Final Thesis

Analysing & Optimising Sand Nourishments at Walcheren

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Abstract

Sand nourishments have been executed throughout the coastline of Walcheren for decades with the goal of improving coastal safety, widening beaches for recreation and reducing the impact of coastal erosion on dune habitats and the landscape. While the coastal engineering benefits of sand nourishments have become clear, it remains challenging to understand the economic rationale of these nourishments compared to other coastal defence strategies. There is demand for direct comparisons between 'soft' building with nature methods, such as sand nourishments, and traditional 'hard' coastal engineering strategies, such as dune and dike construction or reinforcement. This demand is only heightened by the expectation of rising coastal erosion and costs due to sea level rise, land subsidence and increasing storm intensity.

In this thesis, the MorphAn coastal modelling tool was applied to the coastline of Walcheren to determine historical trends in volume and position of individual coastal transects. These trends were then applied to the coastline to model a 'what-if' scenario in which the sand nourishments had not occurred over the last 40 years. Dune safety was then assessed with weak points identified. A final calculation of the necessary dune and dike reinforcements was made along with the estimated costs. It was shown that sand nourishment costs were comparable to the estimated costs of dune/dike reinforcements and also provided other important economic benefits.

Furthermore, a recent important development has been the design and construction of mega sand nourishments. These mega nourishments present an opportunity to improve the cost/benefit profile of sand nourishments even further. Cost per cubic meter of sand is reduced due to the economies of scale with the additional benefit of reduced ecosystem interference. Given the benefits of mega nourishments, it is logical to investigate whether historical sand nourishments could have instead been executed as a single mega nourishment for the equivalent or less cost.

The second part of this thesis outlines a feasibility study for a mega nourishment at the Walcheren coastline. This showed that a particularly vulnerable part of the coastline, Domburg, could have been protected by a single mega nourishment executed in 2000 with a half-life of 14.6 – 29.2 years. This would have an equivalent cost to the multiple nourishments that occurred in the 2000-2019 period. An optimised design also demonstrated the feasibility of a smaller, cheaper mega nourishment that would have achieved a dry beach width of at least 50m with a half-life of 10 – 20 years.

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1. Introduction

The erosion and retreat of coastlines has been a challenge for countries around the world for decades (Luijendijk et al., 2018). The scale of this challenge has increased as urbanisation in coastal areas has led to large populations and the most valuable land becoming more vulnerable. Coastal erosion is not just one separate issue; it is inextricably linked with many factors such as land subsidence, sea level rise[1][2], extreme weather events, recreation/tourism and many more. These factors increase the severity and rate of coastal erosion, and thus the costs of mitigating or preventing these impacts.

One of the most common types of coastal environment are sandy beaches. The analysis carried out by Luijendijk et al. (2018) showed that these sandy coastal zones comprise of 31% of the global ice-free shoreline. 24% of sandy shorelines are retreating at a significant average rate of 0.5m/yr. In addition, more than half of the sandy coasts present in marine protected areas are eroding. This data demonstrates the ubiquity of sandy beaches worldwide and how rapidly up to a quarter of them are retreating. Sea level rise is expected to cause higher rates of sandy coastline erosion; Leatherman et al. (2000) found that every 1cm of sea level rise can cause up to 1.5m of sandy coastline retreat; a relationship of up to 150 times.

In particular, the Netherlands is uniquely vulnerable to the challenges of coastal erosion. Its coastline is sandy in nature which is more susceptible to erosion compared to a rocky coastline. It is also a remarkably flat and low-lying country. As a result, the coastline is protected by a system of dikes and dunes. These dikes and dunes represent an important part of the Dutch flood defense system which protects the low-lying interior of the country. Coastal erosion has to be compensated for in order to hold this protective line and prevent the overall level of national flood safety being reduced.

One such method of mitigating coastal erosion are sand nourishments. Sand nourishments involve artificially placing sand to replace what is naturally lost via erosive mechanisms. It can also involve placing additional sand to act as a buffer against coastal erosion and coastline retreat. This is a type of ‘soft’ coastal engineering and has been increasing in popularity compared to ‘hard’ coastal solutions which typically involve the construction of large civil engineering structures. Sand nourishments can be smaller and targeted at a specific area/beach, or alternatively take the form of a large-scale nourishment that occur further offshore to distribute sand to a wider area.

The Netherlands has been carrying out sand nourishments for decades. Due to the projected increase in coastal erosion from the aforementioned sea level rise and extreme weather events, a significant increase in the frequency and volume of these sand nourishments is forecast. This will inevitably lead to higher costs for the Dutch government and taxpayers.

Despite this extensive experience with sand nourishments, there are many important research questions that have yet to be answered. It remains to be seen whether they offer The Netherlands (and countries all over the world) a more cost-effective solution over the long term compared to other alternative coastal defence methods. It also remains to be determined whether sand nourishments can be optimised by executing mega nourishments instead.

It is therefore the goal of this thesis to compare the historical costs of sand nourishments with dune and dike reinforcement methods. In addition, whether previous sand nourishments could have been replaced with a single mega nourishment will be analysed with a feasibility study. The outcome of this thesis has the potential to have important implications for the future of sand nourishments in the Netherlands and beyond.

1.1 Background Information

Approximately 60% of The Netherlands at risk of being inundated with flood waters[3] in the absence of flood defences. It highly urbanised with 92% of its population living in urban areas[4] and is one of the most densely populated countries in Europe[5]. Being a small, urbanised and densely populated country that is only partially above sea level, it is easy to see why the Netherlands is a particularly vulnerable to coastal flooding. This was demonstrated in the major 1953 storm which killed over 1800 people in the Netherlands and flooded over 150,000 hectares of land[6]. Whilst this storm event was very rare, with high water levels return periods larger than 1 in 500 years in 23 locations nearby in the UK alone, it showed the catastrophic consequences of these storm surges if coastal defences are not properly designed and maintained (M. Wadey et al, 2015, p. 22).

Given how low-lying and flat the Netherlands is, it has had a long history and relationship with water and water management. Beginning hundreds of years ago, residents began to collaborate to construct and maintain dikes and other water defences measures. This collaboration was encouraged by the sheer flatness of the country – if flood defences failed, a whole area would flood even if a particular person lived far away from the river or sea. A process of land reclamation also began to increase the amount of available land by draining marshes and lakes. This process is called poldering. Naturally, these reclaimed areas also required defences to prevent them from being flooded again. Other areas were drained simply to connect individual islands and facilitate transport between them.

Another change that was taking place both in the Netherlands and worldwide was urbanisation. The world has moved from a majority rural to majority urban society over the last century. This led to the rapid growth of cities, most of which are located on the coast. This had a number of significant consequences, such as a concentration of population and economic activity on the coast, leading to rocketing land values. Approx. 65% of the gross national product of the Netherlands is in coastal areas (M. Stive et al, 2013). This transition to an urbanised society meant that a larger and larger proportion of the population and economic value was vulnerable to sea flooding.

With populations and associated economic activity concentrating in cities on the coast, other changes were taking place to increase the risk of flooding. Land subsidence was leading to a lowering of the land relative to the sea itself and continues to this day. Anthropogenic climate change has led to higher global temperatures, increased melting of ice and rising sea levels. The effect of thermal expansion also increases the volume of the oceans. It is possible to summarise these effects to say that subsidence lowers ground level, sea level rise and thermal expansion increases water levels whilst urbanisation increases the population and economic value in need of protection. This greatly increases both the probability and consequences of any flood event along with the costs of preventing these events.

In response to these challenges, the Netherlands altered its coastal defence strategy in 1990 to the 'hold the line' approach. This emphasised the continual maintenance of the coastline at an established reference point (BKL) and safety level with no significant erosion or movement of the coast tolerated. By law, flood defences in the Netherlands have to be able to withstand a storm event to ensure the safety of the hinterland; the maximum permissible failure probability varies between 1 in 1,000,000 for the most urbanised coastal areas and 1 in 300 for the most rural[7]. The sand nourishment 'hold the line' strategy supports this flood safety policy but is not judged on the basis of these standards. Instead, the sand nourishment strategy is based on the BKL; a fixed reference point for the coastline to measure coastal advance or retreat. Adopting this 'hold the line' approach meant that coastal defence costs were certain to increase, particularly in view of projected sea level rise.

As part of its coastal defence programme, the Netherlands started experimenting with nourishments in the 1950s and has been executing sand nourishments on a structural basis since 1990s as a matter of national policy. This strategy is described as 'soft where possible, hard where necessary' (National Coast Strategy, 2013). These sand nourishments replace eroded coastal material, act as a buffer against further erosion and widen the beach for tourism. They also tend to be more popular with the public as their actual and perceived environmental impact is less than constructing hard civil engineering coastal defence structures such as sea walls. The cost and scale of these sand nourishments has increased significantly with the annual expenditure on these nourishments doubling when compared to the 1990s (C. Briere et al, 2018). Further increases in cost are expected in response to the aforementioned coastal challenges.

It is important to understand the context behind this 'hold the line approach in the Netherlands and the role of sand nourishment in this strategy of maintaining dune coasts. Many countries, such as Portugal, have dunes which protect relatively small and often sparsely populated areas which are vulnerable to flooding (J. Stronkhorst et al, 2017). The sandy/dune coast of the Netherlands is protecting a large vulnerable area with severe consequences of any breach.

With the aforementioned increase in frequency, cost and scale of sand nourishments in the Netherlands, the concept of a mega sand nourishment has gained greater prominence. Due to the economies of scale, as sand nourishments become larger, their cost per m^3 of sand decreases. This also has environmental benefits as the ecosystem is able to recover without further sand nourishments causing continued damage and disruption to benthic life. Also, where smaller nourishments maintain the coastline position, large scale nourishments change the configuration of the seashore and provide opportunities for spatial developments in terms of recreation and nature.

As the benefits of larger sand nourishments became clear, the Netherlands decided to design and carry out the world's first mega sand nourishment. The world leading 'sand motor' was constructed near The Hague with a total sand volume of 21.5 million m^3 and a design life of 20 years (M. Stive et al, 2013). This is also known as a 'sand engine' as the design uses natural morphological processes such as tides, currents and wind to redistribute the sand throughout the coastline. This is an example of working with nature and harnessing natural processes to achieve coastal protection. A similar project was also undertaken at Norfolk in the United Kingdom with a sand volume of 2 million m^3 a design life of 15-20 years.

1.2 Problem Description

Coastal defences traditionally were comprised of artificial structures such as:

- Sea walls to increase resistance to coastal flooding
- Dune/dike foot reinforcements to prevent erosion at the base of the coastline
- Foreshore protection to moderate the slope and wave action in front of the coast
- Groynes (ie, beach poles) to increase sedimentation
- Dune/dike reinforcements to raise/widen the primary coastal defence
- Maintenance measures such as planting Maram grass on dunes, placing items such as driftwood on weak points to prevent erosion, placing sand/material in weak points

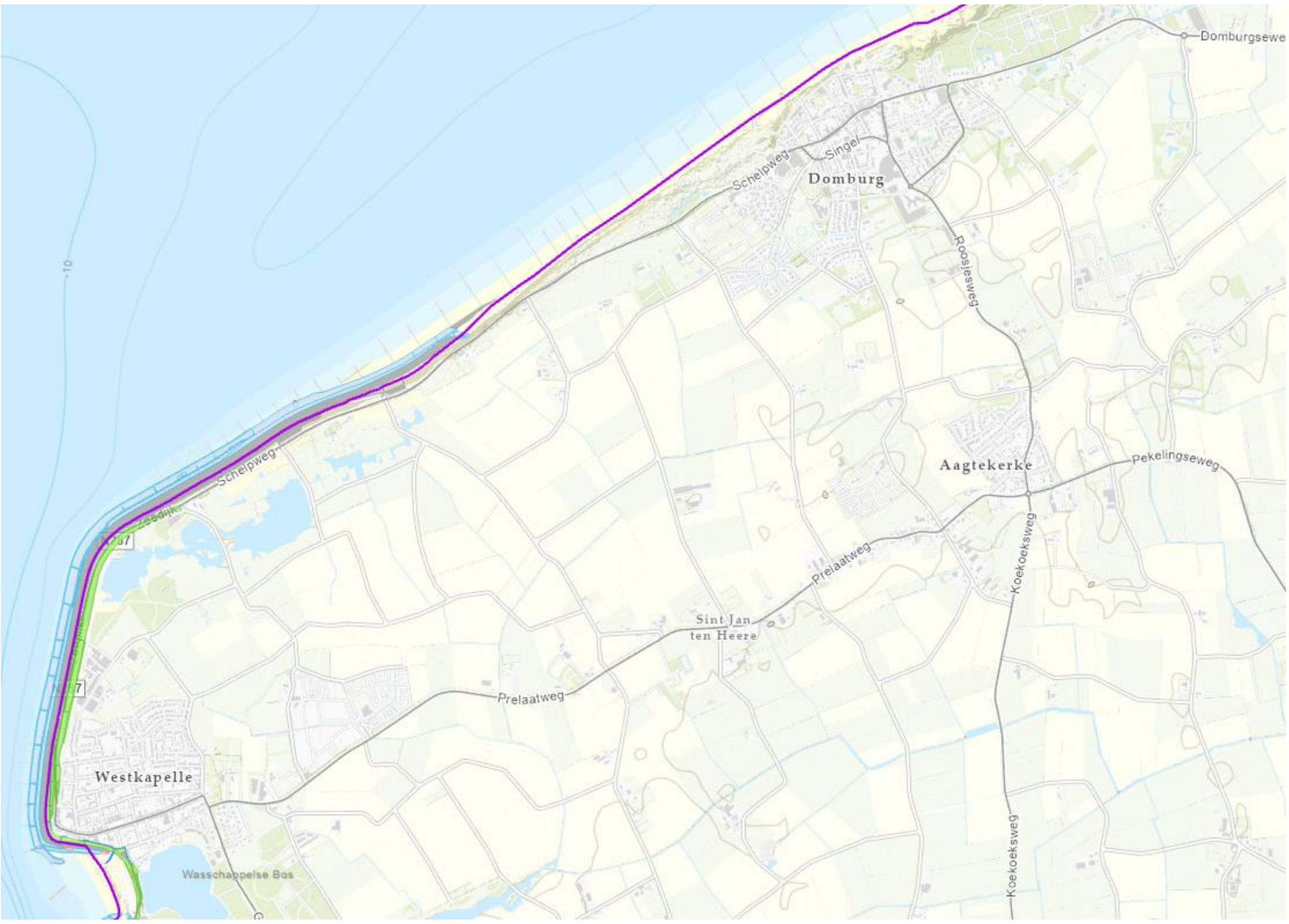


Image 1: Groynes positioned along the Walcheren coastline between Westkapelle and Domburg

There are several drawbacks with these 'hard' coastal defences. They interfere with the natural ecosystem and sediment balance. They are not aesthetically pleasing and can make desirable and appealing locations unattractive for recreation and tourism. They are expensive to construct and maintain and must eventually be replaced. As a result, there has been an increasing focus on ‘soft’ coastal defences which build with nature. These ‘soft’ methods typically have less environmental impact and do not negatively affect the aesthetics of an area. Sand nourishments are one such ‘soft’ coastal defence measure. In areas where sand is abundant, such as the Netherlands, sand nourishments have become one of the most important coastal defence tools.

In the context of increasing costs, it is more and more important that the most suitable and cost-effective solutions are chosen for a specific location. It is however challenging to determine what will be the most appropriate coastal defence measure. Coastal environments are complex with a great many factors influencing their development and change. For these reasons, it has been difficult to compare historically the impact of an actual coastal defence or maintenance activity with another possible one.

Despite the advantages of sand nourishments, it has proven to be challenging to quantify those benefits when compared to dune/dike reinforcements. Coastal defences of any kind are a significant investment and as costs increase require greater justification and analysis to carry out. There is a lack of data in this area to guide decision making, it is an important area of research to investigate locations where sand nourishments have been carried out and analyse the impact of this approach. Specifically, carrying out a direct comparison between the cost of these sand nourishments when compared to the dike/dune reinforcement that would have been necessary had these sand nourishments not occurred. This information would greatly improve the understanding of the costs and benefits of sand nourishments.

Furthermore, it has also been difficult to compare different strategies regarding sand nourishments. Historically in the Netherlands sand nourishments have been carried out frequently. As the costs of this approach have risen, so too has the interest in mega sand nourishments. Mega sand nourishments have several distinct advantages over numerous smaller nourishments. They are more cost effective due to the economies of scale due to the ability to use larger dredging vessels for longer and only require a single large expenditure rather than spreading the cost over a long period of time which results in higher cumulative costs. Their life span is longer with a larger impact on the coastline which can expand the area available for tourism. Mega nourishments also significantly reduce the ecosystem impact since the local environment is allowed to recover for years without after the initial execution of the project.

It is therefore an important question as to whether historical sand nourishments could have instead been executed as a single mega nourishment for the same cost.

The previous chapters have outlined the challenges facing governments worldwide regarding protecting and reinforcing coastlines. Sand nourishments are a vital tool to achieve this whilst working with nature rather than against it. Mega sand nourishments represent a way to further increase the cost/benefit ratio of sand nourishments in areas with large amounts of sand available such as the Netherlands.

The island of Walcheren, located within the province of Zeeland in the Netherlands, has been carrying out sand nourishments extensively since the 1950s. This therefore represents an ideal opportunity to carry out a cost analysis comparing the nourishments to traditional dune and dike reinforcement. In addition, a cost analysis comparing the historical sand nourishments to a single mega nourishment would provide policy makers with important information regarding the viability of continuing on the basis of less frequent, but larger, sand nourishments.

1.3 Research Questions

The previous chapters have introduced the overall challenge of protecting coastlines in the 21st century along with the need for comparable data as to the costs of different coastal defence strategies. Specifically, there is a need to analyse and investigate the costs of sand nourishments when compared to more traditional dike and dune reinforcements. In addition to determine ways of optimising sand nourishment execution via the use of mega nourishments. The island of Walcheren represents an excellent test location for this analysis due to its long history of sand nourishments over many decades.

From this information, it is possible to form two primary research questions along with the necessary sub-questions. These sub-questions provide the structure for obtaining the information needed to answer the main research questions.

The first main research question is a retrospective analysis. It looks specifically at sand nourishments that occurred in the past in the island of Walcheren to determine the impact of those nourishments and what dike/dune reinforcement would have been necessary if those nourishments had not taken place, along with those costs.

Main research question 1: Were the sand nourishments at the island of Walcheren better value for money relative to traditional dune/dike reinforcement methods?

- Sub-question 1: What sand nourishments previously took place at the island of Walcheren? What was their frequency, scale and cost?
- Sub-question 2: Where within the coastline of the island of Walcheren did sand nourishments have the greatest impact on the position of the coastline and greatest benefit?
- Sub-question 3: What was the impact of these sand nourishments in terms of reducing the chance of breaching of the dunes during a storm surge?
- Sub-question 4: Knowing the impact of these sand nourishments, what would have been the costs of traditional coastal defence maintenance and dike reinforcements if they had not occurred? How do those costs compared to the costs of the sand nourishments that were executed?

Having completed a retrospective analysis in the first research question, the second research question then looks at the design of a potential mega sand nourishment for the island of Walcheren. Given the total costs and sand volume used for the sand nourishments in the model period, these resources could have been used for a sand engine similar to the one constructed at The Hague and Norfolk. This mega sand nourishment could have resulted in greater coastal resilience or cost effectiveness than the smaller, more frequent sand nourishments that did occur.

Main research question 2: Would a mega sand nourishment constructed at the island of Walcheren, of the same total cost of the historical sand nourishments, achieve a half-life of 10 years? What would be the cost saving of an optimised mega nourishment design compared to historical sand nourishments?

- Sub-question 1: What would be a suitable coastal location for a mega sand nourishment?
- Sub-question 2: What would be the volume of a mega nourishment constructed at this coastal stretch if the total cost were equal to the costs of sand nourishments during the period 2000-2019? What would be the length, width and half-life of this mega nourishment?
- Sub-question 3: Knowing the answer of sub-question 2, would a mega nourishment of smaller volume achieve a half-life of 10 years and a dry beach width of 50m? What would have been the cost saving of this smaller mega nourishment?

These research questions will be answered in the following chapters and have the potential to have significant implications for the understanding of how sand nourishment strategies can be optimised.

2. Theoretical Framework

2.1 Study Area

The area being analysed for the thesis is the island of Walcheren, located within the province in Zeeland, The Netherlands. A relatively small island with a population of 113,000 and a coastline approx. 30km long, it has two main towns (Vlissingen & Middelburg) and several smaller villages. Examples of important coastline locations are Westkapelle, at the 'tip' of the island, and Domburg which causes the coastline to bulge slightly.

In terms of the coastline, Walcheren can be divided into two distinct parts; north-west and south-west. Along the south-west stretch there is an important shipping channel with a deep gully that leads to Antwerp. There are dikes present at Vlissingen and Westkapelle. The north-west coastline is more rural with fewer populated areas along the coast. The stretch between Oostkapelle and Breezand is a nature reserve and has wider dunes than in other parts of the island. Domburg is an important tourist destination and receives greater beach erosion due to its beaches protruding into the sea.

Walcheren and the Netherlands has a highly dynamic geographic history. At the end of the Pleistocene, approximately 11,700 years ago, Walcheren was not separated from England by the ocean as much sea levels were far lower due to glaciation. As the Holocene began, temperatures and sea levels rose rapidly leading to Walcheren becoming an island. The steady retreat of the coastline resulted in a layer of sea clay (depth of 5-50m) being deposited on top of the existing sand (J. Stronkhorst, 2013, p. 3). Whilst the Netherlands is normally considered to have a sandy coast, this clay layer forms a more solid foundation to the Walcheren coastline.

This clay foundation is significant when considering the behaviour of the coastline in terms of changes in volume (erosion/accretion) and position (regression/transgression). In a sandy coast, coastline erosion/regression tends to occur in a more consistent, linear manner year after year. The clay foundation of Walcheren is more similar to a rocky coastline in which erosion trends reduce over time due to the resistance of the clay base (A. Payo, et al, 2014).

General maintenance of the coastline is the responsibility of the local waterboard. In the past, the waterboard undertook all maintenance (planting of Maram grass, repairing groynes, etc) itself. During the 1970s, there were 8 employees working full-time to maintain the coastline along with other estimated costs of €24,000 / km / yr (Stronkhorst, 2013) in the absence of sand nourishments. With an approximate coastline length of 30km, a cost of €780,000 / yr (adj. 2020 prices) can be estimated to be when sand nourishments were not being utilised.

Over time, the maintenance activities of the local waterboard have decreased. There are now only 3 employees working full-time on coastal maintenance with some activities outsourced to local contractors. When meeting with representatives of the waterboard, it was clear that sand nourishments have made coastal maintenance significantly easier with less reactive/emergency maintenance measures necessary.

Please see appendix 'Waterboard & Coast Visit' for more information.

Image 2: The island of Walcheren

2.2 Fundamental Concepts

- **JARKUS monitoring program** – Annual program to record beach/coastal profile data at set intervals (transects) of 200 – 250m perpendicular to the coast. These measurements are called JARKUS measurements and are recorded in a national database. The dry part of the transect is recorded using aircraft carrying out stereo photogrammetry and LIDAR systems. The wet part of the profile is recorded with automatic sounding systems and GPS.
- **Transect** – set numbered points along the Dutch coastline typically 200 – 250m apart. They are perpendicular to the coast and the coastal profiles are recorded at these locations. The coastline of the island of Walcheren is divided into 194 of these transects.

- **Coastal profile** – A cross-section of the coast at each transect. The coastal profiles comprise of two sets of measurements, wet and dry, which are combined together to give a single profile. The historical records of coastal profiles at each transect go back to 1967 however there are gaps in this data.

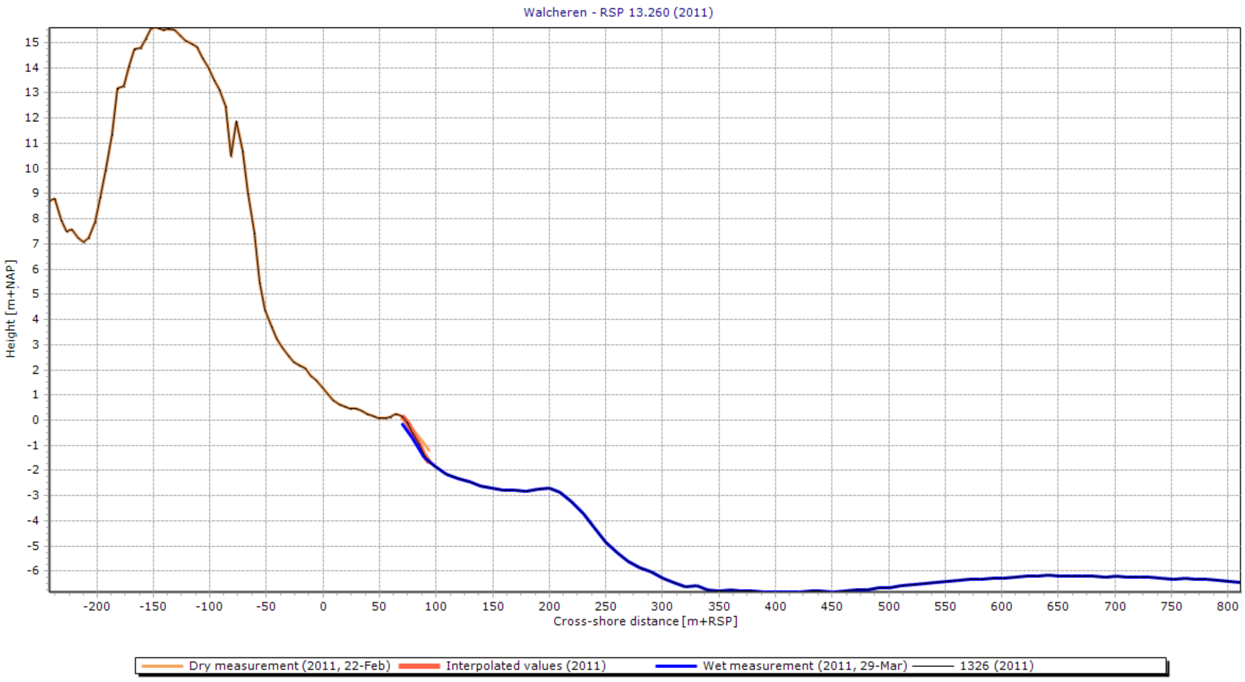


Image 3: The coastal profile of transect 13.260 within the coastline of Walcheren

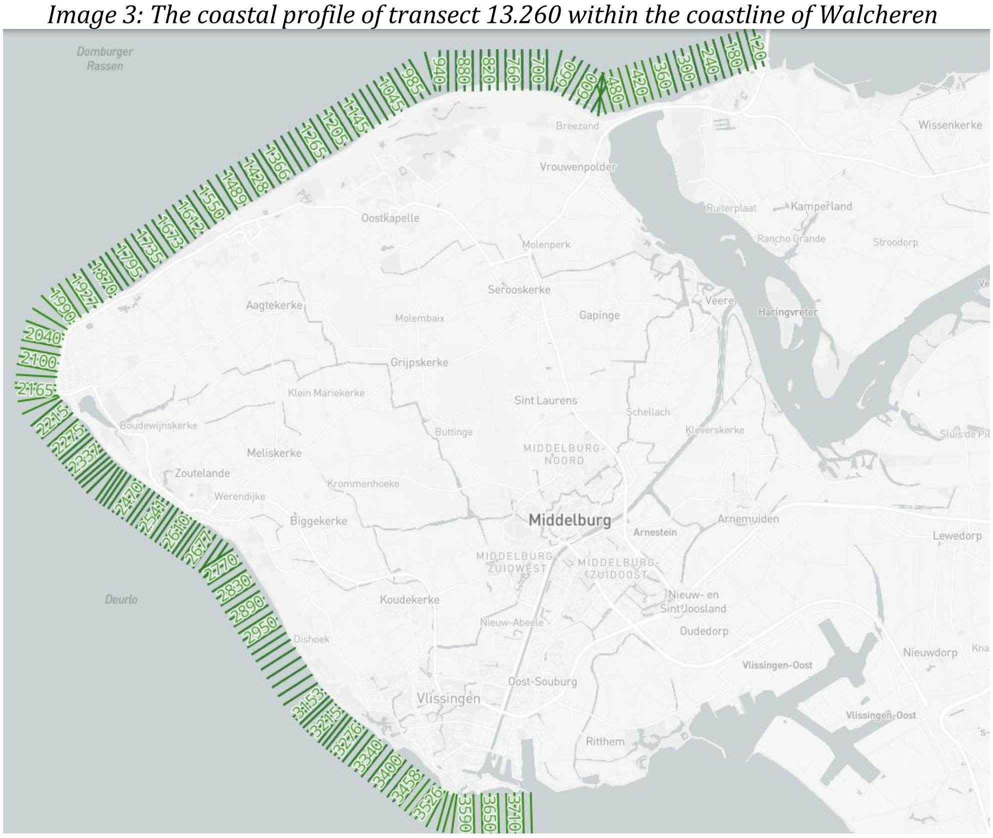


Image 4: The JARKUS transects along the Walcheren coastline

- **BKL** - Base coastline. A predefined point based on coastal management policies agreed in 1990 in the Netherlands. The BKL specifies the minimum position of the coastline relative to the zero point of a coastal location. Some BKL positions were adjusted in 2001.
- **MKL** - Measured coastline. The position of the coastline as it was recorded in a certain year.
- **TKL –** Expected coastline. Projected coastline position on the basis of linear extrapolation of the erosion trend as modelled by MorphAn.
- **Hold the line approach –** The coastal defence strategy of the Netherlands. Beginning in 1990, the Netherlands created reference points for the coastline which are defended and not allowed to retreat or erode further.
- **Deltares –** An independent institute for applied research in the field of water. A world leading research institute.
- **Boundary profile –** A boundary reference point used to compare coastal profile erosion or movement. For this analysis, MorphAn placed the boundary profile behind the first dune facing the sea.
- **Flood safety transects –** the coastline of the island of Walcheren is divided into two flood safety transects; 29-1 and 29-2. Different hydraulic boundary conditions (water level during storm surge, significant wave height, etc) are used in each transect to assess safety. The 29-1 transect covers JARKUS profiles from 5.400 (near Breezand) to 22.550 and the 29-2 transect covers from 22.750 to 33.800 at the outskirts of Vlissingen.

Table 1: Example of hydraulic boundary conditions within the 29-1 flood safety transect

Traject_29-1_signaleringskans

Location	Offset	Hs [m]	Tp [s]	Tm-1,0 [s]	Rp [m]	D50 [µm]
Walcheren - RSP 12.860	1286	5.14	12.36	NaN	5.31	309
Walcheren - RSP 13.060	1306	5.14	12.36	NaN	5.31	309
Walcheren - RSP 13.260	1326	5.14	12.35	NaN	5.31	309
Walcheren - RSP 13.460	1346	5.13	12.35	NaN	5.32	309
Walcheren - RSP 13.660	1366	5.13	12.35	NaN	5.32	309
Walcheren - RSP 13.860	1386	5.12	12.34	NaN	5.32	310
Walcheren - RSP 14.060	1406	5.12	12.34	NaN	5.32	310
Walcheren - RSP 14.280	1428	5.11	12.34	NaN	5.32	310
Walcheren - RSP 14.480	1448	5.11	12.34	NaN	5.32	311
Walcheren - RSP 14.690	1469	5.11	12.33	NaN	5.32	311
Walcheren - RSP 14.890	1489	5.1	12.33	NaN	5.32	311
Walcheren - RSP 15.090	1509	5.1	12.33	NaN	5.32	310
Walcheren - RSP 15.300	1530	5.09	12.32	NaN	5.32	308
Walcheren - RSP 15.500	1550	5.09	12.32	NaN	5.32	307
Walcheren - RSP 15.710	1571	5.08	12.32	NaN	5.32	305
Walcheren - RSP 15.910	1591	5.08	12.31	NaN	5.32	304
Walcheren - RSP 16.120	1612	5.07	12.31	NaN	5.33	303
Walcheren - RSP 16.320	1632	5.07	12.31	NaN	5.33	301
Walcheren - RSP 16.530	1653	5.06	12.3	NaN	5.33	300

Image 5: The coastline of Walcheren divided into two flood safety transects, 29-1 & 29-2

- **Trend period** – 1970-1979. This decade was selected as it is the earliest complete decade within the dataset available and has only one sand nourishment during the period. This makes it a good reference period to obtain erosion and coastline movement data without the influence of sand nourishments.
- **Model period** – 1980-2019. During this period there were a significant number of sand nourishments throughout the island of Walcheren, altering the coastline and coastal profiles. Data from the trend period (flood safety, coastline advance/retreat, erosion/accretion) is used to model the behaviour of the coast during the model period. This allows a comparison at the end of the model period of the actual coastline vs the coastline modelled from the data from the trend period which excludes the influence of sand nourishments.

2.3 Data Collection

- **Sand nourishments –** This data is contained within MorphAn and further records were provided by Rijkswaterstraat and Waterschap (local waterboard).
- **Coastal profiles** – Contained within MorphAn covering the period 1967-2020.
- **MorphAn –** A free open-source software tool for assessing the dune safety (Q.J. Lodder & P.F.C. van Greer, 2012) and coastal development of sandy coasts (Deltares, 2020). MorphAn contains three important models that are used during the thesis; coastal safety assessment, coastline assessment, and volume development model. The below information is taken from MorphAn's user manual (v1.5, Deltares, 2016):
- **Coastal safety assessment model –** a computer model contained within MorphAn. This model is used to assess dune safety according to the principles in the following two documents: 2006 Technical Report on Dune Erosion (ENW, 2007), or TRDA2006; 2011 Report on Dune Water Defenses (Deltares, 2012), or RD2011. There are three distinct steps to the model:

- Erosion calculation – the erosion is calculated using the Duros+ model, by running the erosion sub-model contained within MorphAn.
- Boundary profile calculation – the position of the boundary profile (defined above) based on the calculated erosion results or input parameters.
- Regression analysis – Lastly, a diagram of the normative results is made, showing the calculated erosion results over time compared to the landward boundary of the flood defences.

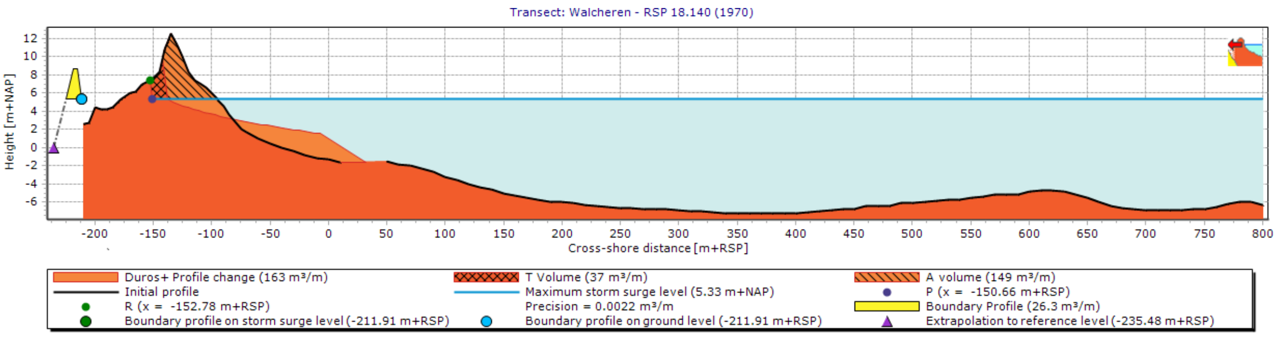


Image 6: Dune safety assessment in MorphAn of a coastal profile

- **Coastline development model** – a model contained within MorphAn to support coastline assessment within the coastline monitoring program. In the Netherlands, results are published in the atlas of coastal charts (Rijkswaterstraat, 2012). This model contains three sub-models which are based on coastal management policies agreed in 1990. A predefined base coastline (BKL) has been in effect since that moment, as defined above. Both the selection of the transects and years, and the specification of the profile measurements and boundary conditions of the coastline development model are carried out based on the inputs selected. There are three steps to the model:
  - Momentary coastline model – calculation of the momentary coastline position (MKL) based on measurement data and boundary conditions for every coastal location, and every year.
  - Trend period model – this uses nourishment data to make an estimate of a valid period for calculating a trend in the development of the MKL values.
  - Expected coastline (TKL) model – based on the MCL points from the MCL model and a predefined trend period, the TKL model calculates the trend in the development of the momentary coastline points. This trend is then used to calculate the expected position of the coastline at predefined times (plus the moment when the expected coastline intersects with the base coastline, if applicable)

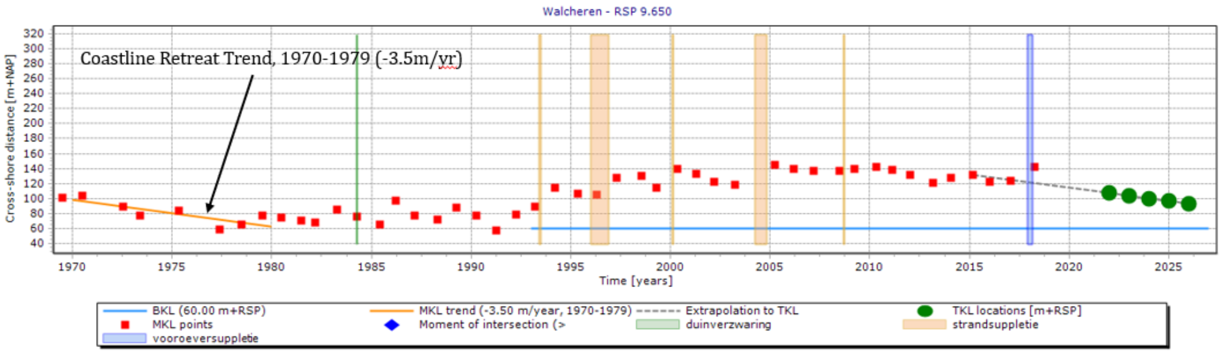


Image 7: Coastline development model in MorphAn showing a trend of coastline retreat

- **Volume development model** – this calculates the volume development in the cross-shore profile at a specified location, within predefined vertical and horizontal boundaries on a transect. As with the coastline safety assessment model and coastline assessment model, this model has three sub-models:
  - Volume model – this model makes identical calculations to the momentary coastline sub-model. The different is that this model offers more flexibility in specifying and working with the boundaries of the slice of coastline for which a volume is calculated.
  - Trend period model – this sub-model operates in an identical fashion to sub-model of the same name within the coastline assessment model.
  - Trend model – this sub-model calculates a trend in the development of the calculated volumes per location.

2.4 Flood Safety Calculation

The primary flood safety calculation is carried out as described in section 2.3 (coastal safety assessment) on each transect and coastal profile. MorphAn calculates the main dune erosion during a storm event and adds a safety factor of 25%. The distance between this maximal erosive point and the boundary profile represents a method of determining the level of flood safety remaining after a modelled storm event.

As detailed in section 3.1.3, the coastal profiles within each transect were adjusted to reflect the erosion/accretion trends from within the trend period. The flood safety was then checked against this.

2.5 Mega Nourishment Design Framework

It was not realistic to design a mega nourishment from start to finish for this thesis, so instead a design framework was utilised. This framework is based on a retrospective analysis of a series of mega nourishments using models to create a more straightforward method of carrying out a feasibility study (P.K. Tonnon, et al, 2018).

In their paper, Tonnon et al (2018) used three models (Delft3D, UNIBEST-CL+ and LONGMOR) to carry out a hindcast of the mega nourishment at The Hague to determine which most accurately modelled the changes in the nourishment. After finding that Delft3D was the most accurate model, they then derived several important relationships and design graphs from this data. This allowed a simplified design framework to be created based on a series of input factors:

- Alongshore length at the seaward boundary
- Seaward extent (cross-shore width above MSL)
- Initial nourishment volume
- Longshore transport intensity

The design framework then determines the half-life of the mega nourishment, volume decay over time and maximum coastline retreat at the centre of the beach reclamation. The mega nourishment is attached to the existing coastline using a length to width ratio of 2:1 as seen below:

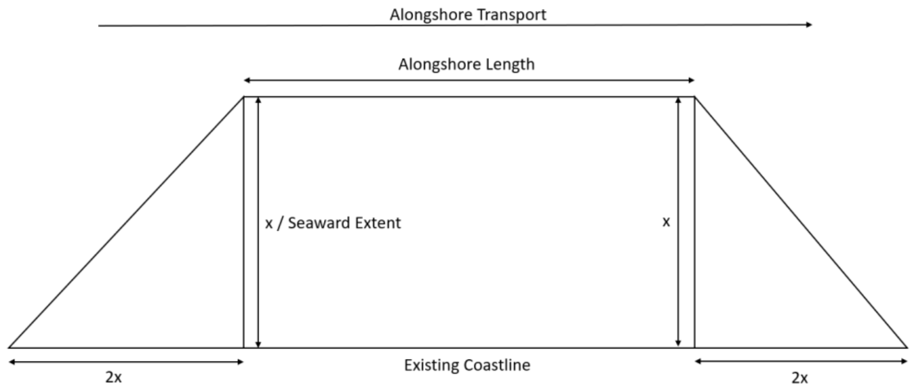


Image 8: Simplified top-down view of proposed mega nourishment (not to scale)

2.6 Mega Nourishment Input Data

The following input values were used to execute the mega nourishment feasibility study:

- The period of 2000-2019 was selected for comparison and analysis due to having actual costs from that period
- The target for the mega nourishment half-life is 10 years (to simulate a lifespan of 20 years)
- The mega nourishment will use three important heights; spring tide(+2m), high tide (+1.5m) and low tide (-1.15m). These were averaged from the mega nourishment location data.
- Half the overall width of the mega nourishment will be dry beach (between +2m and +1.5m), the other half will be intertidal (between +1.5m and -1.15m)
- To slope the mega nourishment to the existing sea bed, this slope must have a shallower angle than the natural angle (angle of repose) of wet sand to prevent the flow of material. This angle is 30 ±3 (L van Rijn, 2018), so a more conservative angle of 25° is used for safety.
- The longshore transport intensity along the coast is an important factor that affects the evolution of a mega nourishment. Values of 10,000 – 15,000m^3/yr/degree for the North-West were provided by B Huisman, Department of Applied Morphodynamics at Deltares. A third value of 20,000m^3/yr/degree to account for uncertainty and to represent a more aggressive erosive climate due to sea level rise and increased wave/storm activity.

2.7 Economic Analysis

All prices were adjusted with inflation to 2020 price levels in order to be directly comparable. Sand nourishment costs pre-2000 were not available and were estimated in sections 3.1 & 4.1. Dune/dike reinforcement costs were estimated in sections 3.1.4 & 4.1.4 and are cumulative values of over the 40 year model period.

3. Material & Methods

3.1 Main Research Question 1: Retrospective Analysis

The general process undertaken for the thesis can be summarised below:

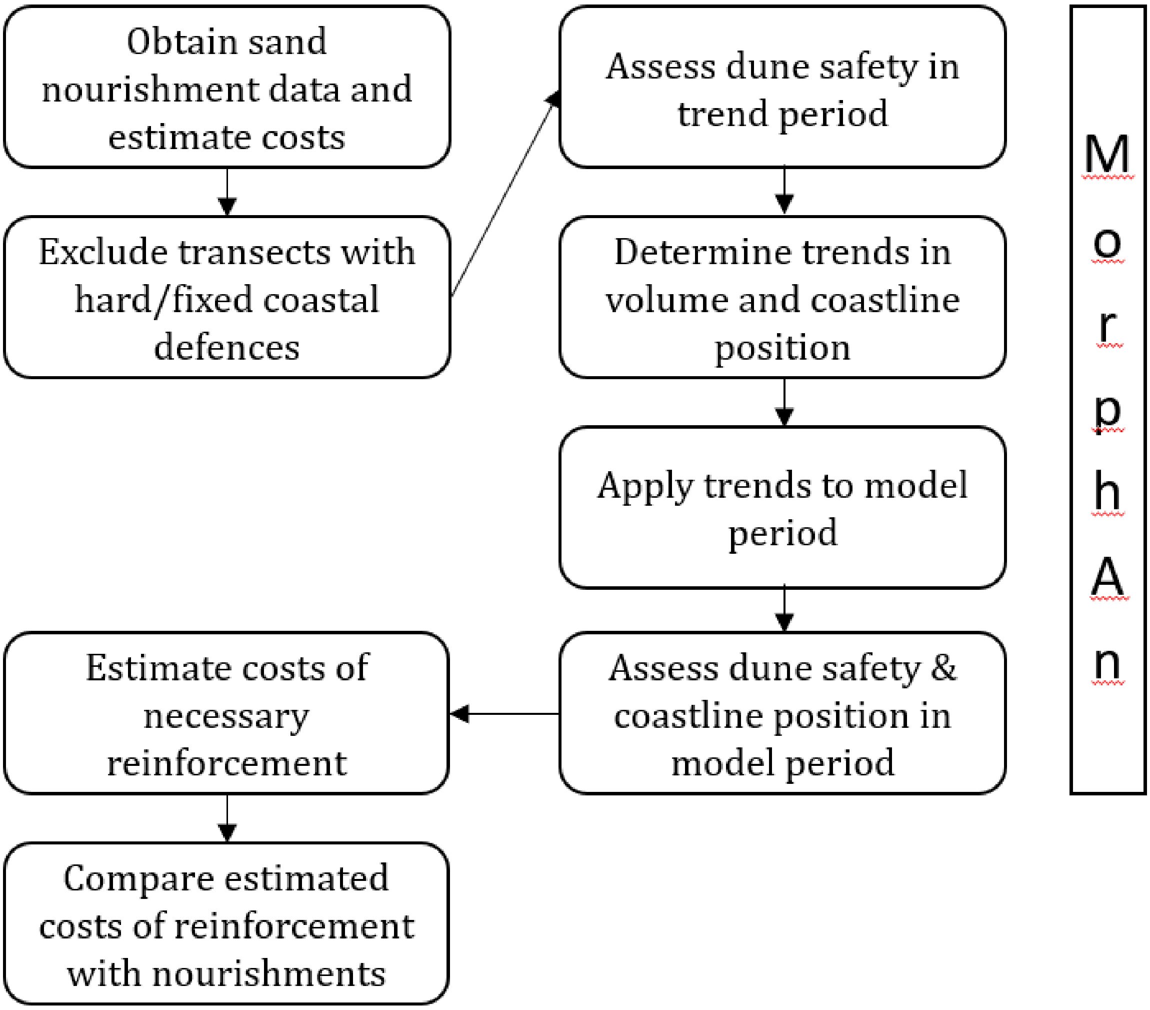


Image 9: Thesis methodology

The goal of the first main research question of the thesis is to model the coastal scenario in which sand nourishments had not taken place at the island of Walcheren. The first step was to select a time period to represent the 'original' coastal profile before sand nourishments occurred. This would act as a control period to compare against the coastal profiles that actually developed up until 2019 with all the sand nourishments that occurred in that time.

Coastlines are typically highly dynamic environments with a number of complex factors affecting their development. The island of Walcheren is no different. As the coastline is constantly changing and seeking an equilibrium between erosion and sedimentation that will never be found, there is no 'original' coastline for the island of Walcheren. This is also constrained by the data that is available. Logically, the earlier in time the less affected the coastal profiles are by human behaviour, but this cannot be utilised if the coastal profiles are lacking the data to allow for computer modelling.

The data available contains coastal profiles within the island of Walcheren from 1967-2019. The previous sub-question has shown that prior to the 1980s, only one relatively small sand nourishment occurred in this period. Therefore, the decade of 1970-1979 represents the most suitable time period to use to act as the 'original' coastal profiles. It is significant that this time period contains the coastal profiles before the vast majority of sand nourishments occurred, meaning that they were relatively unaffected or changed by the nourishments.

The time period of 1970-1979 is therefore selected as the period to determine the trends of dune safety, coastline retreat/advance and changes in volume within the coastal profile. These values will represent changes in the coast without sand nourishments. The single sand nourishment of 45,000m3 that occurred in this period will be disregarded in terms of its impact on coastal morphology and the trends will be assumed to be entirely natural.

3.1.1 Research Sub-question 1: Sand Nourishments

To establish clearly the history of sand nourishments at the island of Walcheren, the following variables were considered:

- Cost (adjusted for inflation to 2020 prices)
- Size (sand volume in m^3)
- Type (was the sand placed on the foreshore, beach or dune)

Sand nourishment data in terms of size, location and type was available from 1952 onwards. However, there were no costs from before 2000 so a methodology needed to be established to determine these.

The sand nourishments in the period 2000-2019 were broken down into three types; dune, beach and foreshore. The average cost per cubic meter of sand was calculated for each of these three types. These averages were then applied to the pre 2000 sand nourishments to estimate the total cost.

3.1.2 Research Sub-question 2: Coastline Position

Answering this sub question meant modelling the rate of coastline regression/transgression to estimate the position of the coast if the sand nourishments from 1980 onwards had not occurred and the trend would have persisted to 2019.

The following methodology was used:

1. The rate of coastal regression/transgression from the trend period of 1970-1979 was modelled using Morphan's coastline development model for each transect
2. In section 2.1 it was discussed how the coastline of Walcheren has similarities with both sandy and rocky coasts. Two mathematical models were applied to the trends of coastline movement to estimate a range between those two scenarios (A. Payo, et al, 2014). The first was a linear model for a sandy shore scenario. This assumes that the modelled rate

of coastline movement continued unchanged to 2019. The second was a natural log model for a rocky coast. The natural log model has the effect of moderating and reducing the rate of coastline regression/transgression throughout the 40-year model period.
3. Transects 5.800, 18.700 to 21.950 & 22.250 were excluded due to there being zero or one profile measurement from the trend period, making it impossible to calculate a trend. Transect 6.000 was excluded due being an extreme outlier due to only two measurements from the trend period causing an exaggerated and unrealistic rate of coastal transgression.
4. Not all locations had an MKL for 1979 and this was modelled using the linear trend identified from previous years. For example, rate of coastline movement was added to the MKL for 1978 to model the MKL for 1979. This was necessary and unavoidable to complete the dataset so that every location had a position in 1979 to perform the analysis.
5. The MKL from 1979 was taken for every location and two modelled rates of coastline change were added to model the 2019 coastline position.
6. With every location having two modelled coastline positions for 2019, this was then compared to the actual MKL taken from 2019. The difference between the modelled and actual coastline position in 2019 can be inferred to be the result and influence of sand nourishments carried out in the model period of 1980-2019

Image 10: Visualisation of research sub-question 2 outcome

3.1.3 Research Sub-question 3: Dune Safety

To assess dune safety, the coastal defence project at Westduin in 2010 was used as an example. The flood defences in this location were reinforced following an assessment indicating possible risk of failure in an extreme storm event. It was logical to use this risk as an evidence-based approach to assess the remaining Walcheren coastline in the model scenario.

The transects spanning the project (at Westduin), 31.530 to 33.600, were checked in MorphAn in 2008 & 2009 to measure the dune erosion that took place. This maximal erosive point within the dune was measured compared to the boundary profile behind it and the results averaged. This represents the margin of safety remaining. The results of this exercise gave an average distance of 16m. This distance was used as the threshold between transects that require dune or dike reinforcement (Category A) and those that do not (Category C).

Image 11: Westduin coastline reinforcement project between transects 31.530 and 33.600 (2010)

Within the highest flood risk transects, it was necessary to make a distinction between two further risk categories. The first, category A2, are transects where the margin of safety is less than 16m but there is some dune remaining following this storm event. The second, category A1, represent the most extreme scenario with complete dune failure. All the transects were assessed into these three risk categories.

A two-step process was followed to make the final determination of the level of dune safety at each transect. First, the margin of safety was used to categorise every transect into the risk categories described above. This however was not sufficient as there are locations with two dunes. MorphAn will place the boundary profile behind the first dune, but a larger second dune may still ensure safety in a storm event. A result indicating dune failure does not necessarily mean that there is high to extreme flood risk. It was necessary to carry out a final visual analysis of each transect to verify the level of risk present.

Table 2: Methodology for classifying dune safety of each JARKUS transect

Category	Flood Safety	Distance between erosion and boundary profile
Category A1	Extreme risk	Less than 0m
Category A2	High risk	Between 16m and 0m
Category C	Low risk	Greater than 16m

Please see appendix 'Method (RQ 1.3 – 1.4)' for this data.

3.1.3.1 Step 1 – Historical Dune Safety Assessment

With the trend period of 1970-1979 selected to represent the coastline without sand nourishments, the beginning of the modelling process was to apply the most modern safety standards (which are based on parameters such as significant wave height) to our test scenario. As the earliest year within the trend period, the year of 1970 was selected to be test against the current safety standards.

Within the dataset of coastal profiles for the island of Walcheren within the trend period of 1970-1979, there are incomplete coastal profiles which lack measurements of the entire dune and foreshore. This is an issue throughout the entire 1967-2019 dataset but is more prevalent in the earlier decades.

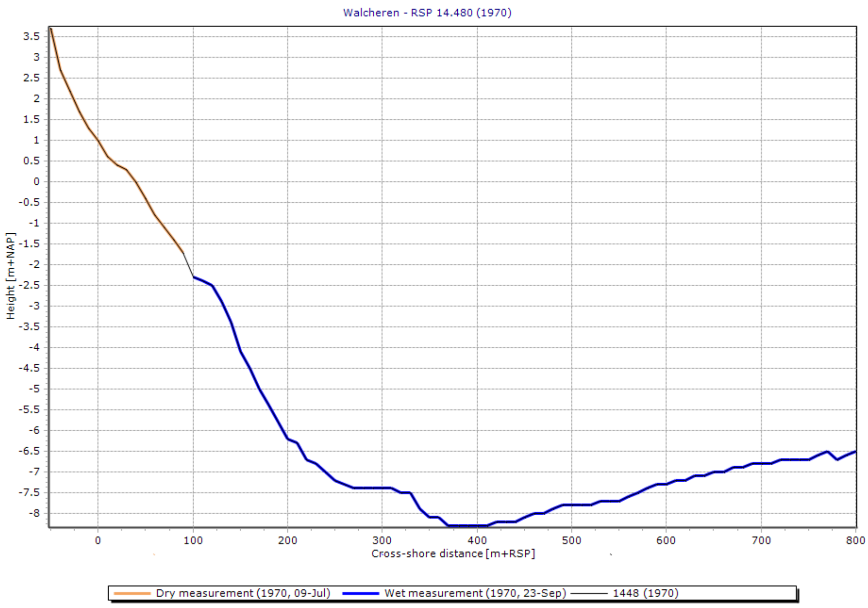


Image 12: Incomplete coastal profile missing dune

The result of this is that it is not possible to test all coastal profiles in 1970 in the manner described as they are not complete; if profile is missing a dune, then the safety of that dune cannot be tested. However, MorphAn provides the functionality to extend and merge coastal profiles with data from adjacent years for the same coastal profile. This is a useful tool as each coastal profile does not typically change significantly from one year to the next.

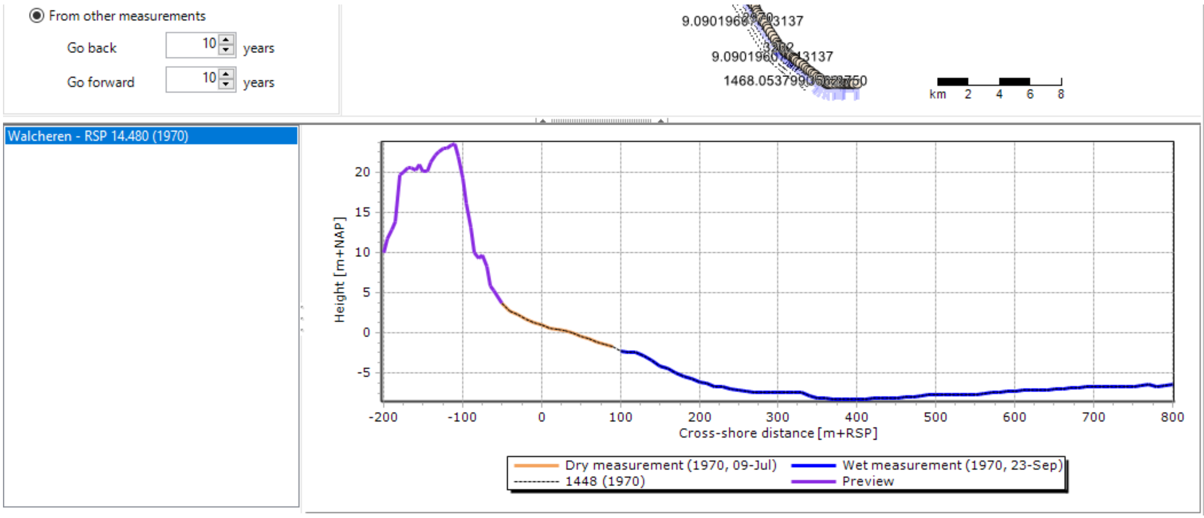


Image 13: Coastal profile merged and completed using 'extend' functionality

The above images show the method being applied. MorphAn allows the user to select the range of years being used to complete the coastal profile. 10 years was selected to cover the 1970-1979 trend period and to ensure that enough data was selected to fill in the gaps.

The below steps detail the methodology followed to identify the historical weak links in 1970 within the island of Walcheren:

1. The boundary profile was chosen as behind the rear of the first dune within the coastal profile and is indicated as 'R' in the graph below. As mentioned in the theoretical framework, the boundary profile acts as a reference point to compare erosion and overall dune safety
2. The dune erosion was calculated for normative boundary conditions (significant wave height, peak wave period, etc) using the dune safety model in MorphAn
3. The distance in the coastal profile between the erosion and boundary profile was calculated, representing the horizontal margin of safety within the dune after the modelled storm event
4. The coastal profiles were categorised into three safety groups; A1, A2 & C (see section 3.1.3)
5. Each coastal profile was then checked sequentially to verify that the safety categorisation was accurate as the topography behind the boundary profile may result in a higher or lower level of safety (eg, there may be a second larger dune present behind the first dune)
6. The locations were illustrated graphically within MorphAn
7. In the final results, safety categories A1 & A2 were combined to represent the weak links within the Walcheren coastline out of an abundance of caution. Both safety categories A1 & A2 were assumed to represent an unacceptable level of flood risk.

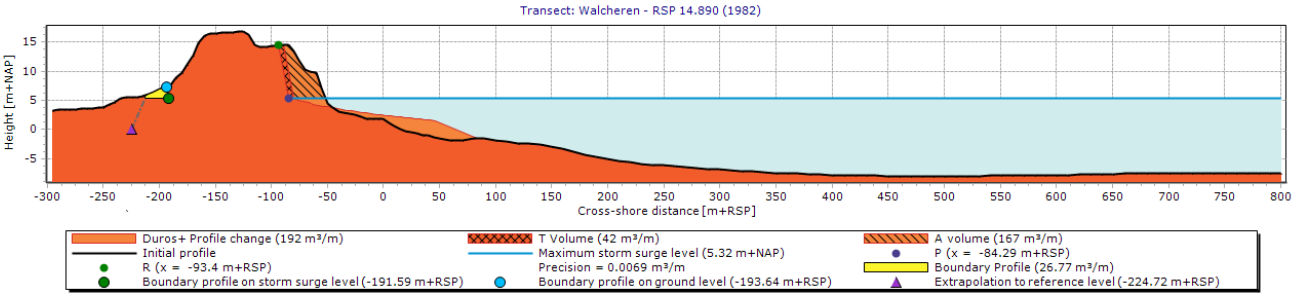


Image 14: Dune safety assessment. The hatched area indicates volume loss due to erosion

3.1.3.2 Step 2 – Modelled Dune Safety Assessment

This step in the modelling process was to establish the level of dune safety that would have existed in 2019 if the sand nourishments had not occurred.

The below methodology was used:

1. MorphAn's volume development model was used to determine the rates of erosion and accretion at all transects throughout the trend period of 1970-1979
2. As with the previous modelling step regarding the coastline position, these trends were modelled until the 2019 using a linear rate and a natural log method to establish the total volume change in each coastal profile over the 40-year model period
3. The modelled volume change was applied to the 1979 coastal profile in each location, resulting in the removal or addition of sand to the coastal profiles. This created a set of coastal profiles which modelled how the profiles would have changed without the influence of sand nourishments in 2019.
4. The dune safety check, as described in step 1, was applied to these modelled coastal profiles
5. The locations were categorised into three safety categories as described in step 1 to display the weak links that would have occurred

3.1.4 Research Sub-question 4: Cost Comparison

The costs of the dune reinforcement project at Westduin were €12.62 million per km. This project widened the dunes by 40-80m and used 550,000m3 of sand with a total cost of €22 million, or €11 million per km. Adjusted for inflation to 2020 prices a figure of €12.62 million per km is obtained.

Image 15: Dune reinforcement project at Nolle-Westduin in 2010

To calculate the dune/dike reinforcement costs and compare them to the sand nourishment costs, the following methodology was used:

1. Every transect that has been assessed as a category A1 & A2 safety risk was assumed to require reinforcement. This was due to the desire to be extra conservative and put safety as the highest possible priority in keeping with the Netherlands overall flood defence philosophy.
2. It was assumed that the category A1 locations, being scenarios of extreme flood risk, required substantial reinforcement including the possible construction of a dike. Artificial structures such as dikes are more expensive. As the Westduin project was primarily dune-based, the cost of reinforcing A1 transects was increased by 25% giving a cost per km of €15.77 million.
3. Category A2 locations, which are at high risk and require dune reinforcement, were assumed to have the same average cost of €12.62 million per km as the Westduin project
4. The width of each transect assessed as category A1 & A2 was calculated.
5. These individual widths were summed to give a total length of dune/dike reinforcements for both the linear and natural log model scenario.
6. These two calculated dune/dike lengths were multiplied by the cost of reinforcements per kilometre.
7. The cost of coastal maintenance without sand nourishments of €780,000 / yr was added to the reinforcement costs. As the model period is 40 years, this totals €31.2 million.
8. The total cost of reinforcing the Walcheren coastline in the linear and natural log model scenario was compared with the total cost of the historical sand nourishments detailed in section 3.1.1.

3.2 Main Research Question 2: Mega Nourishment Feasibility Study

3.2.1 Research Sub-question 1: Location

There are a great many factors that have been considered when deciding the placement of mega nourishments. It is not possible to carry out this type of research and development within the scope as the second part of this thesis, so it is necessary to simplify and reduce the number of factors to two primary factors.

There are shipping lanes which are economically significant as they allow access to the port of Antwerp. There are also deep gullies present which would make a mega nourishment infeasible due to the volume of sand requirement and/or result in a high amount of erosion, decreasing lifespan significantly. These two factors will be used to eliminate stretches of the Walcheren coastline as suitable for a potential mega nourishment.

The remaining viable locations will be assessed for their vulnerability to erosion and coastline retreat to ascertain where a mega nourishment would have the greatest benefit. An optimal location will then be chosen on this basis.

Secondary factors such as tourism and the environment will not be used as part of the decision-making process for the mega nourishment location but may be incorporated as part of refining the design and feasibility of the mega nourishment.

3.2.2 Research Sub-question 2: Volume & Design

For the location selected, the volume of sand available for the mega nourishment will be equivalent to the individual nourishments at that location. This is easily obtained since the section 4.1.1 already details all the sand nourishments executed at Walcheren. When executing mega nourishments, there is a significant efficiency improvement due to the economies of scale. Larger dredging vessels can be used for longer and booked further in advance for mega nourishments, leading to lower costs. Whilst this exact saving will be specific and unique to each situation and market costs, a reasonable estimate would be a 10-20% saving, with 15% chosen as the most likely average saving. The total volume available for the mega nourishment will therefore be increased by 15%.

The basic design and dimensions will utilise the design framework already discussed in sections 2.5 & 2.6. The goals are to protect Domburg from erosion and to widen the beach in the chosen location which allows for greater recreational use/tourism and also increases an environmentally productive area.

Regardless of the location selected within the Walcheren coastline, the coast will obviously be very irregular and will require simplification to carry out the feasibility study using the following steps:

1. The boundaries of the selected location will fall on specific transects
2. All the coastal profiles of the transects contained with the mega nourishments will be averaged into a single coastal profile. This will be done by taking the mid-point between the different coastal profiles every 100m horizontally

3. The average spring tide and low tide will be used as the high and low points of the mega nourishment
4. The seaward extent (width) will be as large as possible within the volume available to maximise half-life and beach area and to ensure the longest possible period of coastline protection
5. The low point of the mega nourishment will be sloped to the existing seabed using an angle of 25° (see section 2.6)
6. The mega nourishment lifespan will be calculated using three different longshore transport values (see section 2.6)

3.2.3 Research Sub-question 3: Optimal Volume

To create a refined mega nourishment design, two factors were used to optimise the width of the nourishment. Firstly, a nourishment half-life of at least 10 years was desired as this is equivalent to the 2000-2019 period being compared. Secondly, a dry beach width of at least 50m remaining after 20 years was sought. This was to allow for an economically optimal design for recreation and tourism since the individual sand nourishments also often fulfil this goal.

The actual dry beach width target after 20 years was 100m. This is because the mega nourishment width is half dry beach and half intertidal. It was assumed that the mega nourishment erodes equally and the 50/50 dry to intertidal ratio remains equal during the lifespan for the purposes of simplicity.

The cost and any saving will be compared to the cumulative cost of the individual sand nourishments that occurred in that location.

3.3 Boundary Conditions

- The primary consideration of the thesis are the financial costs of sand nourishments, mega nourishments and dune/dike reinforcements. It is these strategies whose costs are being compared.
- Other coastal defence strategies, such as managed retreat, are not being considered
- Other factors or costs such as environmental or recreational are not part of the final comparison but will be noted as significant factors
- All costs are displayed as 2020 prices. Any costs will be inflation adjusted to this level.
- The MorphAn software for modelling sandy shores is the only modelling software used for this thesis
- The mega nourishment feasibility study is the basis for the preliminary design of the mega nourishment. Other modelling approaches or software is not used or considered
- Other factors that influence mega nourishments such as particle diameter, wind/tides/currents and ecosystems are not considered for this thesis
- The mega nourishment viability is assessed on the basis of half-life, central width and cost
- Areas of the Walcheren coastline which have hard coastal defences such as dikes are not considered
- The thesis only considers the island of Walcheren and no other areas

4. Results
4.1 Main Research Question 1
4.1.1 Research Sub-question 1: Sand Nourishments
The following graphic was obtained via openearth.nl/coastviewer-static:

Image 15: All historical sand nourishments at the island of Walcheren

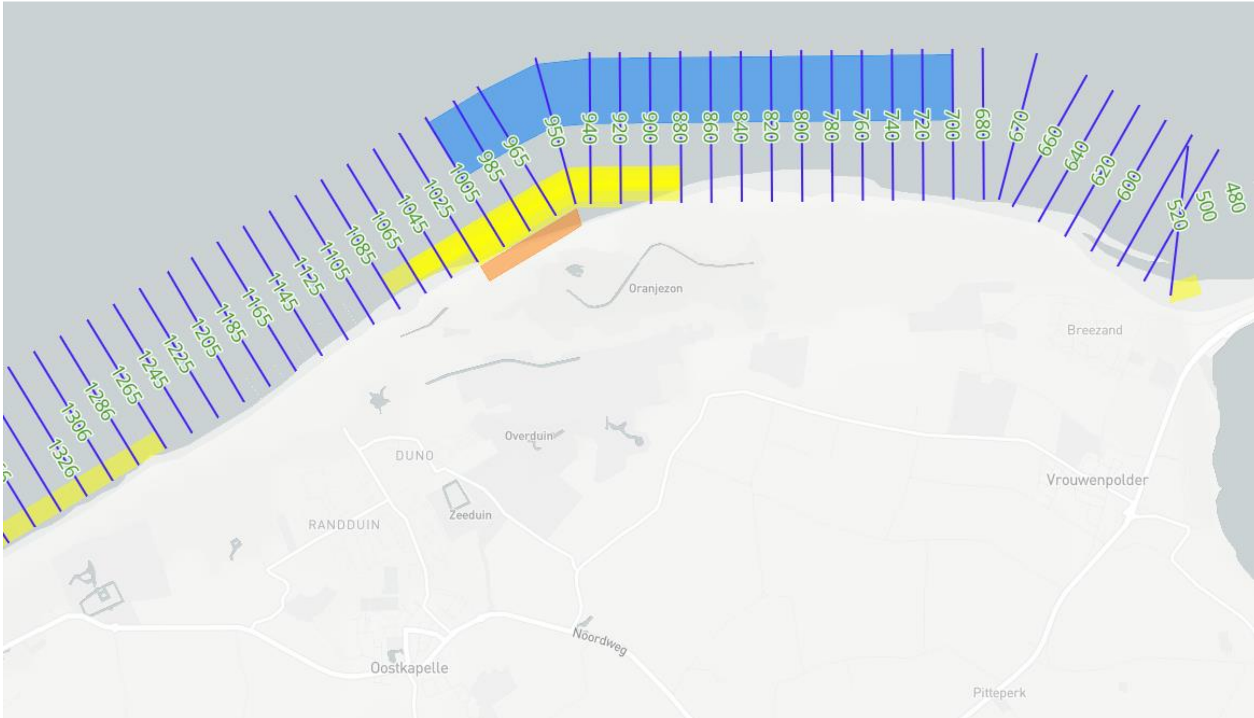
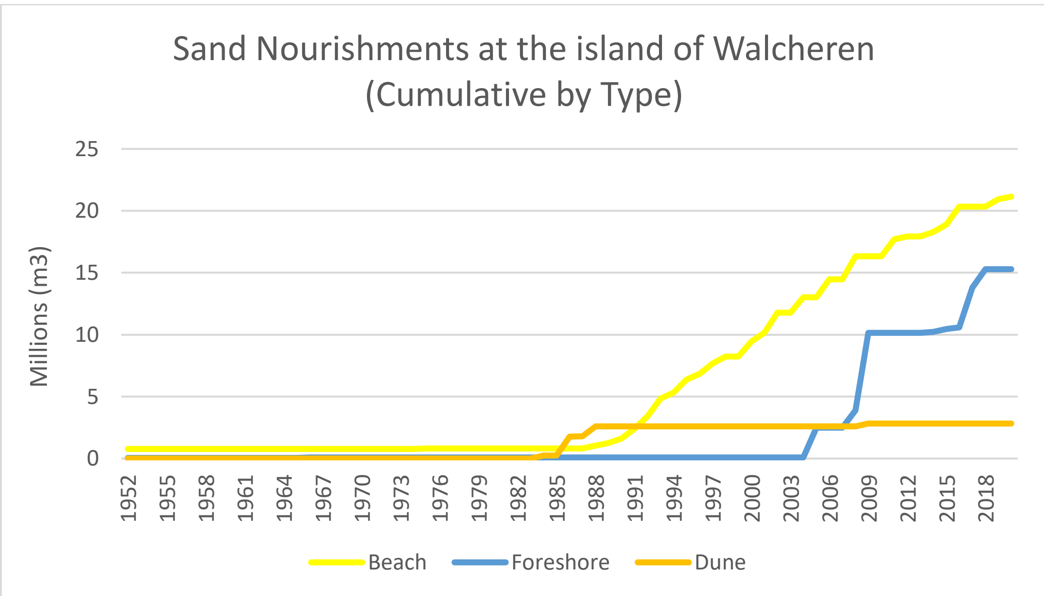


Image 16: Areas where beach nourishments were not executed in the north-west coastal stretch of Walcheren

Beach nourishments occurred over the entire sea-facing coastline of the island aside from two areas near Oostkapelle and Breezand. These two stretches were 1.8km & 3.4km long out of coastline of 29.18km being considered, meaning beach nourishments were executed 82.2% of the coastline.

Dune nourishments were executed in 6 different stretches of the coastline totalling 11.05km. This is 37.9% of the coast. Foreshore nourishments took place over 4 separate areas totalling 14.31km which is 49% of the coastline.



Graph 1: Sand nourishments at Walcheren

Table 3: Average sand nourishments costs by type

Nourishment Type	Average Cost per m3 (2000 onwards)
Beach	€ 4.12
Dune	€ 13.25
Foreshore	€ 2.56

Table 4: Summary of sand nourishments, volume and estimated costs

Decade	No. of Nourishments	Volume of Nourishments	Cost of Nourishments (2020 price adj.)
1950 - 1959	2	825,000m³	€ 3,321,000
1960 - 1969	1	32,000m³	€ 81,920
1970 - 1979	1	45,000m³	€ 185,400
1980 - 1989	14	3,039,390m³	€ 36,334,532
1990 - 1999	19	6,978,067m³	€ 28,749,636
2000 - 2009	18	19,158,087m³	€ 74,826,617
2010 - 2019	17	10,685,840m³	€ 36,377,921
Total	**72**	**40,763,384m³**	**€ 179,877,026**

From the above data, it has been shown that the total volume of all the sand nourishments during the period 1950-2019 was 40.763 million m3. This volume was delivered via 72 separate nourishments. The total cost was estimated to be €179.8 million (2020 prices). The decade with the greatest nourishment volume and cost was 2000 – 2009 due to two major foreshore nourishments in the tidal gully Oostgat.

Furthermore, it can be seen that there were only a handful of sand nourishments prior to the 1980s with a relatively small sand volume when compared to the 1980-2019 period.

Please see appendix 'Results (RQ 1.1)' for more information.

4.1.2 Research Sub-question 2: Coastline Position

Completing the coastline modelling process using the linear and natural log models then comparing this to the actual MKLs for all Walcheren transects gave the following results:

Table 5: Comparison of actual coastline position (2019) to modelled position

Actual MKL (2019) Compared to Modelled Coastline Position (2019)					
Status	Number	Coastline Movement (m)			
		Linear Model		Natural Log Model	
		Average	Standard Dev.	Average	Standard Dev.
Advanced	107	66.2	67.4	47.9	47.2
Retreated	28	-12.2	71.1	-5.4	46.3
Unable to Determine	15	-0.5	N/A	0.6	N/A

The results show that the actual 2019 coastline had significantly advanced compared to the modelled coastline MKL. 71% of the Walcheren transects had advanced with an average of 47.9 – 66.2m. Only a small number of transects retreated relative to the modelled results.

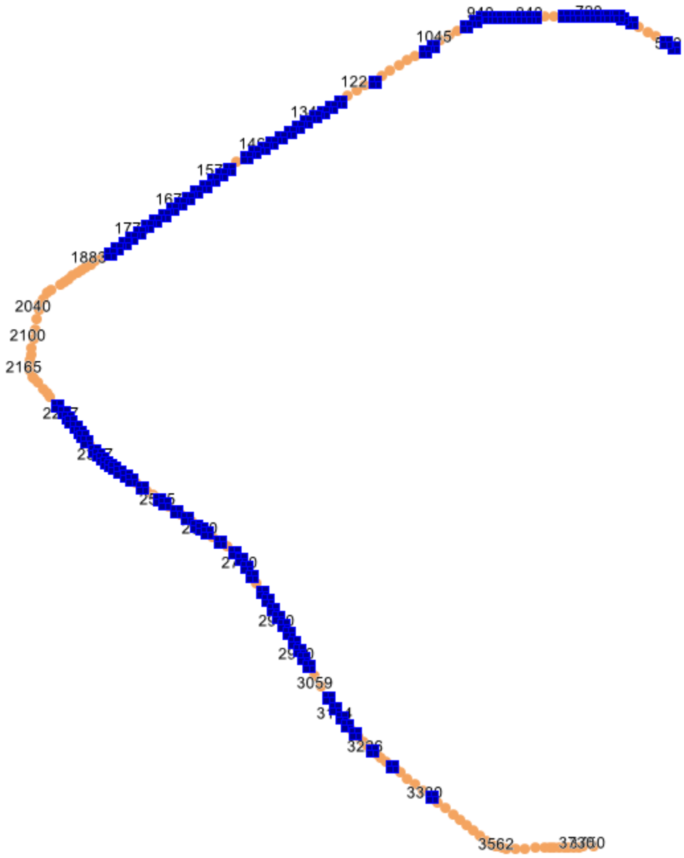


Image 17: Transects that have advanced in 2019 relative to the modelled coastline results

Please see appendix 'Results (RQ 1.2 – 1.4)' for more information.

4.1.3 Research Sub-question 3: Dune Safety

4.1.3.1 Step 1: Historical Dune Safety Assessment

Completing the dune assessment in 1970 with modern hydraulic boundary conditions gave the following results:

Table 6: Summary of historical dune safety assessment at Walcheren

Historical Dune Safety (1970)		
Risk of Dune Breach	Number	Coastline Length (km)
Category A1	39	5.845
Category A2	18	2.990
Category C	93	17.190
Total	150	26.025

62% of the transects within the Walcheren coastline were assessed to be in the low-risk category for flood safety. 38% were high to extreme flood risk.

4.1.3.2 Step 2: Modelled Dune Safety Assessment

Completing the dune safety assessment by modelling a scenario in 2019 gave the following results:

Table 7: Summary of modelled dune safety assessment at Walcheren

Modelled Dune Safety (2019) w/o Sand Nourishments				
Risk of Dune Breach	Linear Model		Natural Log Model	
	Number	Coastline Length (km)	Number	Coastline Length (km)
Category A1	48	7.050	39	5.915
Category A2	19	3.42	18	3.065
Category C	83	15.555	93	17.045
Total	150	26.025	150	26.025

In both model scenarios, coastline length at high to extreme flood risk increased compared to the historical 1970 analysis. The linear model represented the highest number of extreme dune failures and the greatest length of coastline at risk.

Please see appendix 'Results (RQ 1.2 – 1.4)' for more information.

4.1.4 Research Sub-question 4: Cost Comparison

Using the per km dune/dike reinforcement cost data discussed in section 3.1.4 the following data was calculated:

Table 8: New coastline reinforcement costs by safety category

Cost of New Dune & Dike Reinforcements				
Risk of Dune Breach	Linear Model		Natural Log Model	
	Coastline Length (km)	Cost (millions)	Coastline Length (km)	Cost (millions)
Category A1	7.050	€ 111.5	5.915	€ 93.5
Category A2	3.420	€ 43.3	3.065	€ 38.8
Category C	15.555	€ 0.0	17.045	€ 0.00
Total	26.025	€ 154.7	26.025	€ 132.3

These results show that in the absence of sand nourishments, cumulative new costs over the 40-year model period to strengthen the Walcheren coastline would have been €132.3 - €154.7 million. When accounting for the coastal maintenance costs that were needed when sand nourishments were not present of €780,000 / year (see section 2.1), the overall costs of coastal maintenance would have been €31.2 million over the 40-year period.

Table 9: Summary of new coastline maintenance and defence costs

Total Costs w/o Sand Nourishments by 2019		
	Linear Model (millions)	Natural Log Model (millions)
Reinforcement Costs	€ 154.7	€ 132.30
Coastal Maintenance Costs	€ 31.2	€ 31.2
Total	€ 185.9	€ 163.50

This compares to an expenditure of €179.8 million on sand nourishments seen in section 4.1.1.

Please see appendix 'Results (RQ 1.2 – 1.4)' for more information.

4.2 Main Research Question 2

4.2.2 Research Sub-question 1: Location

Selecting an optimal location for a potential mega nourishment throughout the coastline of Walcheren was relatively straightforward and followed a process of elimination. The coast can be divided into two separate stretches – south-west and north-west, separated by the dike at the 'tip' of Walcheren at Westkapelle. The south-western stretch of coastline was eliminated as a possible location for a mega nourishment due to the importance of numerous shipping lanes relatively close to the beaches. These shipping lanes require deep channels running parallel to the coast. It would not be realistic to consider a mega nourishment in this area for this reason.

Image 18: Bathymetry of Walcheren showing deep gully along the south western coastline

The north-west coast was therefore the logical choice for a mega nourishment. Within this section of the coastline, one of the most problematic areas in terms of erosion is the Domburg area. The longshore current travels north-west up the coast where it encounters Domburg. As the coastline is not perfectly straight, and bulges outward slightly, there is greater erosion which has required a significant number of sand nourishments. A mega nourishment located between

Westkapelle and covering Domburg would protect the Domburg coastline and would also allow the longshore current to redistribute sand north-west toward Domburg. Past Domburg, the dunes widen and there has historically been less of a problem with erosion and coastline retreat. This made the coastline stretch between Westkapelle and Domburg the optimal location for such a mega nourishment.

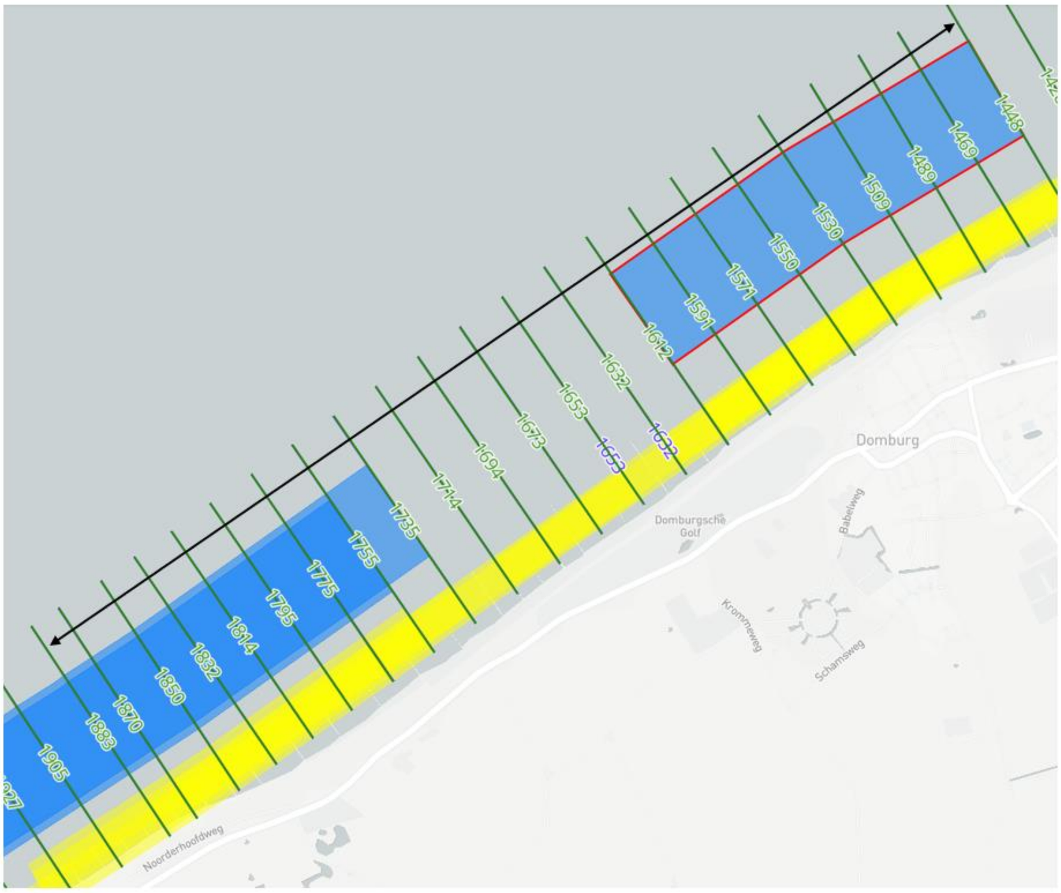


Image 19: Width of proposed mega nourishment between JARKUS transects

The proposed location of the mega nourishment therefore covers the area between transects 14.480 and 18.830 with a length of 3.74km. These specific boundaries were chosen to ‘fill’ the area where the coastline curves slightly inward so that Domburg is protected from the increased longshore current.

4.2.3 Research Sub-question 2: Volume & Design

During the 2000 – 2019 period, the follow sand nourishments were executed in the area between Westkappelle and Domburg:

Table 10: Sand nourishments between Westkapelle & Domburg (2000-2019)

Location	Length	Year	Total Volume	Type	2020 Cost	Euro per m3
Domburg	4770	2000	886,127	Beach	€ 1,808,010	€ 2.04
Westkapelle-Domburg	4200	2004	777,565	Beach	€ 2,408,428	€ 3.10
Domburg	2265	2008	369,565	Beach	€ 1,181,354	€ 3.20
Domburg Strand	1430	2012	250,399	Beach	€ 2,395,357	€ 9.57
Domburg	1430	2014	350,000	Beach	€ 1,306,800	€ 3.73
Domburg	1840	2017	800,000	Foreshore	€ 1,717,716	€ 2.15
Domburg	1840	2019	500,000	Beach	€ 1,961,150	€ 3.92

The total sand volume was 3.9Mm^3 and the total cost was €12.8 million, giving a cost per cubic meter ratio of €3.28 / m^3. Applying the efficiency/economies of scale factor of 15% gives a volume of 4.485Mm^3 available for the mega sand nourishment in this area.

To create a simplified, average coastal profile to cover the mega nourishment area, MorphAn was used to display all the transects contained between 14.480 and 18.830:

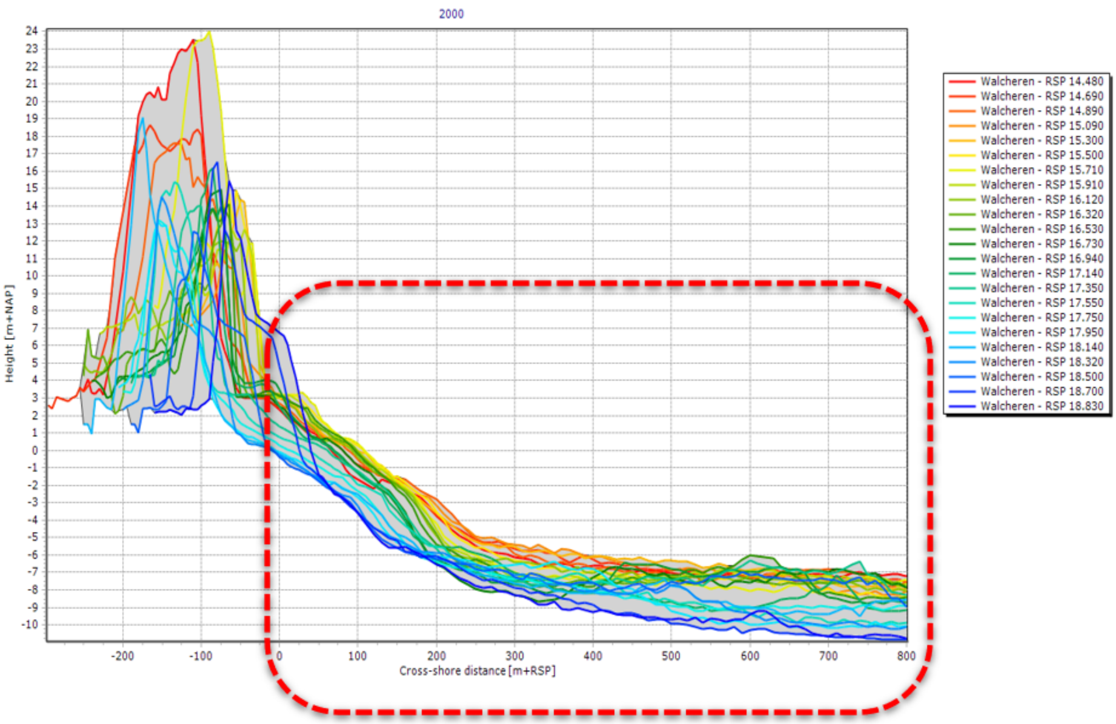


Image 20: JARKUS transects throughout the proposed mega nourishment and the area that was averaged

It can be seen that whilst there is significant variation in the dune position, the beach profile is very similar in this location. The starting point (x coordinate) of the averaged profile was chosen as 0 to disregard the dunes.

Table 11: Coordinates for the averaged JARKUS transect throughout the mega nourishment

Y (m)	**+3.5**	**-1.75**	**-4.75**	**-6.75**	**-7.5**	**-8**	**-8.25**	**-9**	**-9**
X (Msl, m)	**0**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
Y (Low, m)	0	-4	-6.5	-8	-9	-10	-10.5	-11	-11
Y (High, m)	7	+0.5	-3	-5.5	-6	-6	-6	-7	-7

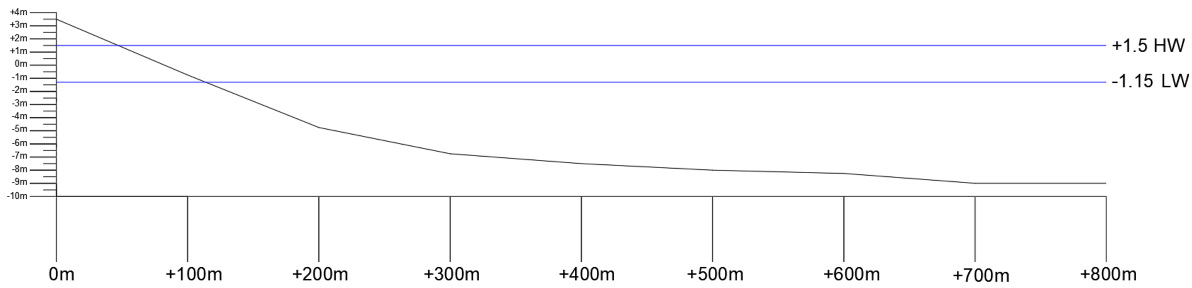


Image 21: Average coastal profile throughout the proposed mega nourishment.

Following the established design parameters (see section 3.2.2), an iterative process was followed to find the mega nourishment of equivalent cost of the individual sand nourishments.

Table 12: Mega nourishment designs with a width of 400m to 275m

Design Number	**1**	**2**	**3**
Coastal Length (km)	4.35	4.35	4.35
Seaward Length (km)	2.75	3.15	3.25
Width (km)	0.4	0.3	0.275
Volume (m3)	8,148,670	5,281,875	4,539,860
% of 2000 - 2019 Cost	182%	118%	101%
Cost (millions)	€ 23.26	€ 15.07	€ 12.96

Table 13: Mega nourishment half-life in three different erosive climates

Half-life of Mega Nourishment			
Design Number / **Longshore Transport Intensity**	**1**	**2**	**3**
10,000	37.0	31.3	29.2
15,000	24.6	20.8	19.4
20,000	18.5	15.6	14.6

Table 14: Change in mega nourishment shape in three different erosive climates

Central Width of Mega Nourishment After 20 Years			
Design Number	**1**	**2**	**3**
Longshore Transport Intensity			
10,000	302.3m	223.3m	202.1m
15,000	267.5m	197.0m	177.9m
20,000	242.2m	178.0m	160.5m

Design number 3, with a seaward width of 275m, was achieved for the same cost as the individual nourishments for period 2000 – 2019. Upon execution, this would have a dry beach width of 137.5m with an intertidal zone 137.5m wide. It would have a half-life of 14.6 – 29.2 years and a width of 160.5 – 202.1m at the central point of the nourishment.

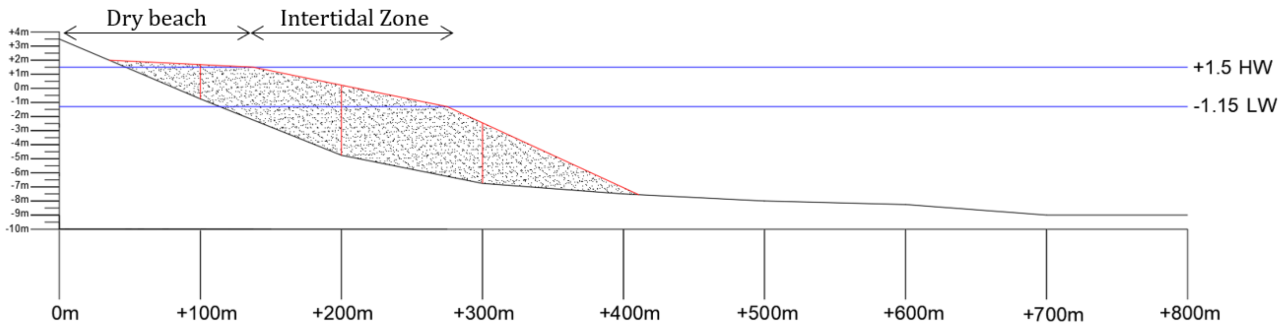


Image 22: Mega nourishment with a width of 275m (Cross-section view)

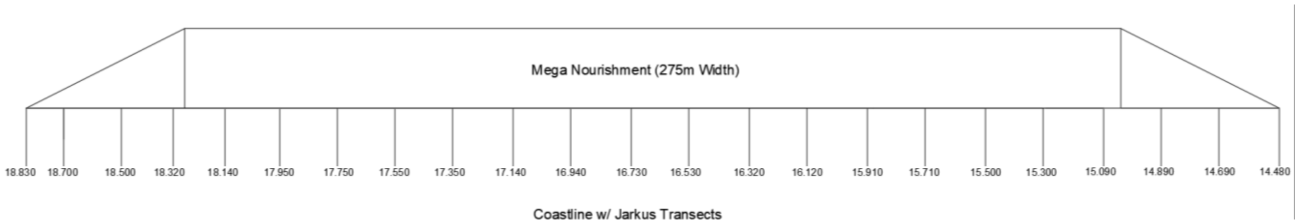


Image 23: Mega nourishment with a width of 275m (Top-down view)

Please see appendix 'Results (RQ 2.2)' for more information.

4.2.4 Research Sub-question 3: Optimal Volume

To achieve a dry beach width of 50m after 20 years (with an overall width of 100m), an iterative approach was again followed. This began with the above 275m wide mega nourishment and continued until the optimal design was found.

Table 15: Mega nourishment designs with a width of 400m to 275m

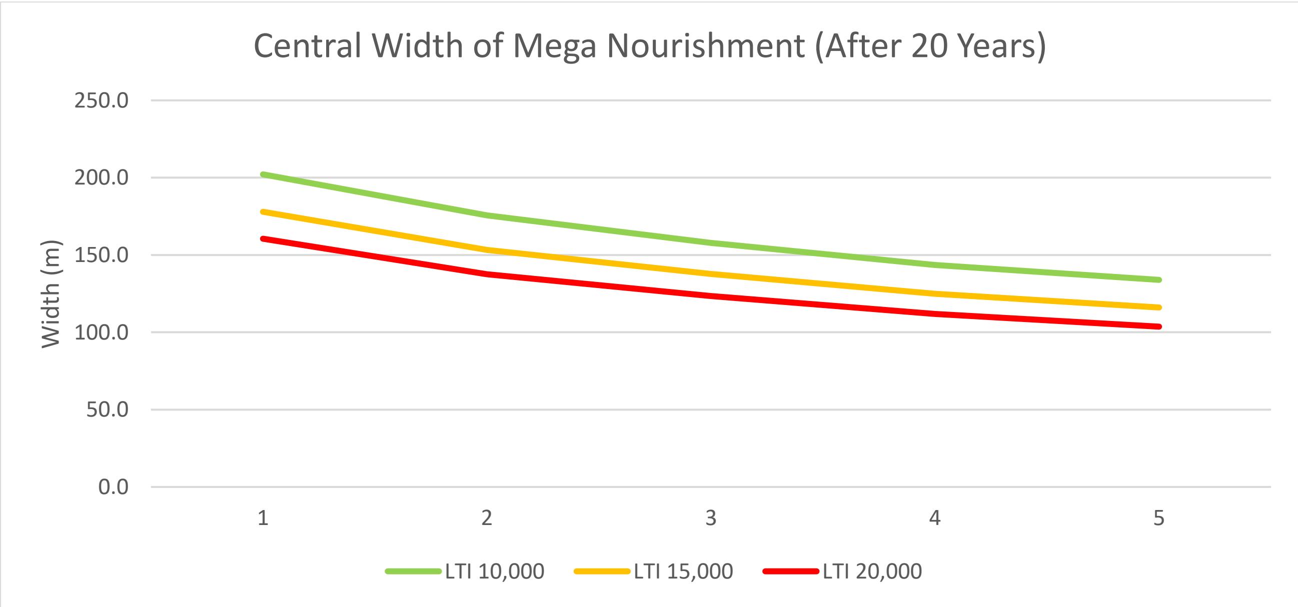
Design Number	1	2	3	4	5
Coastal Length (km)	4.35	4.35	4.35	4.35	4.35
Seaward Length (km)	3.25	3.35	3.45	3.51	3.55
Width (km)	0.275	0.25	0.225	0.21	0.2
Volume (m3)	4,539,860	3,471,545	3,043,950	2,595,765	2,298,110
% of 2000 - 2019 Cost	101%	77%	68%	58%	51%
Cost (millions)	€ 12.96	€ 9.91	€ 8.69	€ 7.41	€ 6.56

Table 16: Mega nourishment half-life in three different erosive climates

Half-life of Mega Nourishment					
Design Number / Longshore Transport Intensity	1	2	3	4	5
10,000	29.2	24.4	23.6	21.5	20.0
15,000	19.4	16.3	15.8	14.4	13.3
20,000	14.6	12.2	11.8	10.8	10.0

Table 17: Change in mega nourishment shape in three different erosive climates

Central Width of Mega Nourishment After 20 Years					
Design Number / Longshore Transport Intensity	1	2	3	4	5
10,000	202.1m	175.6m	157.7m	143.6m	133.9m
15,000	177.9m	153.3m	137.7m	124.9m	116.1m
20,000	160.5m	137.6m	123.5m	111.8m	103.7m



Graph 2: Change in central width in different erosive climates of 5 different mega nourishment designs

The outcome was that design 5, with an original width of 200m, achieved at a central width of 103.7m and a dry beach width of >50m after 20 years in the most severe erosive scenario. This mega nourishment would have been executed at a cost of €6.56 million which represents a saving of €6.24 million relative to the cumulative cost of the individual nourishments in 2000 - 2019. It would have an estimated half-life of 10 – 20 years.

Please see appendix 'Results (RQ 2.3)' for more information.

5. Discussion & Recommendations

5.1 Main Research Question 1: Retrospective Analysis

It is important to discuss the assumptions and methodological basis of the results that were obtained. In order to model a coastal scenario where sand nourishments were not executed at Walcheren, it was necessary to select a time period to act as a source for the trends that existed in the absence of sand nourishments. The very reason that made the island of Walcheren a good location for this analysis also meant that the trend period had to be chosen five decades ago where records and data were incomplete; a high number of sand nourishments have been executed over a 40-year period making it essential to go further back in time. The results obtained are therefore based on those trends in the 1970s even though that dataset is not complete in terms of each coastal profile having the full set of measurements for each year. It would be greatly beneficial to carry out a comparable analysis at a different location in the Netherlands to verify these results. Specifically, a location where a trend period had a complete dataset would allow for greater confidence in the results.

In order to estimate the total cost of sand nourishments at Walcheren, it was necessary to estimate the missing costs from before 2000. This was based on the per nourishment type averages from 2000 onwards. Positive feedback from the local waterboard indicates that this was a sound approach, it is however worth noting that the advances in technology may have affected the results since more sophisticated and efficient dredging vessels are now in use. As a general observation, it is worth noting the scale of the sand nourishment programme at Walcheren throughout the period. A relatively small coastline of approx. 30km has additional sand placed of 1Mm^3/year so it not surprising to see the large impact in the later results.

Similarly, an assumption was made that the 1970s data in the trend period was not affected by sand nourishments as there was only 1 small nourishment of 45,000m^3 executed during that period. The underlying assumption is that the coastal behaviour during this time represents 'natural' coastal trends. This is of course a simplification of the complex and everchanging coastal environment. Many factors such as storm behaviour and human interference such as coastal maintenance could have affected that trend of coastline movement/volume changes.

With regard to the coastline movement results, these show that the majority of transects have advanced due to sand nourishments. This is realistic given the large volumes (approx. 40m^3 million) of sand added in the model period. There does not appear to be a plausible scenario in which any other mechanism could have caused coastline transgression other than sand nourishments. Likewise, there were a small number of transects which regressed during the model period faster than during the trend period. It seems improbable that sand nourishments, which by nature involve adding material to the coast, could have caused a coastline to retreat more rapidly and is likely due to managed coastline retreat.

The coastline position analysis took place on a transect-by-transect basis. Given that the transects are in close proximity (200m – 250m), they would not move independently of each other. In reality there would be an interconnected and dynamic relationship between them which is not reflected in this methodology. This analysis did not contribute to final cost comparison due to the difficulty in quantifying the cost impact of this coastline movement.

The dune safety assessment results showed that a significant amount of dune/dike reinforcement would have been necessary in 1970 to rectify weak links within the coastline when tested against modern hydraulic boundary conditions. This is plausible given the continual strengthening of safety standards throughout the Netherlands in the last 50 years. The methodology used to assess safety was conservative, so this result is likely at the upper bound of what work would genuinely have been necessary. It is however worth emphasising that the coastal defence strategy of the Netherlands is by nature a cautious and conservative one due to the catastrophic consequences of any breach in the coast.

A similar outcome can be seen with the final dune safety assessment. An increase in the length of coastline at risk was observed but particularly in the linear model which models a sandy shore scenario. This indicates significant benefit from sand nourishments. This data was based on erosion trends provided by MorphAn but a limitation of the software is that MorphAn cannot determine where in the profile this annual volume change takes place, so it was assumed to happen evenly through the profile. It would be a beneficial area of investigation to add this functionality into MorphAn so that each coastal profile could more realistically be modelled to reflect the changes year on year.

5.2 Main Research Question 2: Mega Nourishment

Upon selecting a location for the mega nourishment in research sub-question 2.2, it was clear that there are only a small number of locations at Walcheren that would be viable for a mega nourishment due to the deep gully along the south-western coastline. This preliminary analysis would suggest that it is not possible to replace all sand nourishments with larger mega nourishments.

Utilising an equivalent cumulative cost of nourishments in the 2000 - 2019 period would have resulted in a large mega nourishment with a significant expansion of the dry beach and intertidal zone (275m) between the two important tourist towns of Westkapelle and Domburg. This would have had a large central width of 160.5 – 202.1m even after 20 years; not only would this improve tourism but would also protect the Domburg coast from erosion for a long period of time. It is recommended that a more in-depth analysis using Delft3D modelling software is carried out since these results indicate a highly beneficial mega nourishment compared to more frequent nourishments.

Optimising the mega nourishment design further in research sub-question 2.3 shows that large reductions in volume and cost have a smaller impact on half-life and central width that might have been expected. A design with half the cost of the nourishment in sub-question 2.2 still provided a substantial central width of >100m after 20 years even in the most severe erosive climate. This suggest that there is a meaningful opportunity to optimise mega nourishments to deliver better value for money.

The feasibility study and design framework used does not include a methodology to analyse the impact of the mega nourishment on adjacent areas. Given the direction of the longshore current, it is obvious that sand will be transported in a north-west direction and result in higher sedimentation in those areas. It is not possible to quantify that increase in sedimentation in this analysis but logically it would be significant.

An important factor when analysing these results is that the design framework is specifically intended as a straightforward and basic analysis tool. This is very useful given the aforementioned complexity of modelling tools for mega nourishment design but comes with clear drawbacks. As a result, the local erosive climate and environment (such as particle diameter) were not considered and could have affected the results. Delft3D modelling is recommended to more accurately analyse how the mega nourishment would involve in the conditions present between Westkapelle and Domburg.

Whilst the results of the study indicate that it is indeed feasible for a mega nourishment to be executed between Westkapelle and Domburg, it is significant that all the designs involve the mega nourishment and larger beach protruding beyond the 'tip' of Walcheren. This could result in higher-than-expected erosion and reduced mega nourishment life span. It is precisely for this reason that a third, more extreme erosive scenario was included which showed the viability of a mega nourishment with a large half-life of at least 14.6 years.

A significant benefit of the mega nourishment is the protection provided to the coastline protrusion at Domburg which reduces erosion and therefore the sand nourishments that would be necessary. However, it is important to critically assess this benefit during the lifespan of the mega nourishment. It does not seem plausible that the coast at Domburg would be entirely protected throughout the entire lifespan; if only 10-20% of the sand volume remained, it seems likely that the protective effects regarding erosion at Domburg would be small to neglible.

6. Conclusion

6.1 Main Research Question 1: Retrospective Analysis

Sand nourishments have become an important part of the solution and mitigation of coastal erosion, both globally and at the island of Walcheren. The sand nourishment programme at Walcheren has been substantial over the last four decades; over 70 separate nourishments at a cumulative estimated cost of €180 million. It has been difficult to quantify the impact of these nourishments which is why the first part of this thesis is particularly significant.

This thesis has found a clear link between sand nourishments and coastline advance, indicating that sand nourishments are indeed succeeding as part of the Dutch 'hold the line' coastal strategy and increasing coastal resilience by building with nature. Not only did over 70% of the coastal transects advance, they gained on average at least 47.9m. This indicates that not only are sand nourishments preventing erosion but are meaningfully expanding the coastline and the space available in the hinterland.

The analysis also found a connection between sand nourishments and dune safety. By using an evidence-based approach and incorporating a recent dune reinforcement project at Walcheren, it was possible to assess dune safety throughout Walcheren and make reasonable assumptions regarding the level of flood risk. In the absence of sand nourishments, volume trends resulted in a decrease in safety over 40 years and a growing length of the coastline would require dune and dike reinforcement.

The final cost analysis, comparing sand nourishments to 'hard' coastal defences in 1980 – 2019, indicates that the financial costs of the two strategies were broadly comparable when taking into account the additional coastline maintenance that would be needed without sand nourishments. This appears to be a vindication of sand nourishments and the Dutch 'soft were possible, hard where necessary' approach. The overall value of the sand nourishments looks to be very positive as they also advanced most of the coastline substantially, reduced reactive maintenance and increased beach area for recreation.

The conclusion of the first main research question, whether sand nourishments at Walcheren were better value for money relative to dune/dike reinforcement, is that sand nourishments are the more optimal strategy of the two coastal defence methods and should continue to be utilised where feasible.

6.2 Main Research Question 2: Mega Nourishment

In the second part of this thesis, the question of whether sand nourishments at Walcheren can be optimised with larger mega nourishment was considered. This is an important question given the large cost of sand nourishments and the expectation that those costs will grow over the coming decades primarily due to sea level rise.

The initial location analysis found that there is a suitable location between Westkapelle and Domburg for a mega nourishment, but most of the coastline would not support such an approach. This indicates that mega nourishments can, at best, be one component of the coastal defence strategy on the island. It does not seem realistic that a mega nourishment would ever be viable along the south-western stretch of Walcheren given the deep gully and shipping lanes present there.

It is challenging to make a preliminary design of a mega nourishment as a smaller component of the overall thesis. By utilising a design framework, developed by Tonnon et al (2018), the opportunity was present to create a feasibility study for a mega nourishment at Walcheren. Whilst simplified, this design framework is based on more complex modelling of evolution of the the 'sand engine' mega nourishment. It allowed for the design of a mega nourishment which could have been executed between the sea-dike at Westkapelle and Domburg in 2000.

This would have had the same cost as all the sand nourishments executed in this area during 2000 – 2019. The output data (such as half-life & width) regarding the mega nourishment indicate that this would have protected the Domburg coastline and would have substantially reduced the environmental impact of the nourishments whilst increasing beach size. This analysis demonstrates that it may be possible to optimise sand nourishments in this location with one mega nourishment.

The second phase of the feasibility study investigated whether the mega nourishment could be optimised and refined further. By designing to achieve a set half-life and width after 20 years, it was shown that this was indeed possible for half the total cost of the sand nourishments during 2000 – 2019. It is notable that these design parameters were achieved even in the most aggressive erosive climate. This mega nourishment would have saved over €6 million whilst still achieving the goals of the original larger mega nourishment that was twice the cost.

Despite these benefits, it is important to understand the limitations of this analysis. This feasibility study was carried out within the boundaries of the design framework detailed in the theoretical framework. This did not include a specific analysis of the local factors (currents, tide, sand particle diameter, etc) that may have negatively affected the viability of any mega nourishment in this location. As a result, it is not possible to definitively conclude that mega nourishments are a viable alternative to frequent smaller nourishments in this location. Further research and development is necessary to answer this question.

The conclusion of the second research question, whether sand nourishments can be optimised as a mega nourishment, is that at least one location is viable for a mega nourishment at reduced cost relative to individual nourishments.

7 Appendices

Waterboard & Coast Visit: Contains details and photos of a visit to Westduin dune with the local waterboard to discuss coastal maintenance methods.

Method (RQ 1.3 – 1.4): Contains results of dune safety assessment at Westduin prior to dune/dike reinforcement project and safety classification system for research sub-questions 1.3. Also contains cost/km for A1 & A2 categories.

Results (RQ 1.1): Contains historical sand nourishment data for research sub-question 1.1

Results (RQ 1.2 – 1.4): Contains modelling results and cost analysis for research sub-questions 1.2 – 1.4.

Results (RQ 2.2): Contains mega nourishment designs of different widths along with a half-life and central width change over time calculation for research sub-question 2.2.

Results (RQ 2.3): Contains mega nourishment designs of different widths along with a half-life and central width change over time calculation for research sub-question 2.3.

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