental authorization required, Natura 2000 permit for reclamation of salt marshes (-)	45%
Socio-economic impact	• Higher aesthetic, touristic and public acceptance value (+) • Higher recreational value (+) • Good value for stakeholders (+) • Positive impact on community (+) • Agriculture, loss of land from reclamation (-) • Maintenance required, possible labour (+/0)	75%
Safety Risk	• Higher durability and resilience (+) • Same severity of damage in case of flooding (0) • Lower probability of flood damage (+)	70%
Reliability	• Currently in use in Germany (+) • Enough research conducted (+) • No testing conducted in NL (-)	65%
Costs		€ 8.1 M

Revetment Change

Criteria	Description	Score
Environmental impact	• Negative impact on flora and fauna (-) • Not preserving biodiversity (-)	50%
Practical Implementation	• Not much adaptability or expansion (-) • Material transport required (-) • Already implemented in the Netherlands (+) • Low maintenance required (+)	60%
Socio-economic impact	• Lower aesthetic, touristic, recreational value (-) • Not much job creation as work would need to be done by specialists (0) • No effects on local economy (0) • Possible lower stakeholder and public acceptance (-)	45%
Safety Risk	• Safe overtopping value (+) • Durability but maintenance required after big storms (-/0) • Same damage and flooded area if major failure occurs (0)	85%
Reliability	• Many implementation cases in the Netherlands, current practice (+) • Much research and reliable results (+)	90%
Costs		€ 12.3 M

Sandy Dike

Criteria	Description	Score
Environmental impact	• Growth of new species of vegetation can create new habitats for birds (good for fauna and flora), even though it could also eliminate the current organisms in the grass (+) • The material is completely natural and only affects the landward side (no land reclamation) (+) • The asphalt cover remains (-)	65%
Practical Implementation	• Sand could be obtained from natural dunes nearby, it can be transported using dump trucks and placed with bulldozers (+) • The placement method of sand is simpler than clay, easier to compact the sand (+) • Shorter construction time than with clay (+) • Regular maintenance necessary due to wind and rain (-)	70%
Socio-economic impact	• The attractive dune landscape can raise the recreational value and tourism in the area (+) • The placement of sand layers has been done • Mostly used for landscaping purposes, not for strengthening purposes, so there may be negative reaction from the water board (-) • Sand is not part of the local ecosystem (-)	60%
Safety Risk	• The sand layer may only withstand less than 3 hours of extreme storms (-) • The sediment transport model for the sand should be properly calibrated (-) • Strong wind and rainfall can erode the sand and also affect the road as well (-)	35%
Reliability	• Very experimental method (-) • No definitive design guidelines (-) • After every reshaping, the sand needs to be replaced (-)	30%
Costs	• Costly regular maintenance necessary (-) • Sand is cheaper than clay (+) • Cheapest solution overall (+)	€ 6.5 M

Base Case Scenario

Criteria	Description	Score
Environmental impact	• Removal of subtidal benthic species and communities (-) • Temporary increase in the level of suspended sediment (-) • Negative effect on marine flora and fauna by increased turbidity and possible releases of organic matter, nutrients and/or contaminants (-) • Smothering or blanketing of subtidal communities and/or adjacent intertidal communities (-) • Aquatic organisms are exposed to many stressors, including a variety of pollutants from dredging operations (-) • Recirculation of dredged material during flood-ebb flow (-) • Dredging volume continues to increase exponentially (-)	50%
Practical Implementation	• Duration of project – all the year (-) • Availability of equipment (+) • Dumping or pumping of dredged material, no additional transport required (+)	50%
Socio-economic impact	• Job creation: employees in the dredging sectors (+) • Creates highly turbid situations which are considered to be very unappealing by most people; publicly unaccepted (-) • Ferry sailing time increased due to delays, partly caused by dredging operations (-) • Dredging costs are too high (-)	25%
Safety Risk	• Provide sufficient depth for navigation (+) • Dredging operations interfere with ferry sailings (-) • Navigational risk; narrowing channel widths (-)	45%
Reliability	• Recirculation of dredged material during flood-ebb flow; not reliable in terms sediments coming back (-)	20%
Costs	• Cost of dredging ranges between € 2 - € 6.5 per m^3, assume 75% cost value. • Assume the same dredging volume for next 30 years until 2050 (for relative comparison)	€ 290 M

Adjust Vessel Fleet

Criteria	Description	Score
Environmental impact	• Amount of the dredging would decrease relatively (+) • Temporary increase in the level of suspended sediment during dredging (-) • Less turbidity effect on marine flora and fauna and compared to the base case (-) • Recirculation of dredged material during flood-ebb flow (-)	65%
Practical Implementation	• Duration of project – all the year but dredging is less frequent (+) • Same dredging operations as base case, equipment available (+) • No transport required (+)	40%
Socio-economic impact	• Faster vessel, reduce sailing time (+) • More reliable ferry service, reduction in delays (+) • Relative decrease in dredging costs (+) • Shorter total traveling time – shorter loading/unloading (-) • No cars (-) • Opportunity for public transport (+)	60%
Safety Risk	• Smaller vessel, reduce channel width requirement (+) • Navigational risk; still require dredging to ensure safe minimum depth (-)	60%
Reliability	• Recirculation of dredged material during flood-ebb flow; not reliable in terms of sediments coming back (-) • Not guaranteed that operator can purchase new vessel (-) • Effect on morphology unknown (-)	35%
Costs	• Smaller sized vessel, with no cars capacity • Cost of dredging ranges between €2 - €6.5 per m^3, assume 75% cost value. • Assume the same dredging volume for next 30 years until 2050 (for relative comparison)	€ 258 M

Bend Cuts

Criteria	Description	Score
Environmental impact	• Potential to reduce the required amount of dredging, but not guaranteed (+) • Similar dredging operation to current dredging activities, no additional negative effects are foreseen (+) • Relative reduction in environmental effects of base case (+)	60%
Practical Implementation	• Implementation is relatively easy as the existing hopper dredger can be used (+) • No new hard infrastructure is necessary and no construction materials (+) • Some logistical issues for closing the current navigation channel and dredging simultaneously (-) • No new permits necessary (+)	70%
Socio-economic impact	• Shorter sailing time, so the commuters and tourists will benefit, i.e. public acceptance (+) • Will possibly make the ferry service more reliable (+) • No negative impacts on aesthetics as no new major infrastructure is built (+) • May cause ferry to not be operational for some time (-)	40%
Safety Risk	• Provides sufficient water depth as required (0 /+) • Could cause safety risk if dredging during the time ferry needs to depart (-)	60%
Reliability	• Morphodynmic changes are not certain (-) • Requires further detailed testing and monitoring (-) • Only guaranteed for 10 years, thereafter sedimentation problem again (-)	45%
Costs	• Cost of dredging ranges between €2 - €6.5 per m^3, assume 75% cost value. • Cost of only one bend cut. • Percentage decrease in sedimentation until 2030	€ 252 M

Ferry Terminal Relocation

Criteria	Description	Score
Environmental impact	• Excessive dredging can be eliminated (+) • Existing salt marshes would be damaged due to the constructions (-) • Hard solution: changes of morphology in new location (-)	40%
Practical Implementation	• Further expansions would not be possible and hence less adaptable (-) • Legislation issues + Authorizations (-) • Infrastructure improvement might be required (construction phase + operational) (-) • Material transport is required (- /0) •	20%
Socio-economic impact	• Less sailing time and high economic impact (+) • Positive impacts on the local economy in the new location+ job opportunities (+) • Oppositions from local community in Holward and municipality (-)	75%
Safety Risk	• Higher durability (+) • Minimum flooding if designed properly (0) • Safe navigation (deep and stable water) (+)	80%
Reliability	• Level at which results can be guaranteed is significantly depends on morphological changes (-/0) • Morphological changes take larger time scales and significant level of positive results can be expected (+)	40%
Costs	• Capital cost for construction of new ferry terminal • Consider contingencies • 5% dredging for 20 years	270 M €

APPENDIX I: Wide Green Dike Design

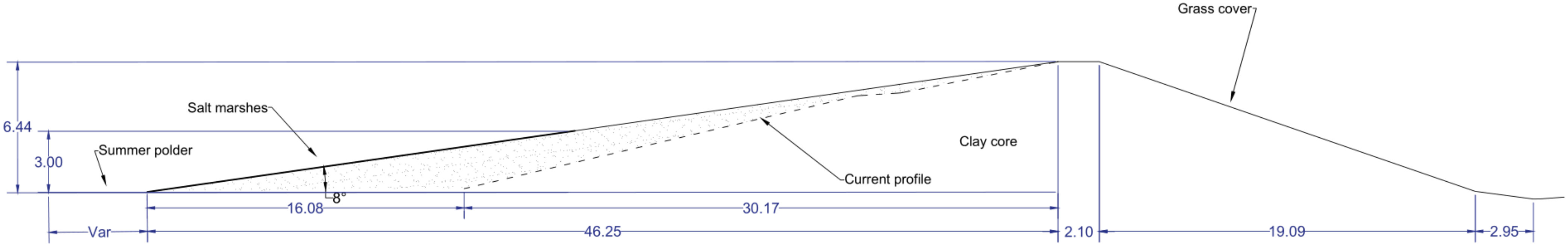


Figure I-1: Detailed Wide Green Dike drawing

APPENDIX J: Salt Marsh Map

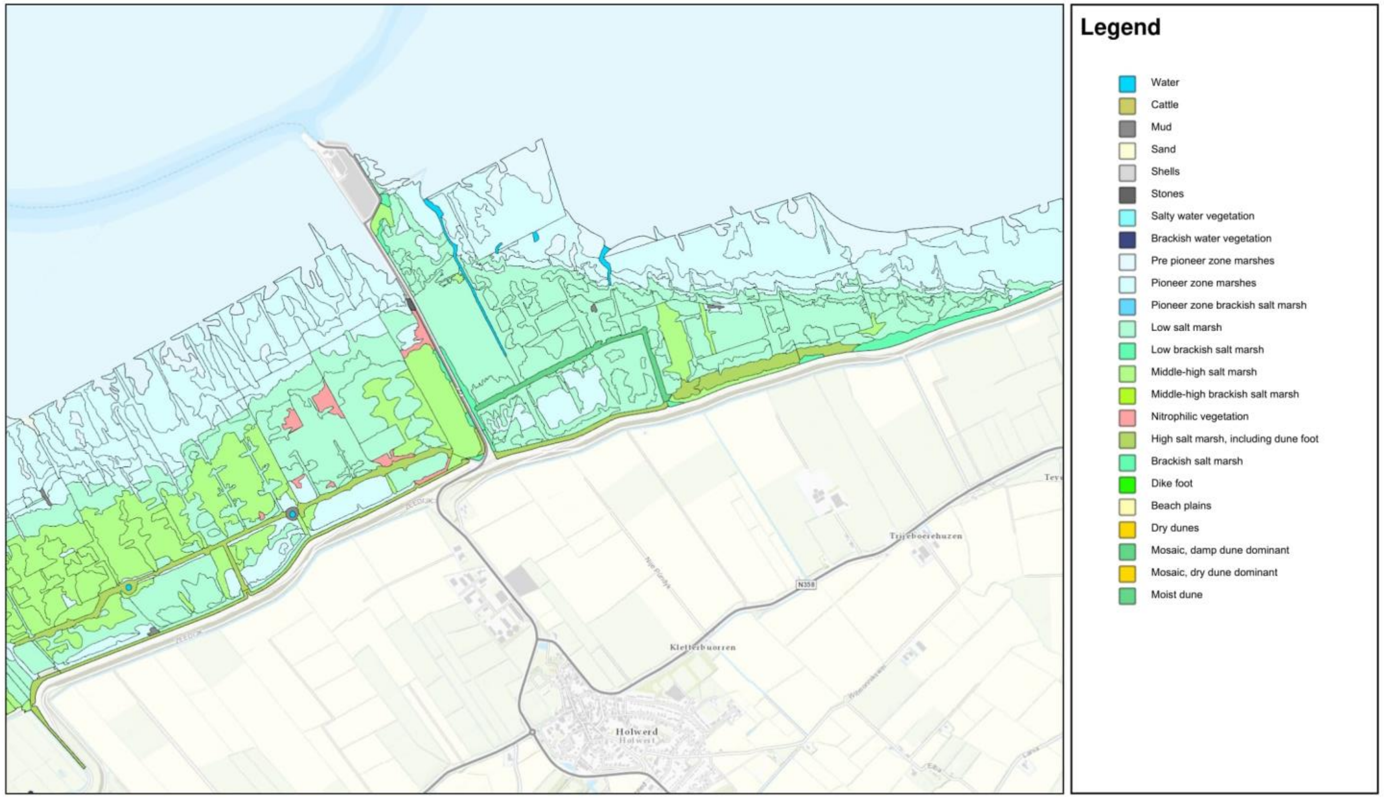


Figure J-2: Detailed salt marsh map. Adapted from (Rijkswaterstaat, 2018c)

APPENDIX K: Ecosystem Services

Ecosystem Services

The contribution to salt marsh development in the Wadden Sea provides many ecosystem services. They refer to benefits provided by an ecosystem actor, in this case, salt marshes. These can be separated into 4 different sections; provisioning, regulating, cultural, and supporting. Each section is explained further below.

Provisioning

The major provisioning service is that the salt marshes lead to the production of fish, algae and other invertebrates (MilleniumAssessment, 2005). This is because salt marsh growth provides a greater area for species relying on salt marshes to live and thrive. An increase in fish population is an increase in food supply for humans. Salt marshes may also provide fiber, timber, and fuel (MilleniumAssessment, 2005). They lead to land reclamation and greater land area for natural development. This is proved through history since in this region the salt marsh area was reclaimed and used for agricultural purposes (Loon-Steensma, 2015).

Regulating

The main regulating services that the salt marshes in the Wadden Sea provide are flood control and storm protection (MilleniumAssessment, 2005). This is accomplished due to their relatively high elevation within the tidal frame, causing dampening of wave energy and the reduction of wave height during storms (Vuik, et al., 2016). This service is further strengthened by the ability of salt marshes to keep up with sea level rise (Van der Eijk & Esselink, 2014). They act as a climate buffer, limiting the effect of climate change. Another significant regulating service is the pollution control and detoxification. An example is that salt marshes can intercept watershed-derived nitrogen before it reaches the nearshore oceans, which is a dominant driver of global-change impacts on ecosystems [15] (Nelson & Zavaleta, 2012). Other regulatory services include biological regulation meaning causing resistance to species invasion or regulating interactions between different trophic levels, climate regulation through carbon sequestration (Nelson & Zavaleta, 2012) and prevention of soil erosion.

Cultural

The cultural services provided by the salt marshes include aesthetic features, educational features, recreation and tourism opportunities, as well as those related to physical/mental health (Bakker, 2012). The aesthetic features relate to the enhancement of nature as a result of the salt marshes. Education is a major service related to salt marshes. Research is necessary to further understand how salt marshes attenuate wave energy and this project may act as a valuable research source. Also, this project may be used to educate the public on their many benefits to nature and the coastal ecosystem. Recreation and tourism will increase with the increase in salt marshes. Recreation in forms of sun bathing, walking and camping or fishing and birdwatching. The tourism in the region is mainly due to the fact that it is a World Heritage site. The large system of intertidal sand and mud flats and ecosystem diversity, which salt marsh development will help contribute to is a main reason that the area has this distinction. Lastly, salt marsh development will aid in opportunities for wilderness and areas for personal space which contribute to physical and mental health (MilleniumAssessment, 2005).

Supporting

The supporting services of the nature-based design include biodiversity, soil formation and nutrient cycling (MilleniumAssessment, 2005). Regarding biodiversity, salt marshes add habitat space for resident or transient species. Soil formation is acquired through the reduction in flow velocities resulting in increased sedimentation. This further grows the salt marsh area and is the backbone of the entire design. Lastly, nutrient cycling is accomplished through the storage, recycling, processing and acquisition of nutrients (MilleniumAssessment, 2005). Nutrient cycling and accumulation processes by salt marshes contribute to reduce eutrophication (N and P retention) and also to reduce atmospheric CO_2 (Sousa, et al., 2010)

APPENDIX L: EIA Supporting Documentation

Table L-1: Values used to define the significance level of impacts (Conesa, 2006)

Criteria		Magnitude value scale
IN	Low impact	1
	Medium impact	2
	High impact	4
	Very High impact	8
	Total impact	12
EX	Isolated	1
	Partial	2
	Widespread	4
	Total	8
	Critical location	add 4
PE	Fleeting impact: < 1 year	1
	Temporary impact: between 1 and 10 years	2
	Permanent impact: > 10 years	4
RV	• Short-term: less than 1 year	1
	• Medium-term: between 1 and 5 years	2
	Irreversible: self-reconstruction is unlikely or extremely difficult without human intervention	4
RC	Recoverable: effects can be neutralized within a given time by corrective and restorative measures	
	• Immediate	1
	• Medium-term	2
	Likely to be mitigated: the alteration can be mitigated by establishing corrections	4
	Non-recoverable: when the alteration of the environment is unlikely to be entirely repaired by human intervention. Neutralization time may take longer than 15 years	8

Table L-2: Potential impacts and significance levels for wide green dike solution

Impacts		Description	Sign	IN	EX	PE	RV	RC	I	Impact
Construction phase										
Physical	Noise	Noise invasion due to construction equipment and traffic	-	2	1	1	1	1	11	Compatible
	Ambient air quality	Flume emission from construction equipment	-	4	2	2	2	2	22	Moderate
		Dust from material handling and other construction activities	-	2	2	1	1	1	13	Compatible
	Vibration	Vibration caused by the construction equipment	-	2	1	1	1	1	11	Compatible
	Water quality	Increased turbidity caused by the dredging	-	4	4	2	2	2	26	Moderate
		Discharge of pollutants on the water	-	4	2	2	4	4	26	Moderate
		Oil/ Fuel spill from construction equipment/storages	-	4	2	4	4	4	28	Moderate
	Soil quality	Discharge of pollutant on the soil	-	2	2	4	4	4	22	Moderate
	Morphology	Alteration of natural morphodynamic processes due to the construction	-	8	4	4	4	2	42	Severe
Biological	Flora	Destruction of the salt marshes and disturbances to the other vegetation present in the area	-	8	2	4	4	4	40	Severe
	Fauna	Damage and alteration to the present biodiversity	-	4	2	4	4	4	28	Moderate
Socio-Economic	Employment	Creation of new job opportunities for the local community	+	4	2	2	2	4	24	Moderate
	Traffic	Traffic congestion may be caused by trucks when materials are transported to the ripening location	-	4	2	2	4	2	24	Moderate
	Solid waste	Solid waste generation within the area of construction site and campsite will be increased	-	2	2	2	4	2	18	Moderate

Impacts		Description	Sign	IN	EX	PE	RV	RC	I	Impact
Operation phase										
Biological	Flora	Guarantees an increase of biodiversity and allows for saltmarshes to grow on the lower part of the outer slope	+	8	2	4	4	4	40	Severe
	Fauna	Creation of new habitats after development of mudflats and saltmarshes	+	8	4	4	4	4	44	Severe
Socio-Economic	Employment	Creation of new business opportunities for the local community	+	4	4	4	4	4	32	Moderate
	Tourism	Possibility of increasing the area's income from tourism	+	4	4	2	2	4	28	Moderate
	Infrastructure development	With the possibility of the increasing the recreational value of the area infrastructure development can be occurred	+	2	2	2	2	4	18	Moderate
	Aesthetic and Land scaping	Higher aesthetic value	+	4	4	2	4	4	30	Moderate
	Solid waste	Solid waste generation within the area will be increased with the increased recreational activities	-	2	4	2	4	2	22	Moderate
		Overall	**+**	**30.9**						**Moderate**
			-	**23.8**						**Moderate**

Table L-3: Mitigation measures for wide green dike risks

<table>
<tr><th colspan="2">Impacts</th><th>Description</th><th>Mitigation measures</th></tr>
<tr><td colspan="4">Construction phase</td></tr>
<tr><td rowspan="14">Physical</td><td rowspan="2">Noise</td><td rowspan="2">Noise invasion due to construction equipment and traffic</td><td>Constant maintenance of the equipment and motor</td></tr>
<tr><td>Construction activities involve with high intensity noise levels will be carried during the day time</td></tr>
<tr><td rowspan="2">Ambient air quality</td><td>Flume emission from construction equipment</td><td>Constant maintenance of the equipment and motor</td></tr>
<tr><td>Dust from material handling and other construction activities</td><td>Continuous monitoring to ensure emission levels comply with the applicable emission norms</td></tr>
<tr><td>Vibration</td><td>Vibration caused by the construction equipment</td><td>Constant maintenance of the equipment and motor</td></tr>
<tr><td rowspan="5">Water quality</td><td rowspan="2">Increased turbidity caused by the dredging</td><td>Continuous monitoring</td></tr>
<tr><td>Use silk curtains or appropriate techniques if the levels are too high</td></tr>
<tr><td>Discharge of pollutants on the water</td><td>Proper disposal of construction debris and portable sanitary facilities</td></tr>
<tr><td rowspan="2">Oil/ Fuel spill from construction equipment/storages</td><td>Ensure proper storage facilities for harmful substance</td></tr>
<tr><td>Develop an action plan in case of emergency spill over</td></tr>
<tr><td>Soil quality</td><td>Discharge of pollutant on the soil</td><td>Proper disposal of construction debris and Portable sanitary facilities</td></tr>
<tr><td>Morphology</td><td>Alteration of natural morphodynamic processes due to the construction</td><td>Understand the system behaveour and minimize the alteration through a proper design</td></tr>
<tr><td rowspan="3">Biological</td><td rowspan="2">Flora</td><td rowspan="2">Destruction of the salt marshes and disturbances to the other vegetation present in the area</td><td>Investigate the quality of salt marshes and maintain disturbance levels</td></tr>
<tr><td>Restoration of saltmarshes may be necessary</td></tr>
<tr><td>Fauna</td><td>Damage and alteration to the present biodiversity</td><td>Implement an ecological survey and establish proper management plan to minimize the damage</td></tr>
<tr><td>Socio-Economic</td><td>Employment</td><td>Creation of new job opportunities for the local community</td><td>Positive impact. But maintain the proper safety standards to ensure the safety of the workers</td></tr>
</table>

	Traffic	Traffic congestion may be caused by trucks when materials are transported to the ripening location	Avoid operation during peak hours Carrying out night time operations

	Solid waste	Solid waste generation within the area of construction site and campsite will be increased	The skips and bins at both the construction campsite and construction site should be emptied regularly to prevent overfilling Disposal of the contents of the skips and bins should be done at an approved disposal site
Impacts		**Description**	**Mitigation measures**
Operation phase			
Biological	Flora	Guarantees an increase of biodiversity and allows for saltmarshes to grow on the lower part of the outer slope	Positive impact
	Fauna	Creation of new habitats after development of mudflats and saltmarshes	Positive impact
Socio-Economic	Employment	Creation of new business opportunities for the local community	Positive impact
	Tourism	Possibility of increasing the area's income from tourism	Positive impact
	Infrastructure development	With the possibility of the increasing the recreational value of the area infrastructure development can be occurred	Positive impact
	Aesthetic and Land scaping	Higher aesthetic value	Positive impact
	Solid waste	Solid waste generation within the area will be increased with the increased recreational activities	Skips and bins should be strategically placed within the area

Table L-4: Potential impacts and significance levels for adjusting the vessel fleet

Impacts		Description	Sign	IN	EX	PE	RV	RC	I	Impact
Operation phase										
Biological	Flora	Reduced amount of dredging will result in less turbidity and disturbance to sea bed (benthic) plants	+	2	4	4	2	2	22	Moderate
	Fauna	Less dredging will result in less turbidity and disturbance of benthic organisms	+	2	4	4	2	2	22	Moderate
Physical	Ambient air quality	Less air pollution, since the smaller vessel with use less fuel and dredging vessel will operate less.	+	1	2	4	4	2	17	Moderate
	Water	Less water pollution, since the smaller vessel with use less fuel and dredging vessel will operate less.	+	1	1	4	2	2	13	Compatible
Socio-Economic	Travel experience	A better and faster travel experience as the vessels can complete the route in a shorter time	+	8	4	4	4	2	42	Severe
	Tourism	Tourists will be more attracted to utilise the service with a shorter travelling time	+	4	4	4	4	2	30	Moderate
	Employment	Less crew required on the vessel, less job opportunities	-	2	2	4	4	4	22	Moderate
	Ferry capacity	Smaller passenger capacity which is problematic for the peak season in Summer	-	4	1	2	4	4	24	Moderate
	Car transport	Less/no cars can be transported by the vessel, resulting in Ameland's inhabitants' discontent.	-	4	4	2	4	8	34	Moderate
Overall			**-**	**27**						**Moderate**
			+	**24**						**Moderate**

Table L-5: Mitigation measures for adjust vessel fleet risks

Impacts		Description	Mitigation measures
Operation phase			
Biological	Flora	Reduced amount of dredging will result in less turbidity and disturbance to sea bed (benthic) plants	Positive impact
	Fauna	Less dredging will result in less turbidity and disturbance of benthic organisms	Positive impact
Physical	Ambient air quality	Less air pollution, since the smaller vessel with use less fuel and dredging vessel will operate less.	Positive impact
	Water	Less water pollution, since the smaller vessel with use less fuel and dredging vessel will operate less.	Positive impact
Socio-Economic	Travel experience	A better and faster travel experience as the vessels can complete the route in a shorter time	Positive impact
	Tourism	Tourists will be more attracted to utilise the service with a shorter travelling time	Positive impact
	Employment	Less crew required on the vessel, less job opportunities	Creation of alternative jobs at the ferry terminal
	Ferry capacity	Smaller passenger capacity which is problematic for the peak season in Summer	A busier ferry schedule during the peak season. Purchase 3rd smaller ferry.
	Car transport	Less/no cars can be transported by the vessel, resulting in Ameland's inhabitants' discontent	Opportunity for Ameland to become 'car free'. Provision of good public transport on Ameland. Create a car parking area close to the Holwerd ferry terminal.