# Master thesis

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

*Committee members*

| | |
|---|---|
| Prof. dr. ir. S.G.J. Aarninkhof | Delft University of Technology |
| ir. M. Onderwater | Delft University of Technology, Arcadis |
| Dr. ing. M.Z. Voorendt | Delft University of Technology |

*In collaboration with*

| | |
|---|---|
| H. Lavooij | Initiator, DELTA21 |
| L. Berke | Initiator, DELTA21 |

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department Hydraulic Engineering

Cover Image: Artist Impression Delta21.
Sentinel2 - 10m resolution. 25-07-2019. Credits: European Space Agency (ESA)

*"Water shapes its course according to the nature of the ground over which it flows, the soldier works out his victory in relation to the foe whom he is facing."*

Sun Tzu

# CONTENTS

# PREFACE

This document entails the master thesis "The effects of the Delta21-project on the alongshore sediment transport and erosion". It has been written to fulfil the graduation requirements of the Master Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences, Delft University of Technology.

The idea for this thesis came from a personal interest in the Delta21-project's ambitions and potential. Although the Delta21-project is a never before seen concept with many challenges, I believe thinking outside the box and developing a new mindset can help tackle the challenges of the future, while paving the way to integrated solutions worldwide with its unconventional concept.

Through collaboration with the initiators of the project, an inventory was made of the challenges and unknowns that the Delta21-project still has from which this thesis was then formulated.

This thesis was written in the midst of the corona pandemic, a period in which the work-life balance became disturbed for many and in which remote working and meeting became the norm. Despite this, I worked on this thesis with great enjoyment and gained value experience and knowledge, which I hope to put to good use in my future career. It has shown to me that the field of hydraulic engineering is ever changing and more relevant than before. It has compelled me even more to contribute to this by creating sustainable hydraulic solutions for future generations worldwide.

I would like to thank Thomas Vijverberg (PUMA/Boskalis) for the required bathymetric data of Maasvlakte 2 and his assistance and feedback on all parts Maasvlakte 2 related. Furthermore, I would like to thank my supervisors and committee-members for their guidance and keeping me on the right track. Your feedback was much appreciated into bringing this thesis to a successful end. In specific, I would like to thank my daily supervisor Martijn Onderwater (Arcadis) for his contributions and valuable criticism on my work and report. You could always find the time for a meeting, even in busy times, and your feedback, recommendations and questions kept me engaged, sharp and on point. Lastly, I would like to thank my family and friends for their continued support in bringing this thesis to a good end.

*Delft, August 20, 2021*

# Summary


The Delta21-project is a proposed alternative solution to the increasingly higher risk of flooding in the southwestern delta of the Netherlands. Located at the mouth of the Haringvliet, it has three main ambitions: flood protection, storage of renewable energy and the recovery and preservation of nature. Flood protection is achieved by the installation of high capacity pumps, that pump out water from the rivers towards the sea in the case of a high river level, in combination with a closed storm surge barrier during a severe storm at the North Sea. Storage of renewable energy is accomplished by an artificial lake in which turbines generate renewable energy and the aforementioned pump capacity can empty the water back out to sea. The project does however pose various challenges regarding the local ecology, morphology and coastal maintenance. In this thesis, the impact on the latter is studied. The objective is to study the consequences of this Delta21-project on the alongshore sediment transport and resulting erosion volumes.

Using a sediment transport proxy, the offshore wave climate near Maasvlakte 2 is reduced to 100 representative wave conditions. This reduced wave climate is then transformed to the nearshore by the wave-model SWAN, after which the coastline modelling software UNIBEST-CL+ is used to calculate the alongshore sediment transports and erosion for the coastal profile above NAP -8.0m.

In Model 0, the models are firstly validated to check whether the models are an accurate depiction of the present conditions in the area of Maasvlakte 2. This validation is done by comparing the measured erosion and performed coastal nourishments for Maasvlakte 2 to that of the modelled erosion. This confirms the model's validity and applicability for modelling the effect of the Delta21-project in Model 1. In addition, the implementation of tidal data from an external Delft3D-model is modelled. However, due to the inability of UNIBEST to model the tidal effect above NAP -8.0m accurately based on the available data and model, no conclusive remarks can be given on the effect of this.

In Model 1, the alongshore transports and erosion due to implementation of the Delta21 project are then modelled. The extent and characteristics are summarised as being similar to those found at Maasvlakte 2. This study furthermore shows that the grain size can have a significant impact, with alongshore sediment transports and erosion a factor of 2.5 higher for a grain size of 160 $\mu m$ instead of 370 $\mu m$. A large temporal and spatial uncertainty and variability in wave energy and consequent sediment transport and erosion for Delta21 can be expected, as was also observed for Maasvlakte 2. This leads to a total bandwidth of the estimated erosion for the current design of the Delta21 coastline in between 0.4 and 1.2 million $m^3$/year, for a grain size of 370 $\mu m$.

This study shows that the current layout for the Delta21-project will behave similarly to Maasvlakte 2 in regards to alongshore sediment transport and erosion above NAP -8.0m.

# 1

# INTRODUCTION

## 1.1. AMBITIONS OF THE DELTA21-PROJECT

In July 2021, due to continuous rain, several floods occurred in mid- and northwestern Europe, including the Netherlands. Increased frequency and intensity of extreme weather, caused by climate change, is seen as an important contributing factor. More frequent heavy rainfall causes river discharges to be higher and more extreme *(IPCC, 2021)*. This event showed that continuous steps are therefore required to ensure sufficient flood protection, now and in the future. A recent example is the Room for the River project, which offers high water level protection for the four million inhabitants of the river catchment areas in the Netherlands *(Rijke et al., 2012)*.

The Delta21-project is another proposed plan which can offer a future-proof solution to the flood protection of river catchment areas in the Netherlands. Situated at the Haringvliet, south of Maasvlakte 2, the Delta21-project has three ambitions;

1. **Flood protection.**
   The Delta21-project is an alternative to the continuous reinforcements of the dikes around the main rivers. During high water levels on the rivers, water is pumped out using high capacity pumps, which relieve the stresses on the current dikes and reduce the need for strengthening them.

2. **Energy storage.**
   Electricity is generated by allowing water to flow into an artificial lake through turbines. The available pump capacity is then used to pump this water out to sea again. This creates a 'Green Battery' from the Energy Storage Lake.

3. **Recovery and preservation of nature.**
   The project can also aid in bringing back the original biome to the Haringvliet, with brackish water, tidal waters and the subsequent reintegration and migration of fish species. The plan also allows for the creation of more than 2000 ha of new dune area.

1

## 1.2. FLOOD PROTECTION.

### 1.2.1. MAIN AMBITION

The main goal of the Delta21 is to protect the area around the main rivers from flooding during high water events *(Berke and Lavooij, 2018)*. More than 60% of the Netherlands is below sea level or the high water level of rivers and the possible consequences and risks of flooding are significant *(Jonkman et al., 2008)*. The province Zuid-Holland is of great importance as it is a highly populated and industrialised area and the area that is most at risk of flooding in the Netherlands. Climate change and the subsequent sea level rise, in a scenario of increasing population growth will make the consequences of a potential flood in the future even more severe. *(IPCC, 2013)* Therefore, it is important to continuously reassess the flood risk and protection demands and to maintain our flood defences to meet these new demands.

### 1.2.2. WORKINGS

With the Delta21-project, during a high water event, pumps can be turned on with a capacity of up to 10,000 $\mathrm{m}^3/\mathrm{s}$ and pump water out to sea, lowering the level on the river. The pumps are situated at the westward of the Haringvliet-sluices at the energy-storage lake and pump the water from the Haringvliet estuary to sea. Lowering the water level of the river will decrease the chance of flooding and will decrease the pressure on the dikes. Even in the event of a failure of the Maeslantkering, which is not completely unlikely, the Delta21-project allows for the extraction of a large river discharge during a high water event on the rivers. Furthermore, because of the lower water level on the river and the reduced frequency of closings, the expected lifespan of the Maeslantkering is also increased. *(Vrancken et al., 2008)*

It is estimated that such a pumping event will only occur once every 10 years. To ensure continuity of the pumps however, they should be used regularly, which is why they will also be used to pump water out to sea from the energy-storage lake. This allows for the flow of water inside this lake through turbines, generating electricity.

### 1.2.3. ALTERNATIVE TO DIKE IMPROVEMENT

This project is an alternative to the Delta commission's current plan to strengthen and increase the height of the dikes in this area in the upcoming years *(Berke and Lavooij, 2018)*. The high water levels in rivers is expected to rise as a result of high river discharge and sea level rise and the subsequent consequences are expected to increase. According to the IPCC, the sea level is expected, dependent on the scenario and future greenhouse gas emissions, to rise significantly within the next 100 years. *(IPCC, 2013)* For low-lying countries such as the Netherlands, this will have large impacts in the future protection. Strengthening the dikes accordingly will demand a larger horizontal space, in addition to the large financial investment it requires. The Delta21-project can therefore potentially be a less intrusive and economically more viable alternative for increasing the height of the surrounding dikes, while still complying with the Delta plan requirements and the expected sea level rise in the future.

## 1.3. ENERGY STORAGE.

### 1.3.1. SECOND AMBITION

The second ambition of the Delta21-project is the creation of a 'green battery'. The large pump capacity that is required in high water events will be used to pump water from an artificially created lake out to sea. In this lake the water level can drop and rise significantly, up to 17 meter *(Berke and Lavooij, 2017)*. During low electricity demands and abundance of capacity, the lake will be emptied and water will be pumped out into sea. During high energy demand, seawater will enter the energy lake through turbines, which will generate electricity.

### 1.3.2. RENEWABLE ENERGY STORAGE

Nowadays, there is a energy transition towards the usage of more renewable sources of electricity, such as wind and solar energy. The Dutch government has set a goal to get at least 70 % of its electricity from renewable energy sources and to cut greenhouse gas emissions by 49 % by 2030 and even a 95 % reduction by 2050 compared to 1990 levels *(Ministry of Economic Affairs and Climate Policy, 2019)*. Worldwide agreements have also been made in the Paris accords to combat climate change and to limit the worldwide average temperature increase to 2 degrees Celsius *(IPCC, 2013)*. By meeting the challenges that these renewable energy sources have, such as the grid stability, pumped hydroelectric energy storage can help in this pursuit. Pumped hydroelectric energy storage is one of the most cost effective and environmentally friendly, long-term energy storage solutions currently available. It can storage a large capacity for a low cost per kWh, especially when compared to other methods of energy storage, such as batteries, which are not suitable for the long-term storage of large amount of energy *(Andrijanovits et al., 2012)*. The energy lake can store a large amount of energy, while also providing significant efficiency rates. The renewable energy is stored when the demand is low and the production is high, for example during nighttime. It can then 'release' this energy through turbines when the demand is high and the production is low, e.g. during a day with low wind and solar energy.

### 1.3.3. ENERGY GENERATION

Not only can energy be stored by means of a pumped hydroelectric energy storage, but the vast area of the energy lake can also be used to generate electricity in the form of a floating solar park, in which the water surface area of the lake is used to generate electricity *(Berke and Lavooij, 2017)*. Furthermore, wind turbines can be placed on and around the dune area to generate wind energy. Finally, tidal energy can be generated by placing tidal turbines in the inlets. The estimated total pumped hydroelectric energy storage in the energy lake is 1.8 GW, while the floating solar- and wind park have an electricity generation of 1.2 GW and 3.0 GW respectively *(Berke and Lavooij, 2017)*.

1


Figure 1.1: Delta21 project and its parts. Image: Sentinel2 - 10m resolution. 25-07-2019. Credits: European Space Agency (ESA)

## 1.4. RECOVERY & PRESERVATION OF NATURE.

### 1.4.1. THIRD AMBITION

The third main ambition of the Delta21-project is the recovery and preservation of nature, most notably by the return of the unique brackish water biotope, that used to be present in the area *(Berke and Lavooij, 2018)*. Additionally, there are ecological opportunities for the creation of nature.

### 1.4.2. BRACKISH WATER BIOTOPE & KIERBESLUIT

The desire to return the brackish water biotope to the Haringvliet has been present for many decades. The construction of the Haringvliet sluices in 1970 has made the Haringvliet a fresh water-body and limited the interaction with the North Sea. This created a barrier for many migratory fish species, such as salmon and trout. In 2013 a plan was made to open the sluices and since 2018 the 'Kierbesluit' has been in effect, in which the Haringvliet-sluices open for the entry of seawater during high river water levels. The amount of salt intrusion is monitored, such that the freshwater dependency for the water-inlets is still maintained. The Delta21-project will maintain this interaction with the sea and the subsequent intrusion of salt. *(de Vriend et al., 2015)*

### 1.4.3. BUILDING WITH NATURE

The ambition for Delta21 is to integrate these three main ambitions with the Building with Nature principle *(Berke and Lavooij, 2018)*. This is a fairly new principle which stands for working and building *with* nature, instead of building *in* nature. Hard solutions or hydraulic structures and reactive engineering are avoided and approached by pro-actively integrating ecology and ecosystem services into the design of more sustainable hydraulic structures *(Borsje et al., 2011)*. With the Delta21 plan, the desire is to use nature-based solutions to deal with the threat of floods, waves and sea level rise. These solutions provide a more sustainable and adaptable approach in which natural processes and materials are used and anthropogenic impacts on ecosystems are minimised or even enhanced *(de Boer et al., 2019)*.

### 1.4.4. ECOLOGICAL OPPORTUNITIES

Opportunities for aqua culture and ecotourism are also present. Due to the new interaction with the North Sea, the salt intrusion and the presence of the tidal lake, oysters, mussels and seaweeds can be grown *(de Boer et al., 2019)*. Although nature is lost with the construction of the Delta21 plan, a net increase in flora and fauna due to the presence of the tidal lake and the created dune area can be achieved, which would lead to an increase in ecotourism in the area. Although is it hard to estimate the social and ecological of this project, there is an opportunity to increase the combination of ecological functions with the construction of the Delta21-plan.

### 1.4.5. NATURA 2000

It is important to note that the location of the Delta21-project is in the midst of a Natura 2000 area, an area assigned by the European Union as a protected environment for flora and fauna that are threatened and for which its living environment needs protection

*(Commission, 2007)*. This area stretches from Maasvlakte 2 along the Dutch coast to around halfway the island Walcheren and was the first Natura 2000 area established in the Dutch North Sea. It is an important seabed protection area and resting area for many wildlife species.

The Natura 2000 areas are part of the EU policy for biodiversity, to create a establishment of a marine network of conservation areas that contribute or halt the loss of biodiversity in the EU *(European Commission, 2000)*. In particular for offshore marine environments, the number of Natura 2000 sites is low. The nature compensation that was developed for the construction of Maasvlakte 2 was not limited to the creation of new nature by the realisation of 25.000 ha of marine reserve and 35 ha of new dunes. In addition, the strengthening and improving of the quality of existing nature in the Voordelta, such as the creation of resting areas for birds and seals and the exclusion of fishing activities in the area was part of this nature compensation. *(van Leeuwen, 2009)*.

It is vital to understand the consequences of the Delta21-project for the flora and fauna of the current Natura 2000 area. An extensive research should be performed, as has been done for the consequences of Maasvlakte 2. The nature area in which the Delta21-project lies has been strengthened and improved as compensation for Maasvlakte 2, but this compensation will be lost upon Delta21's construction. Maasvlakte 2 has only recently been executed and many natural values and bio-topes have yet to be developed completely. Therefore, the recovery and preservation of nature is one of the major issues that has to be tackled. Currently, numerous research groups are already investigating the ecological effects of the project in the area. In this research, ecological effects will only be lightly touched.

## 1.5. LESSONS FROM MAASVLAKTE 2

Leading up to the construction of Maasvlakte 1, several human interventions have already been made in order to provide flood protection, reduce the salt intrusion of the sea on the fresh water bodies or facilitate the construction of Maasvlakte 1, such as the closure of the Brielse Maas and Brielse Gat. All these human interventions have changed the morphology of the area, the river and the way tides and waves interact with the area. For stakeholders such as Rijkswaterstaat, the city of Rotterdam and the Port of Rotterdam, it is vital to know whether the Delta21-project will have a positive or negative impact on its operations at Maasvlakte 2. While in the past, these impacts were investigated by physical scale models, nowadays these impacts are primarily researched using numerical models. It can be expected that the Delta21 will impact Maasvlakte 2 due to its scale and close proximity. Therefore in this thesis, an emphasis is given to Delta21 itself and the effect it will have on Maasvlakte 2, primarily at the north-western side.

### 1.5.1. BEACHES AND SOFT SEA DEFENCE

It is to be expected that the Delta21-project will also have a large impact on the existing beaches and soft sea defence of Maasvlakte 2, which protect the local south and west region of Maasvlakte 2 and in addition provide recreation for the region.

A large section of these beaches, in particular those at the south and west part of Maasvlakte 2, will be cut-off from direct interaction with the North sea. Instead, the dunes at this area will now be part of the dune-row that circumferences the Energy Storage Lake (ESL). Due to this, the dunes are now subjected to the rising water levels of the ESL, which imposes different criteria on the dunes and the sea level defence. The difference in water level is higher, but the hydrodynamic forcing is lower due to decreased interaction with the North Sea and a relatively small fetch on the ESL itself. The consequences of this cut-off and the subsequent rapid draw down of the water level on the existing dunes and beaches have been studied in a previous study. *(Van Adrichem, 2021)*

Another coastline section is situated between the hard coastal defence in the north connection of Delta21 further south. The length of this is dependent on the exact attachment point of the Delta21 dunes to Maasvlakte 2. This coastline section will maintain its interaction with the North-Sea and is not directly linked to the ESL. It is however heavily influenced by the sheltering function of the dune-row that forms the ESL and the subsequent altered tides and waves that it causes. Since this section is the main and only protection at the western part of Maasvlakte 2, it is vital to know their response to the Delta21-project. If the altered hydrodynamic forces caused by the Delta21-project have a negative effect on the area, such as stronger currents, steeper slopes of the beach or even major erosion, this could impact the beaches and dunes present at this location. This threatens the flood protective- and recreative functioning of the present beach and dunes and will therefore need to be studied.

At the western bend of Maasvlakte 2, the formation of large-scale scour is present. With the development of Maasvlakte 2, scour was expected and calculated, but appeared to be smaller in practise than previously anticipated, due to artefacts in the fmodel concepts applied, such as the absence of armouring effects and clay sub-layers *(S. Boer, Roelvink, et al., 2006)*. The effects of large scale scour are important, since they can have environmental impacts, such as habitat loss and reduction of feeding areas, but it can also cause erosion of the coastal profile, beaches and dunes present at Maasvlakte 2. Furthermore, the Maasgeul can experience sedimentation due to sand originating from a nearby scour hole.

### 1.5.2. HARD SEA DEFENCE

The most northern stretch of coastal defence present at Maasvlakte 2 is a hard sea defence. Here, large concrete cubes weighing up to 40 tonnes have been placed in front of a cobble beach over a length of almost 3.5 kilometre. This more northern area is subjected to closely passing vessels calling the Port of Rotterdam and as such a smaller footprint was needed than what a soft defence option requires. These cubes, combined with the cobble stone beach , protect the northern section of the Maasvlakte 2. The cube reef dissipates and absorbs a large section of the wave energy and limits the wave energy acting on the cobble stone beach. The cubes are placed in front of the beach in the breaker zone and as such create an area between the cubes and the dunes, a so called 'lagoon'. This lagoon is expected to fill up with sand over the course of time, causing a sand fill-in on the cobble beach and a more seaward directed sediment transport, which negatively impacts the dune stability. Furthermore, there is a dam in between the transition of soft- to hard defence, perpendicular to the coast. The function of this dam is to prevent sediment transport northward from the soft sea defence in the south *(Mann, 2019)*.

It is important that the presence of the Delta21-project does not negatively impact this hard sea defence, whether it is the cube reef, the cobble stone beach or increase the process of sand deposition inside the artificial lagoon. If any of these processes is to be severely altered, there can be consequences for the flood safety risk of Maasvlakte 2. Is it therefore important to research what the effect of the Delta21-project will be on the hydrodynamic forcing and subsequent sediment regime at this area.

## 1.6. RESEARCH AREA

The research area for this thesis is shown in Figure 1.2. This research area is chosen such that the entire current hard- and soft coastal defence of Maasvlakte 2 is included. This way, the occurring processes along the entire coastal defence of Maasvlakte 2 can be better understood and applied to the Delta21 project. For Delta21, the entire northern section will be modelled, from the connection to Maasvlakte 2 in the north to the location of the pumping stations in the south.

Figure 1.2: The research area of this thesis. The current soft sea defence of Maasvlakte 2 in red, the current hard sea defence in yellow and the to be researched soft sea defence of Delta21 in green.

## 1.7. PREVIOUS DELTA21 STUDIES

Studies regarding the morphological impact or change in hydrodynamics of the project have already been done or are currently in execution by various students. These studies focused mainly on the southern part or ebb-tidal area of the area that is affected by the Delta-project. The Haringvliet mouth response on the Delta21-project was studied using a long-term morphodynamic 2DH computational simulation using Delft3D-FLOW and Delft3D-WAVE *(Zaldivar Piña, 2020)*. The initial morphodynamic changes of the Voordelta were studied with a short-term morphostatic 2DH computational model in Delft3D *(IJntema, 2021)*. In another study, the design of the Delta21-layout was improved by analysing the large scale morphological development caused by tidal currents and the coastline deformation induced by tidal- and wave motions *(Li, 2020)*. The study performed in this thesis continues to build on these previous studies and provides a more accurate quantitative analysis of the erosion due to the wave-induced alongshore sediment transport.

## 1.8. PROBLEM ANALYSIS

### 1.8.1. CHANGING DELTA

The south-western delta of the Netherlands is an ever-changing delta, with high flow rates and large sediment outputs due to the main rivers that flow through the Netherlands. The Western-Schelde, Grevelingen and Haringvliet that are part of the south western delta allow for large deposition of sediments into the sea, while the currents and waves distribute these sediments across the Dutch coastline. The majority of the Netherlands is shaped due to the rivers that have deposited their sediments over the course of many millennia. In recent years, man-made interventions, mostly for the purpose of flood protection, have severely altered these tidal deltas, with large consequences on the natural state. Ecological problems with fresh water intrusion and the decline of native aquatic species are already occurring in the Haringvliet estuary. It can be expected that the Delta21-project will affect the ebb-tidal delta of the Haringvliet significantly and studies by several students have already shown this. Due to the opening of the Haringvliet sluices and the construction of the tidal lake the inter-tidal interaction and tidal prism changes significantly, which will have large effects. A new flood-ebb tidal delta will also be created *(IJntema; Zaldivar Piña, 2021; 2020)*, however this is outside the scope of this report and more over this can be read in the respectively studies.

### 1.8.2. MORPHOLOGICAL IMPACT

The Delta21-project is a large scale project and as such will have a large impact on its surroundings. Ecological changes, such as the increased interaction with the sea and the creation of the tidal lake and dune area will change the flora and fauna present in the area. Due to changes in tidal flows, currents and waves, sediment transport and local morphology of the nearby coastline as well as the current delta and estuary can change. In certain areas, such as around the inlets of the tidal- and energy-storage lakes, a higher water velocity can be expected due to the water flow contraction through a confined area, which would result in higher levels of erosion. The construction of the Delta21-project should therefore not negatively impact the sediment balance around Maasvlakte 2. It is important to understand these changes, so that any negative impacts can be found in an early stage and potential solving or mitigation can be performed.

Furthermore, the somewhat extruding shape and the location of the Delta21-project will also have several effects, as it will alter the waves and squeeze tidal currents. This can have impacts on the nearby coasts, especially the Delta directly south of the Delta21-project and the Maasvlakte 2 area north of the area. Due to the location of the Delta21-project south of Maasvlakte 2, waves from the south-western direction will come into contact with the tidal- and energy-storage lake first thus completely encapsulating that side of Maasvlakte 2. Waves from a more north-eastern direction can no longer reach the Haringvliet estuary, as this is also sheltered by the Delta21-project. These effects have already been somewhat investigated in previous studies performed by various students working on the Delta21-project.

## 1.9. PROBLEM STATEMENT

In conclusion, the proposed Delta21-project can permanently change the hydrodynamics and morphodynamics in the Dutch south-western delta, and the Haringvliet estuary in particular. On a large scale, the extruded shape of the Delta21-layout will cause tidal contraction, leading to higher tidal velocities and scour in the western bend. At a more local scale, this development will lead to a change in sediment transports and erosion, and ultimately can lead to economical, ecological and flood safety concerns.

This study therefore aims to give more insight on the initial local effects of the changed hydrodynamics and morphology on the wave-induced sediment transport and the subsequent erosion that the Delta21-project will cause in the research area for the near future.

# 2
# Objective and research questions

## 2.1. Objective

The objective of this thesis is to determine and quantify the initial expected behaviour of the alongshore sediment transport and the maintenance requirements in response to the construction of the Delta21 project, based on the observations and measurements that have been made for the soft sea defence at Maasvlakte 2. It is of importance to research this, as the project can potentially have a large (negative) impact on its surroundings. For example, the hydrodynamics and morphology of Maasvlakte 2 can be affected, with subsequently a change in its maintenance requirements. Stakeholders of the project, such as PUMA and the Port of Rotterdam, would therefore interested in the results regarding flood safety, reduced port access and increased yearly maintenance costs. As previously stated, due to the close proximity and similar characteristics, the expectation is that the Delta21 will behave similarly to Maasvlakte 2. The initial hypothesis, or default position, therefore is that the Delta21 project will show similar alongshore transport behaviour and maintenance requirements in comparison to Maasvlakte 2.

The null hypothesis for this research proposal is therefore formulated as follows:

*"The DELTA21-project will have alongshore sediment transports characteristics and maintenance behaviour comparative to Maasvlakte 2."*

## 2.2. RESEARCH QUESTIONS

To test this hypothesis and verify whether or not the DELTA21-project will indeed show comparative behaviour, the following research question is formulated, with sub-questions to help answer this.

The main research question for this research proposal is as follows:

---

**What is the expected alongshore sediment transport and erosion for the soft sea defence of Delta21, based on the knowledge of Maasvlakte 2?**

---

To help answer this, the following sub-questions have been formulated:

1. What were the modelled and measured alongshore sediment transport and coastal erosion for Maasvlakte 2?
2. How have the bathymetry and coastal profile of Maasvlakte 2 changed over time?
3. What are the wave- and tidal characteristics in the research area and what is the expected variability?
4. What is the expected alongshore transport and erosion for the Delta21 coastline?
5. What is the influence of the sediment characteristics and the proposed usage of sediment from the Energy Storage Lake (ESL) for the coastal defense around the ESL?

# 3

# METHODOLOGY

## 3.1. INTRODUCTION

In this chapter, the planned methodology of this study will be explained by providing a contextual framework and theoretical perspective to determine which set of methods will be applied to the research questions at hand. As previously stated, this thesis' approach can be differentiated in a part done by a literature and site study and a part done by numerical modelling. The site study is mostly a quantitative data selection and -collection process of the current situation to gain understanding of the system at Maasvlakte 2 and to meet the data-requirements to run the numerical model, while the modelling will give an understanding into the various effects that are present at Maasvlakte 2 and that the DELTA21-project will have on the hydrodynamics, sediment balances and -transports and the required maintenance.

## 3.2. RESEARCH APPROACH

For answering, each of the sub-questions require a different approach. While some can be answered by the site or literature study, others can only be answered using the results from numerical models. In Figure 3.1, the research approach for each research question is presented.

The first three research questions will mostly be answered with the literature or site study for Maasvlakte 2 and creates an inventory of the present boundary conditions, while the remainder must be answered with the help of wave modelling software and coastline modelling software.

## 3.3. LITERATURE STUDY AND DATA HANDLING

### 3.3.1. THESIS OUTLINE

The site study aims to answer the questions which are regarding the 'what', 'where' and 'how' currently at Maasvlakte 2. The current characteristics of the maintenance requirements at Maasvlakte 2 and what the current parameters are in the area is performed as a site study.

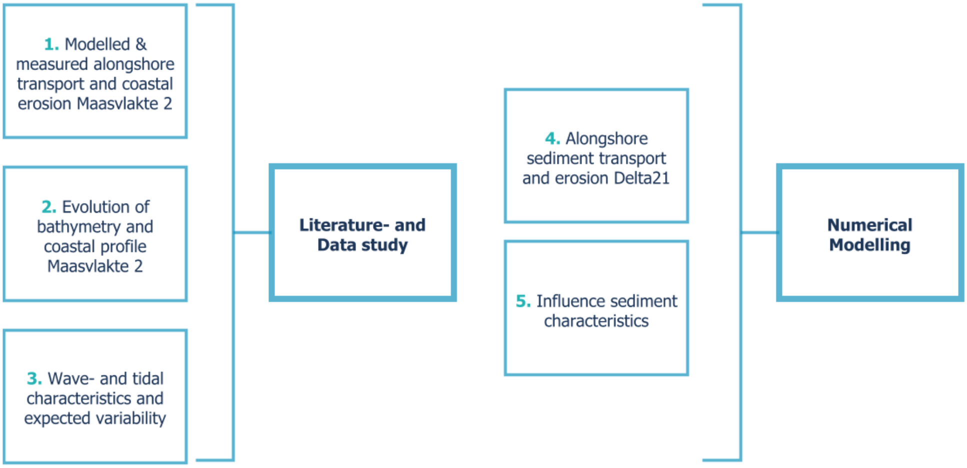



Figure 3.1: Differentiation of the research approach for the research questions.

The literature study will consist of using public-domain sources such as research papers, technical reports, articles and guidelines specific for the research area. Understanding is gained about the maintenance requirements for Maasvlakte 2, the actual performed maintenance and the variation in sand losses and maintenance, both temporally and spatially. This information is used for calibrating numerical models. This information will be mostly obtained from sources such as PUMA (Project Uitvoering MAasvlakte), Rijkswaterstaat and public sources such as the Dutch national weather service.

The site study is furthermore required for creating a more clear understanding of the hydrodynamic and morphodynamic processes that cause the need for coastal maintenance, in specific those responsible for the behaviour at the nearshore and beach above -8m NAP along Maasvlakte 2. In addition, the data regarding these parameters will be gathered and processed. The current hydrodynamic-, morphodynamic- and meteorological data, valid for the research area, are included in the site study. This is used as a reference point to which the modelled data can later be compared with and validated to. The gathered information will be used to identify and focus on certain processes which are of most influence on the hydrodynamics and maintenance requirements, e.g. sediment characteristics. The impact of Delta21 on these maintenance requirements is then assessed with use of the calibrated and validated numerical modelling tools.

It is important that the obtained data is actual, reliable and if applicable; calibrated for the research area. To save computing time in the execution of the models, certain data will have to be reduced, such as the wave climate. The basis for this is that the modelled sediment transport is as accurately portrayed as reality, given the time constraints. To achieve this, input reduction (IR) techniques will be used.

Finally, an attempt is made for the flaws, assumptions and acknowledgements of the data and methods to be accounted for in every step of the study. Missing or lacking data will be reported accordingly to produce a transparent study.

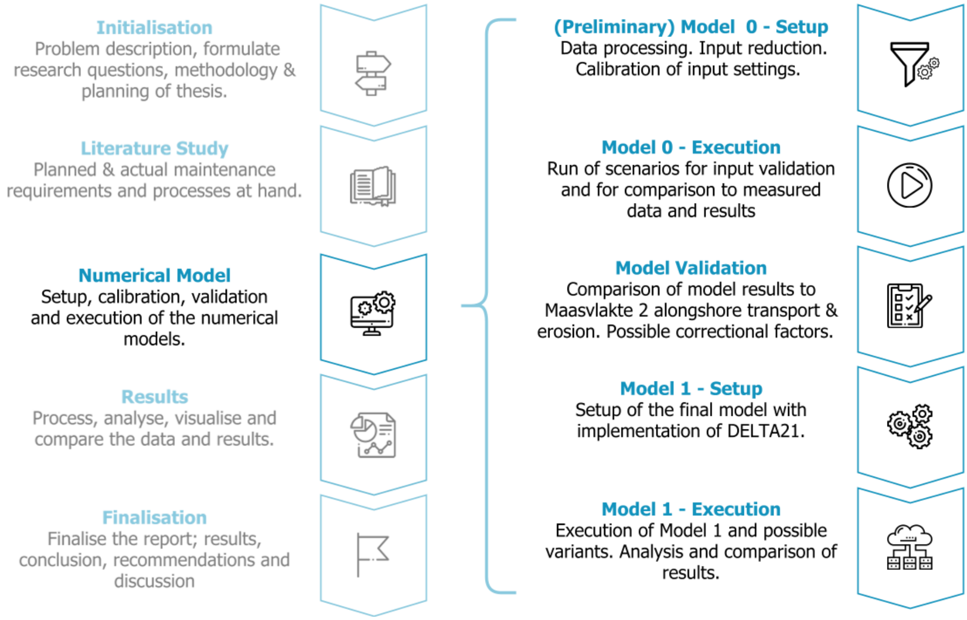



Figure 3.2: Outline of the modelling-approach. This process is iterative.



### 3.3.2. NUMERICAL MODELLING

In this section the process of setting up the models is explained. The general outline can be seen in Figure 3.2. In Section 3.2 it is clarified that the numerical model is used to answer a large portion of the research questions and will require the largest investment, resource- and time wise, of this thesis. Setting up the model accurately, executing it timely and efficiently is a task best done meticulously. This ensures an accurate model and prevents errors from propagating into the next model and influencing the results.

To choose the models best suited for this study, a closer look needs to be made at the research problems and -objectives, the spatial and temporal scales that are required. Since not all processes can and will be studied, emphasis is put on the processes that affect the alongshore sediment transport and erosion above -8m NAP. The majority of the research questions must be answered by models that simulate flows, waves and alongshore sediment transport.

For an accurate depiction and modelling of the waves and how they will transform towards the nearshore, SWAN will be used. SWAN is a wave model that can provide realistic estimates for wave parameters at the nearshore. SWAN will be used to model the transition of offshore waves to nearshore, which in turn is used as an input for the coastline modelling model. This choice for wave-modelling with SWAN is made, since it has been conceived to be a computationally viable wave model for waves in shallow water with low return times on a personal computer *(Booij et al., 1996)*.

UNIBEST, a coastline modelling software best suitable for the larger temporal- and spatial scale modelling then simulates the coastal response based on alongshore transport gradients. In the case of the SWAN and UNIBEST models, these will be set up specifically for this study. A Delft-3D model previously executed by other students on the Delta21-project will primarily be used for the data acquisition of modelled tidal currents and water elevations. The choice for UNIBEST-CL+ is made since it is shown to be a versatile, readily-available and user-friendly tool capable of modelling a wide range of coastal problems on the basis of many combinations of wave- and tidal conditions *(Deltares, 2011)*.

Two of the distinctive models will require setup and execution; SWAN and UNIBEST. The Delft3D-model will not be set up, but merely the output will be used as input for the other models. The SWAN and UNIBEST models will be built from scratch, as no readily available, reliable, high accuracy model has been set up yet for this area yet. A model is however still a simplification of a real problem and the results of the models should be interpreted as such. Not all aspects can and will be taken into account in the models.

### 3.3.3. DATA PROCESSING AND PREPARING

The first step before setting up the numerical model is to analyse, process and the collected data appropriate for usage for modelling. Certain data, such as bathymetric-, wave- and tidal data will need to be made suitable for the specific research area that is going to be investigated. This needs to be done carefully, as any mistake here can cause the model to fail and the results to be inaccurate or invalid.

### 3.3.4. MODEL ACCURACY

For UNIBEST, accurate wave data specified for each output location is needed. This data will come from the SWAN model. The following alterations and settings for the models are suggested, for the purpose of having a higher accuracy and more robust model:

- A review of the wave input reduction (IR) technique used. The IR-method in the used Delft3D-model is that of largest contribution based on CERC sediment transport formula. A preferred method is that of groups with equal contribution instead of equal bins. Alongshore sediment transport, especially at the near-shore, is also more accurately simulated using a wider range of reduced wave conditions. An higher directional resolution in the form of increased bins for the wave directions bins can help in the pursuit of higher accuracy *(de Queiroz et al., 2019)*.
- A higher spatial resolution. For the SWAN model, this is conveyed as the usage of nested-grids. The total calculative area will be smaller and coarser outside the research area, especially in the region in the south and at the Voordelta, as this region will have a lower impact on waves affecting the sediment transports at Maasvlakte 2. A finer grid will be made specifically at the research area. This will provide a higher resolution and accuracy for the nearshore. For UNIBEST, a higher spatial resolution is achieved by having a large number of output locations and rays, each with their distinctive wave- and tidal conditions based on coastal orientation, bathymetry and sheltering effects.

### 3.3.5. MODEL VALIDATION AND CALIBRATION

The numerical models used will need validation that it is an accurate representation of reality and the conditions present at Maasvlakte 2. For this, Model 0 is validated using

available data to see how and to what extent it matches. The Delft3D model used has already been validated on several keys points, mostly in terms of the hydrodynamics present in the area. However, the modelled sedimentation has not been verified yet, although this is a difficult task. The currents and water levels in the Delft3D model used have been validated at the measuring station at Hoek van Holland.
In this study, an effort is done to also validate the used models. For this, the following validations will be performed to validate the SWAN or UNIBEST Model 0 at Maasvlakte 2.



1. Validation of the SWAN Model 0 by means of comparison to the available nearshore wave data at Maasvlakte 2.
2. Validation of the Model 0 erosion volumes by UNIBEST can be achieved by comparing these results with the erosion- and nourishment volumes that have been measured and applied at Maasvlakte 2.
3. The erosion and sedimentation volumes that occur at the nearshore and beach at Maasvlakte 2 can be validated with the bathymetric data available from the interpolation of these XYZ-values. For each calculative area these volume changes can then be compared.

A more detailed overview of the model execution and model interfaces can be found in Figure 3.3.

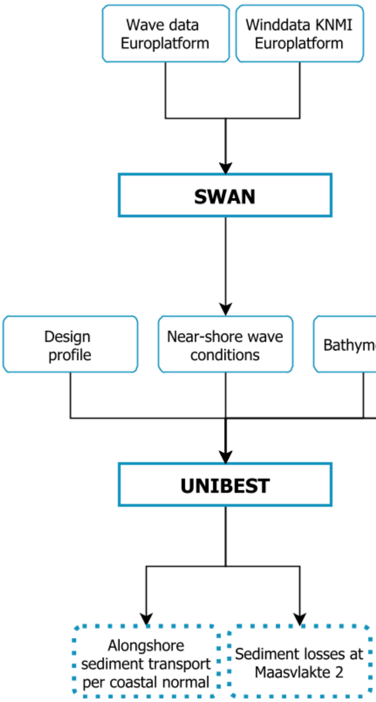



Figure 3.3: Model setup and interfaces of the wave modelling (SWAN), coastline modelling (UNIBEST) and external Delft3D model.

# 4

# PREVIOUS MAASVLAKTE 2 STUDIES

## 4.1. INTRODUCTION

In this chapter, a literature study is performed and a closer look is taken at the historical studies and models performed for the longshore transport and subsequent erosion at Maasvlakte 2. For this, previously executed models and reports are studied and compared. The important parameters for the coastal maintenance and the modelled and actual performed coastal maintenance can also be obtained. This is then used as basis for, and as comparison to, the numerical modelling, such as the previously modelled influence of the sediment characteristics for Maasvlakte 2 in comparison to that for Delta21.

## 4.2. DESIGN PROFILE

The design profile for the land reclamation of Maasvlakte 2 was based on the natural profile, found along the nearby coast *(S. Boer and Roukema, 2004)*.

- Between NAP +3m - NAP +1m > 1:25
- Between NAP +1m - NAP -1m > 1:50
- Between NAP -1m - NAP -5m > 1:75
- Between NAP -5m - NAP -10m > 1:75 - 1:150 (varying profile)
- Below NAP -10m > 1:20 to local depth

During the modelling for the determination of the coastal maintenance of Maasvlakte 2, in trans-lateral direction, the lower border was set at NAP -8m. This is a middle way between maintenance of the entire coastal zone and maintenance of the shallow zone *(Steijn, 2000)*. For determination of the coastal maintenance of Maasvlakte 2, the potential erosion due to tidal contraction at the toe of the nourishment-profile was not taken into account in the UNIBEST modelling, as this was outside of the extent. For this reason, the area below NAP -8m will also not be taken into account in this study, as no good validation and comparison of the model results can be made. The cross shore wave-induced sediment transport for the Maasvlakte 2 coast has been determined in different studies and sensitivity analysis. It was concluded that in almost all cases there was a cross-shore sediment transport towards the coast for a $D_{50}$ of 285 $\mu m$ *(Steijn, 2002)*. In the sensitivity analysis there was a large spread in the quantities of the cross-shore transports, up to a factor of 3, dependent on the used grain size. The alongshore transport transports are dominant over the cross-shore transports and, similarly to the calculations for Maasvlakte 2, these were not taken into consideration. Additionally, it is important to mention the modelling for coastal profile developments and cross-shore transport processes still incur in great uncertainties. For this study, the focus is therefore solely on the alongshore sediment transports.

## 4.3. SEDIMENT CHARACTERISTICS AND INFLUENCE

4

The grain size has shown to play a major role for the maintenance of Maasvlakte 2. *(Boer, 2004)* concluded that the usage of finer materials, <285 $\mu m$, will increase the effect that the cross-shore transport will have on the sand losses. It was furthermore calculated that when a grain size $D_{50}$ of 200 $\mu m$ was used instead of 285 $\mu m$, the alongshore transport would increase by a factor of 1.7-2.1. For a grain size $D_{50}$ of 160 $\mu m$ the factor would increase up to 2.0-2.5 *(Steijn, 2000)*. This increased transport can also be deduced when looking at the influence of the grain sizes in the different sediment formulae *(Van De Graaff and Van Overeem, 1979)*. During the design-phase of Maasvlakte 2,it was advised that the coastal maintenance of the soft sea defence was best performed with sand of the same grain size ($D_{50} = 285 \mu m$), as used during construction *(S. Boer and Roukema, 2004)*.

*(Steijn, 2000)* furthermore found that the grain size heavily influences the cross-shore sediment transport for Maasvlakte 2. Calculations for the cross-shore transports showed almost twice as high yearly-averaged sediment transport for a $D_{50}$ of 160 $\mu m$ compared to a $D_{50}$ of 200 $\mu m$. From the sensitivity-analysis it was shown that, with a grain size $D_{50} = 285 \mu m$, the cross-shore sediment transport was directed landward for most cases *(Steijn, 2002)*.The contribution of the alongshore sediment transport to the sediment losses is dominant compared to the cross-shore transport. This has led to the decision that for the original modelling of the coastal maintenance for $D_{50} = 285 \mu m$, the cross-shore sediment supply was also not been accounted for *(S. Boer and Roukema, 2004)*. The grain size was also at the base of the design of the coastal profile for Maasvlakte 2. For the earlier mentioned landward directed sediment transports for $D_{50}$ of 285 $\mu m$, the slope of the design profile was assumed to be too gentle. (Boer, 2004) advised that the design profile slope be changed due to this. In addition, the grain size distribution also played a significant role in the determination of the scour hole development. A 2006 study showed that there was an overestimation of the scour development and subsequent erosion due to the usage of uniform non-graded sediment *(S. Boer, Roelvink, et al., 2006)*. Especially scour holes at depths larger than NAP -20m seem to be affected by the use of non-graded material. For an accurate depiction of the erosion and extent of the scour at the western bend that likely will form, a graded sediment transport model should provide a better insight.

## 4.4. TIDAL CONTRACTION

In a previous study, it was calculated that after construction of Maasvlakte 2, a scour hole would develop along the entire north-western coastline due to tidal contraction *(S. Boer, Roelvink, et al., 2006)*. Sand from this scour hole would be deposited in the access channel, which would lead to more frequent and higher volumes of maintenance dredging to keep the access channel at its required depth. Since the formation of scour holes can also have an impact on the maintenance requirements of Maasvlakte 2, it would be advised to take it into account when modelling. The formation of large scale scour at the western-bend, caused by tidal-contraction, in combination with a tide driven sediment transport will carry sediment northward, towards the Euro-Maasgeul. This process was however expected to decrease in the long term *(S. Boer and Roukema, 2004)*.

The formation of the erosion-hole is governed by many factors, such as sediment characteristics, sediment supply, the location of the western bend in Maasvlakte 2 and the magnitude of the tidal-contraction that it causes. The spatial development of the erosion-hole is also heavily influenced by the presence of eroding layers in the sub-soil *(Kuijper, 1998)*.

Modelling and monitoring of the development of the erosion-hole is important to assess:

- The negative impact of the erosion-hole on the nautical demands regarding currents.
- Impact of the erosion hole on the coastal maintenance, indirectly via altered wave- and current climate or directly, when the scour hole moves towards the coast and alters the coastal profile.
- The contribution of extreme waves on the coastal maintenance can change.
- A scour hole will require nature compensation for areas at depths lower than -15m NAP.

For the coastal maintenance, the scour hole was not taken into account, since the created beach profile has its maintained lower boundary at NAP -8m, while the scour hole occurs at depths between NAP -10m to -20m. The sediment transport due to this appeared to be somewhat limited and in the range of 200.000-250.000 $\mathrm{m}^3$/year for the total coastal section *(S. Boer and Roukema, 2004)*. In reality, the position of the scour hole and the slope of the eastern-flank could shift. This would cause intersection with the cross-sectional profile of the coast and eventually cause sediment losses, however this was not accounted for in the aforementioned study. It can be expected that the location and extruding shape of Delta21 will cause a similar local effect at the western bend of Delta21, however, the erosion will occur more towards the south. The impact of this will then take longer to become apparent and the impact will also have a longer duration.

Lastly, scour protection was advised sea-ward of the western-bend in the profile, to limit the formation of the scour hole and to reduce siltation in the Euro-Maasgeul. The costs of applying erosion-protection at the scour hole were compared to the effects on the Euro-Maasgeul and the reduction of maintenance dredging it has. The reduced maintenance dredging costs did however not outweigh the costs for the soil defence *(Boer, 2004)*.

## 4.5. UNCERTAINTIES AND SEA LEVEL RISE

Modelling sediment transport is accompanied by large uncertainties. Morphological changes occur due to gradients in the net sediment transport. Since these net differences tend to be significantly smaller than the gross changes, modelling of sediment transport is prone to a high uncertainty. Furthermore, sediment transport is a complex mix of various processes and their interactions and there is still a large knowledge gap to the underlying processes for sediment transport and the exact physics have yet to be fully understood. Furthermore, nature itself possesses a natural variability, and as waves, wind and currents are natural phenomena with each their own distinct variability, so will the sediment transport. The wave variability is further discussed in Section 5.2.4. For the studies into the coastal maintenance of Maasvlakte 2, these uncertainties have also been quantified. The uncertainties for the coastal maintenance for any given year and an average year were estimated to be 70% and 55% respectively in a study done by Steijn *(Steijn, 2002)*. In the PUMA study for the sediment transports, the uncertainties were mostly expressed in sediment bandwidths for the various years.



In early studies to the effect of sea level rise on the maintenance requirements for Maasvlakte 2, an expected increase of 0.2 million $\mathrm{m}^3$/year were assumed, based on a grain size $\mathrm{D}_{50}$ of 160 $\mu\mathrm{m}$ *(S. Boer and Roukema, 2004)*. In the PUMA study, a sea level rise of 0.006 m/year was maintained, resulting in an additional nourishment need of 30.000 $\mathrm{m}^3$/year, which is limited in comparison to the total nourishment volumes. In other studies, the sea level rise was not directly taken into account, however implicitly a larger uncertainty was considered on the long-term morphological predictions to account for this. In this study, where possible, the uncertainties will be also be included, either calculated directly from the variability in wave-climate and sediment transport or estimated based on the shown variability for Maasvlakte 2. The specific effect of sea level rise is then not taken into account and is advised for future studies.

## 4.6. COASTAL MAINTENANCE

Firstly, the term coastal maintenance itself will need a proper definition, as it can be defined as the net difference in total volume in the profile or solely keeping the profile within its design perimeters. For example, an erosion of 100 $m^3/m$ at the breakerzone has much more impact on the profile stability than an erosion of 100 $m^3/m$ at the coastal foundation. In this study, profile-stability and the cross-shore distribution of sediment in the profile itself is not looked at and coastal maintenance is defined as the pure yearly volumetric differences in the entire profile. Also, no statements will be given about the best maintenance practices in terms of timing, location, efficiency and effectiveness of the required maintenance and coastal nourishments.

Initial estimation for the coastal maintenance required for Maasvlakte 2 was primarily based on the coastal sections of the 'Slufterdepot' at Maasvlakte 1. Projections for erosion of the Sluftercoast were 270.000 $m^3$/y for $D_{50} = 250\mu m$ up to 750.000 $m^3$/year for 130 $\mu m$ *(Boer, 2004)*. (Boer, 2003) shows that during the 90's, multiple sand nourishments were carried out at the Slufterdam, with an average of 900.000 $m^3$/year over the period 1991-2001. Morphological research that was executed as part of the Project Mainport ontwikkeling Rotterdam (PMR) showed that the largest portion (2/3) of the eroded sediment of the Sluftercoast was transported north and the remainder (1/3) south *(Steijn, 2000)*. This is also due to the fact that the Hinderplaat was lowered in the 90's and shifted towards the east, such that the Sluftercoast was losing more sand.

The total modelled coastal maintenance for the 'Doorsteek'-alternative for Maasvlakte 2 was calculated to be 570.000 $m^3$/year for a $D_{50}$ of 285 $\mu m$, with a probability spread of 70% for any given year and 55% for an average year *(S. Boer and Roukema, 2004)*. At the western-bend, 200.000 $m^3$/y was directly northward, 240.000 $m^3$/year was directed southward. At the northern coastal-section, 130.000 $m^3$/year was directed northward. At the southern coast-section, no sand losses were expected, since the wave-induced surfzone transport here was more or less balanced *(S. Boer and Roukema, 2004)*.

In the study by *(Onderwater, 2008)*, the coastal maintenance above -8m NAP was modelled by means of a Delft3D-Sed Online and UNIBEST-LT model. For this, 11 representative wave conditions were used to acquire the yearly average sediment transport for 16 locations along the Maasvlakte 2 soft sea defence. The study concludes a mostly current driven transport below -8m NAP and a wave driven transport above -8m NAP. Figure 4.1 shows the gross northbound (red) and southbound (blue) sediment transports for the various locations and the yearly averaged net transport (black). The basis for the bandwidth were the UNIBEST models of the wave climate for each individual year from 1979 to 2001. For the coastal profile above -8m NAP, for the south side of the soft sea defence, a net southbound sediment loss of 140.000 $m^3$/year was modelled. At the north side a net northbound sediment loss of 120.000 - 300.000 $m^3$/year was modelled, for a combined modelled mean yearly maintenance of approximately 260.000 - 440.000 $m^3$/year, with a bandwidth of 50%.

The actual maintenance executed was tracked by PUMA. In the initial period from 17 April 2013 to 16 April 2018 several examinations were performed to get insight in the performance of the nourishments and the required maintenance. The examinations were also to check whether the planned nourishment frequency of once every two year is sufficient to keep up with the erosion trend. The original plan for determination the re-

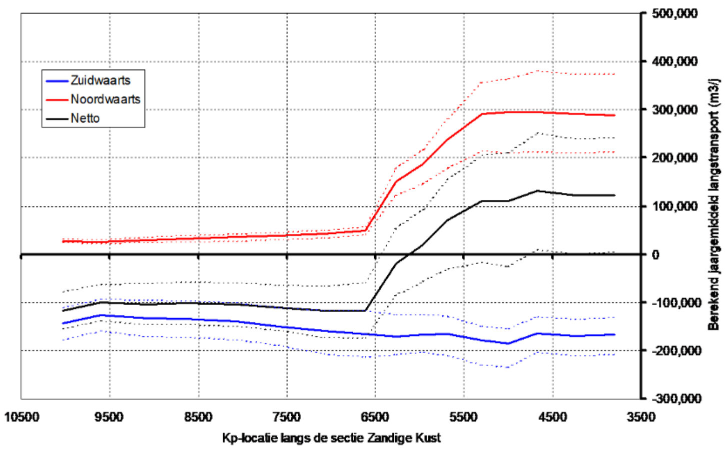



Figure 4.1: Alongshore gross- and net sediment transport above -8m NAP, as modelled by PUMA with UNIBEST-LT. Source: PUMA.

quirements of coastal nourishments was based on so-called 'test-volumes', determined with a model prognosis. Later it was decided to base the required volumes on the actual behaviour, while looking further ahead and maintaining a larger buffer. *(PUMA, 2018)*

For the determination of this the cross-shore was divided in the parts (so called 'shells'), which were assessed separately:

1. backshore (duinreep), coastal profile above +3m NAP
2. foreshore (strandoever), coastal profile between +3m NAP and -4m NAP
3. breakerzone (vooroever), coastal profile between -4m NAP and -8m NAP
4. coastal foundation (kustfundament), (deep and non-deep), below -8m NAP

| **Nourishment Year** | **Nourishment Strandoever (Kp.5300 - Kp.6600) [Million** $\mathrm{m}^3$**]** | **Nourishment Vooroever (Kp.3495 - Kp.7000) [Million** $\mathrm{m}^3$**]** | **Nourishment Total [Million** $\mathrm{m}^3$**]** |
|---|---|---|---|
| *0 (initial)* | *0.82* | *1.54* | *2.36* |
| 1 | 0.57 | 0.99 | 1.55 |
| 4 | 0.83 | 1.55 | 2.38 |
| 5 | 0.83 | 1.55 | 2.38 |
| **Total** | **2.22** | **4.09** | **6.31** |

Table 4.1: Initially planned coastal nourishment volumes soft sea defence Maasvlakte 2. Source: PUMA.

*(Vijverberg, 2018)* mentions that in the foreshore the volumes were fluctuating the most and the change in relation to the design profile is strongest at the interface between the soft- and hard sea defence, while around the recreational beach a limited margin exists with light erosion. Furthermore, the breakerzone is more stable than the foreshore

and undergoes light erosion. The coastal foundation north of ray 7000 showed a more dynamic behaviour, while south of this the profile is more stable. This can also be seen from the data available and is further elaborated in the data study, as seen in Chapter 5.

In Figure 4.2 on page 28 the measured average yearly sedimentation/erosion in $m^3/m$ for the period 2013-2017 per cross-shore section can be found. These figures match well with the modelled coastline changes for the entire coastline, as calculated in Section 5.5 and show the locations where the most erosion and sedimentation takes place. These places do not entirely coincide with the PUMA model, as rays 8200-9600 show more erosion than originally modelled and rays 6800-8000 show more accretion than modelled, even though no coastal nourishment were performed here. Rays 8200-9600, at the location of the recreational beach, furthermore needed multiple nourishments to compensate for significant erosion, which was not originally modelled. The proposed reason for this was the strong inclination of waves in this area. The interaction at the soft- and hard sea defence transition also proved to be a larger sediment sink than initially modelled. The spatial and temporal variation in the observed erosion was also more significant than initially planned. In certain years, such as 2016-2017, a much larger erosion was observed, especially in the western- and northern rays. While initially, a variability in sediment transport of around 50% per year was modelled, in certain time-periods and locations, this was measured to be noticeably more.

4

The initial planned nourishment volumes that were estimated and modelled can be seen in Table 4.1 per year and per section, while the actual performed coastal nourishment volumes can be seen in Table 4.2. A total sediment loss of $\frac{3.1}{3} = 1.0$ million $m^3$/year was measured for the total segment, of which $\frac{2.2}{3} = 0.7$ million $m^3$/year for the profile above -8m NAP. Furthermore, in the PUMA report 2016.004 itself, an averaged yearly erosion of 1.09 $m^3$/year and 0.91 million $m^3$/year was calculated for the total segment and the segment above -8m NAP respectively, over the period 2013-2016. This is a factor of 3-4 times more than what was initially modelled, which confirms the high variability and unpredictability of quantitative sediment transport modelling.

| **Year** | **Location** | **Quantity in million $m^3$** | **Total $Mm^3$** |
|---|---|---|---|
| 2014 | 7500-10200 | 0.76 | |
| 2014 | Cone-5000 | 0.31 | |
| 2014 | 3495-4800 | 0.35 | |
| 2014 | 5600-6600 | 0.30 | **1.7** |
| 2016 | Cone-6200 | 0.46 | |
| 2016 | 8200-10000 | 0.35 | |
| 2016 | Cone-8800 | 0.58 | **1.4** |
| 2018 | 3800-6200 | 0.42 | |
| 2018 | 8800-9400 | 0.64 | **1.1** |
| Total | | | **4.2** |

Table 4.2: Actual performed coastal nourishment volumes soft sea defence 2014-2018 for Maasvlakte 2. Source: PUMA.

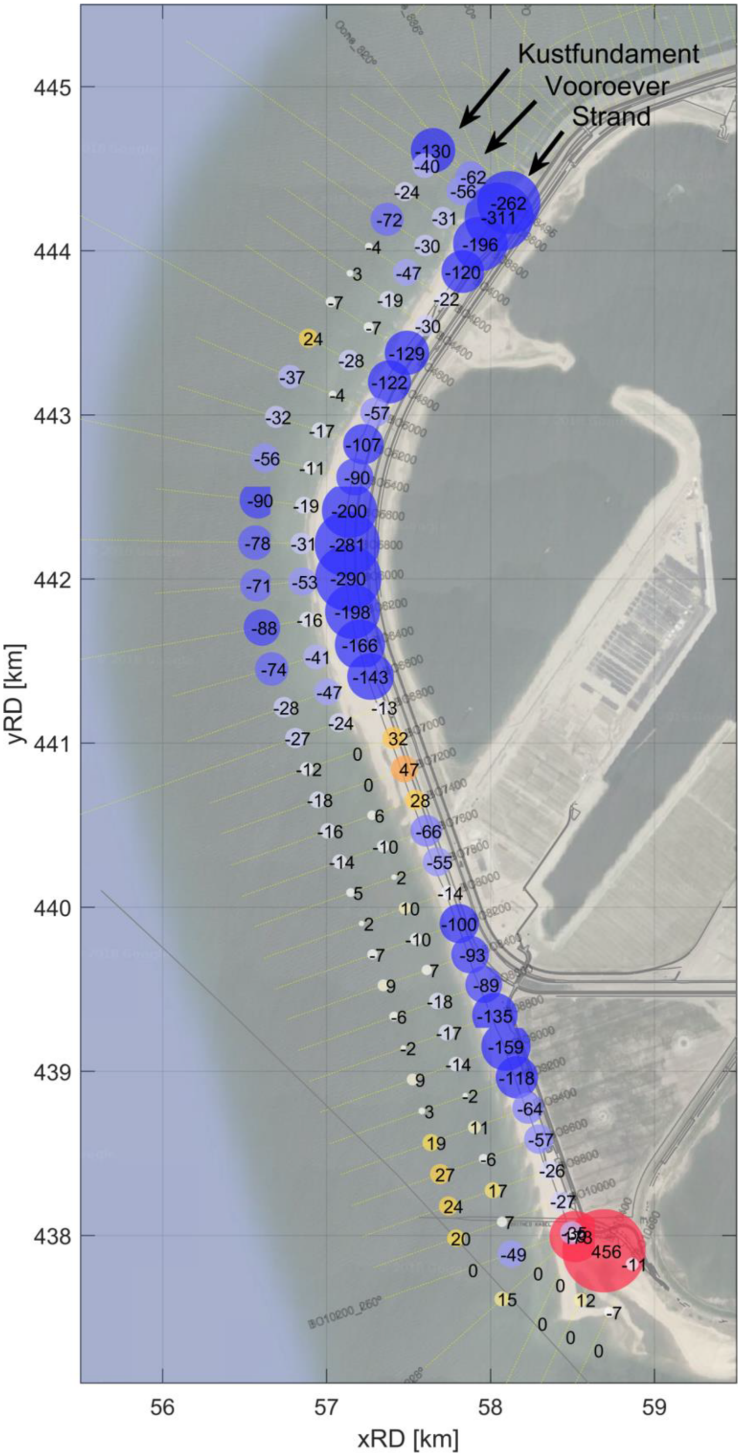



Figure 4.2: Average erosion/accretion per year for the three different sections, foreshore, breakerzone and coastal foundation. Average over 2013-2017. Source: PUMA.

# 5

# STUDY AREA: MAASVLAKTE 2

## 5.1. INTRODUCTION

In this chapter a closer look is taken at the study area. The origin, extent and usage of the data and boundary conditions, such as the wave climate, wind and bathymetry that are present in the study area are further elaborated. Additionally, for a transparent and reflective study, the used assumptions and shortcomings of each data-set used in the modelling are also listed. This inventory forms the basis for the data used in the wave- and coastline-modelling with SWAN and UNIBEST respectively, and the results which they produce.

## 5.2. WAVES

### 5.2.1. MEASUREMENTS

The wave data used in this study is data from Rijkswaterstaat from the period 1997 to 2021. Measurements stem from the Europlatform measurement location in the North Sea, installed in 1982, some 50 kilometre off the coast from Maasvlakte 2. Minor data manipulation was needed to remove outliers and error values, such as unrealistically high wave heights or -periods. Furthermore, the entire measurement was discarded if any of the variables measured (wave height, wave period, wave direction) was unavailable or rejected. The revised and adjusted wave data for the entire duration that was used has been plotted as a time - wave height, direction - wave height and as a wave rose in Figure 5.1 and Figure 5.2 respectively. These figures have been compared to other figures from the literature review and appear to match identically. Therefore, it is safe to assume that the data acquisition was performed correctly.

For the verification of the UNIBEST model, the wave climates of various other periods were used to match with the measured bathymetry periods and to allow for more precise modelling and comparison. From these graphs it can be seen that there can be quite a variation in the wave height and direction between different years. The wave climates for the various periods (ranging between the second quarter of each respective year) can be found in the Appendix. Furthermore, the wave-roses for the entire dataset and the different modelled years can be seen in the Appendix. It can be seen that the

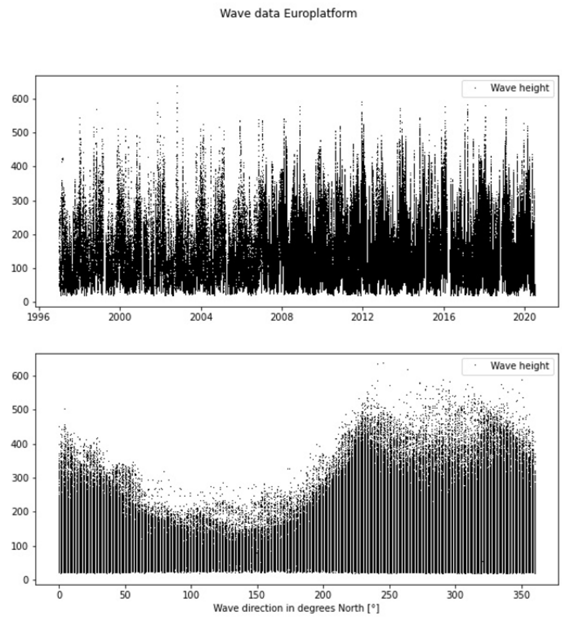



Figure 5.1: Wave data 1997 - 2020 for Europlatform. Some gaps in the available wave data can be seen. The directional resolution is also visible in the bottom graph, as shown by the vertical white bars.

5

wave climate between different years can vary significantly. Therefore, for Model 0; modelling sediment transport within a given period and compare this to actual, measured data in a more accurate way, it is better to use the (reduced) wave climate in that period. For Model 1, the actual modelling of the effect of Delta21, it is better to use a reduced wave climate of the entire data-set, rather than a specific wave climate of a certain period.

### 5.2.2. FLAWS, ASSUMPTIONS AND ACKNOWLEDGEMENTS

The wave data measured at the Europlatform has a directional resolution of 1 degree, a resolution of 1 cm for the wave height and a resolution of 0.01 seconds for the period, as can be seen in Figure 5.1 by the lack of data in between these points. For the most part, the wave data was measured consistently, with only small periods of data missing or occasional data that was unusable, as can be seen in the wave climate graphs for 2014Q2-2015Q2 or 2018Q2-2019Q2 in figure 5.1. However, for Fp, the wave period at the maximum of the variance density spectrum was measured very irregularly and the data was deemed unusable. For this purpose, a general relationship between the spectral period determined from the relationship between the spectral moments m0 & m2 and the peak period was used. It should also be noted that the sensors at the Europlatform can only measure frequencies between 30 and 500 mhz and as such, very high and small wave periods are not measured and not taken into account.

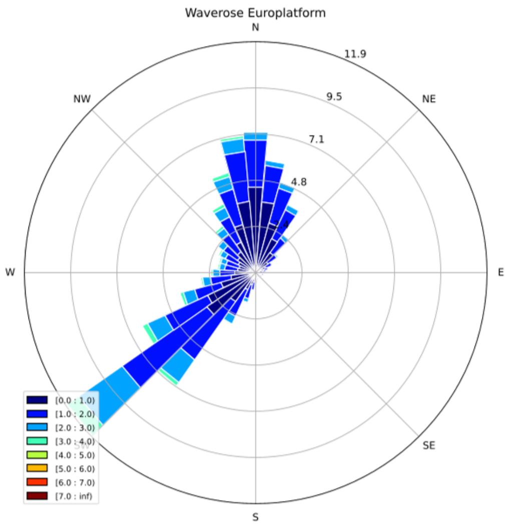



Figure 5.2: Wave rose for 1997 - 2020 for Europlatform.

5

### 5.2.3. WAVE INPUT REDUCTION

The wave-data needed for the SWAN model, and ultimately the UNIBEST model as well, needs to be accurate and fully represent the wave-climate present. A fully representative wave-model not only models the average wave characteristics, but also their variability. Since the goal of this study is to find the changed hydrodynamics and maintenance requirements for Maasvlakte 2, for an accurate modelling of the sediment transport and the coastline changes, especially in UNIBEST, the wave data will have to modelled for the purpose of sediment transports. The input reduction for the wave-data will therefore have this as a goal. The criteria used for this reduction are the two leading shore angles. As seen in the literature, the wave-induced alongshore current is mainly responsible for the net sediment transport, which is highly dependent on the angle of the waves. For this purpose, a simplified alongshore sediment proxy is used, in which the simplified CERC formulation for bulk alongshore sediment transport is proportional to the wave height $H_{s,b}$ and wave angle $\varphi_b$ and proportional such that $S_y \subset f(H_{s,b}^{2.5}\sin(2\varphi_b))$. *(de Queiroz et al., 2019)*

The two leading wave angles for Maasvlakte 2 can be found from the orientation of Maasvlakte 2 and are verified in a study *(Arcadis Nederland B.V., 2017)*. The coast-normal for zero alongshore transport (for a $D_{50}$ of 285 $\mu m$) for the southern and northern coast were determined to be 250 and 295 degrees, respectively. For the Delta21-dunes in the current design, the leading coast-normal for the southern coast is 240 degrees and for the northern coast 325 degrees, which is thus similar to that of Maasvlakte 2. Since only one set of coastal orientations can be used, the Delta21 orientation is governing. If the input reduction in Model 0 for Maasvlakte 2 is validated for these, then it is also applicable for Delta21. The SWAN model will firstly be verified and validated in 'SWAN-model 0' by modelling the transformation of the offshore waves to Maasvlakte 2 and comparing these results to the available wave data measured. The Python-script used for the wave input reduction can be found in the Appendix. This reduced wave-climate is then used as input for the different .SWN files for the three different grids.

The determination of the 'weight' is visualised by the plots as shown in Figure 5.3. The input reduction is performed according to the following steps:

- First, for each wave, calculate its 'weight' according to the sediment transport proxy. This is done by the directional factors for the south- and north coast normal angles respectively, based on $\sin(2\varphi_b))$ and the separate $H_{s,b}^{2.5}$ weight.
- Next, calculate the positions of the directional bins based on the total weight of all waves divided by the desired amount of directional bins
- Lastly, calculate the positions of the vertical bins by dividing the total weight of all waves in a single directional bin by the amount of vertical bins

5

From the Figure, It can be seen that waves originating from 50-150 degrees have little to none impact on the expected sediment transport for the Delta21 dunes, while waves between 250 and 325 have the largest expected impact on sediment transport for the Delta21 dunes.

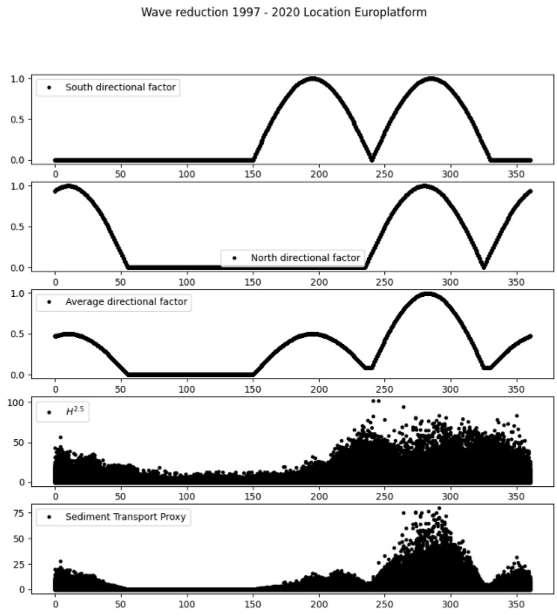



Figure 5.3: Wave reduction for period 1997 - 2020 Location Europlatform

The result for this reduced wave-climate is the graph as seen in Figure 5.4. In this graph, the vertical blue lines represent the directional borders of the bin, while the horizontal blue lines represent the wave height borders of the bin. The red crosses within each bin represent the means of all the wave conditions within the respective bin. Note that the bin between $\approx 25-180°$ is very wide. This is a result of wave conditions coming from the shore. These wave directions have a lower or no impact on the alongshore sediment transport of the research area and are therefore bundled in a larger bin. Additionally, it is worth noting that the bins at the higher wave heights are smaller, since wave height is one of the key parameters in the determination of the sediment transport. Even though there are fewer values in these top bins, due to their high wave heights, their weighted value is similar to those at the bottom bins. A table with the full representative wave conditions can also be found in the Appendix.

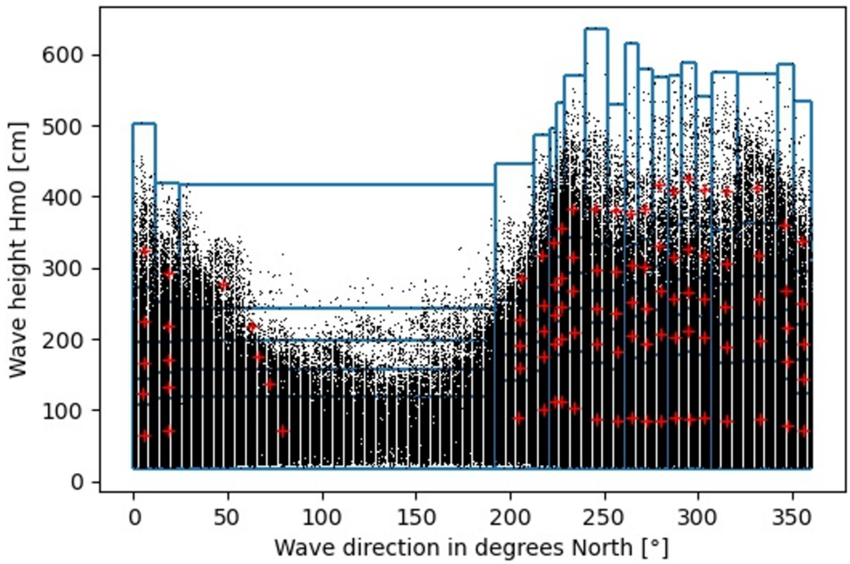
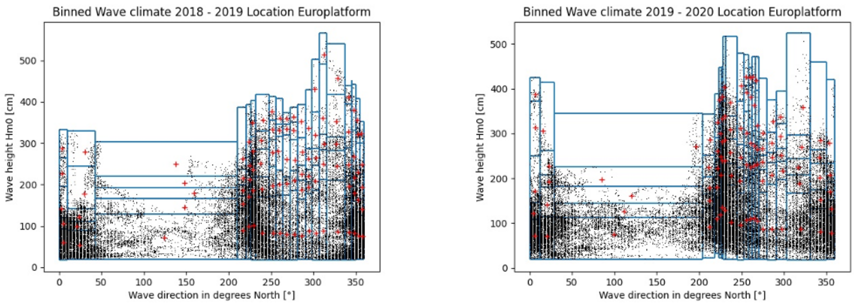



Figure 5.4: Variable bin-size, 2D-binned wave climate for the period 1997-2019 by means of Sediment Transport proxy. Location Europlatform.



For the UNIBEST model, for the purpose of an accurate modelling of the sediment transport within a given time, the reduced wave climate in between each bathymetric survey was used. Thus the reduced wave-climate of 2013Q2 - 2014Q2 for the difference between the bathymetric surveys of 2013Q2 and 2014Q2 etc. An example of these reduced wave climates can be found in Figure 5.5. It can be seen that the distinct reduced wave climates between years can differentiate significantly, as can be seen in the difference between 2018Q2-2019Q2 and 2019Q2-2020Q2. While the first has its representative wave conditions more evenly spread, the latter has a higher concentration of representative wave conditions between 220 and 270 degrees.




(2018Q2 - 2019Q2) (2019Q2 - 2020Q2)

Figure 5.5: 2D binned wave climates for various years. Wave reduction based on Sediment Transport proxy.

5

For comparative reasoning, the wave climate of 1997-2020 has also been reduced by means of equal-distant binning for wave height and wave-direction. This method of wave climate reduction was also used in the original Maasvlakte 2 modelling. This reduced wave climate results in 91 representative wave conditions and can be found in the Appendix. The impact of the different wave-climates and their comparison on the alongshore sediment transport can be found in the results in Section 7.2.

### 5.2.4. WAVE CLIMATE VARIABILITY

To analyse the variability in alongshore sediment transport that occurs at the nearshore at Maasvlakte 2, the variability in wave climate at the Europlatform needs to be understood and compared as well. Variability in the wave climate present can be expressed in various ways, e.g. variability in the wave height, wave energy, period, wave direction etc. From the variability in wave climate from Maasvlakte 2, we can then estimate the expected variability for Delta21. As such, the wave variability has been studied and expressed in a variability of wave direction per year and wave flux per direction.

In Figure 5.6 and Figure 5.7, the variability of the wave direction per year and the wave energy flux per wave direction are shown, respectively. These indicate that the spreading of the wave directions across the years is rather stable, with the mean around 240 degrees. A small variation in wave direction in combination with a variation in wave height can however have a combined larger variation on the gross alongshore sediment transport in a certain direction. The variation in the wave energy flux per direction shows a larger variation for the higher wave energy flux from the directions between 200 - 340 degrees and a lower variation in the other directions. This means that the alongshore sediment transport from these directions also shows a higher variability. Combined with a variation in expected sediment transport per year, this can result in a rather large confidence interval of the expected north- and southbound alongshore sediment transport for Delta21. This can be visible in the modelling of the UNIBEST variants, as can be seen in Section 7.2.

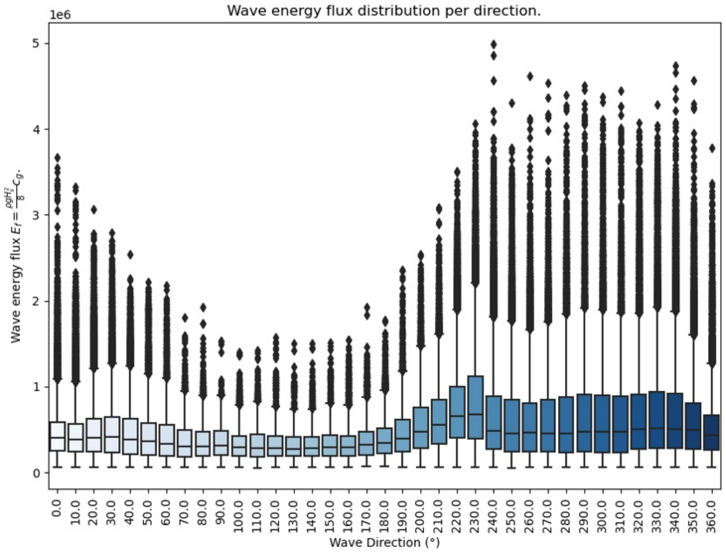



Figure 5.6: Variability of the wave climate by means of a box plot of the wave energy flux per wave direction. The many outliers are due to the way wave energy flux is calculated and the amplification of large waves.

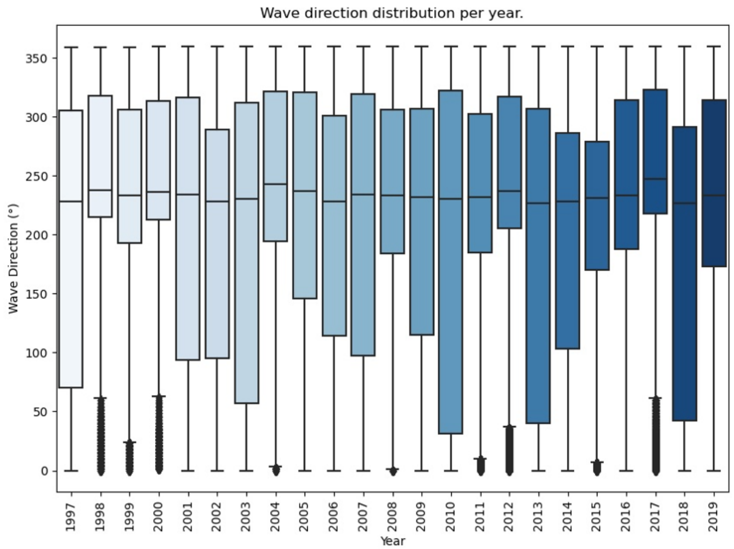



Figure 5.7: Variability of the wave climate by means of a box plot of the wave direction per year.

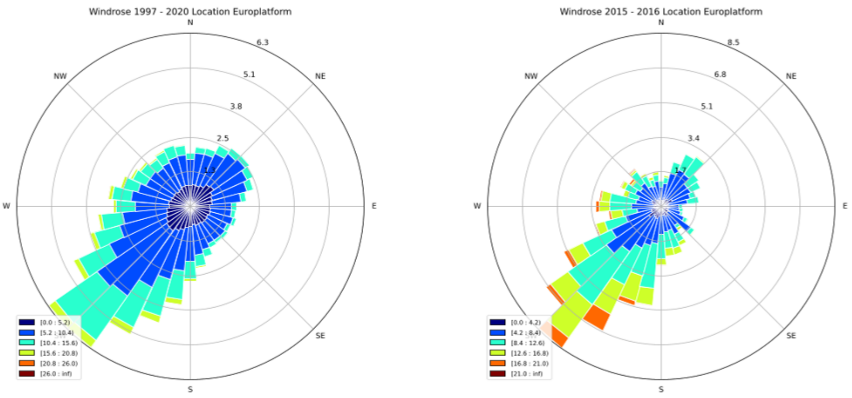
# 5.3. WIND

## 5.3.1. WIND DATA

The wind data used in this study comes from the Royal Netherlands Meteorological Institute (KNMI). Wind data here is available from 1991 to 2021, from which the wind direction in degrees and the wind speed in dm/s are used. A wind rose representing the wind direction and wind speeds for the period 1997-2020 can be found in Figure 5.8, visualising the wind speeds and chance of occurrence from each wind direction at the Europlatform, grouped in 36 bins.

Some data manipulation on this data was performed, such as the removal of unrealistic (error) values and values for which no clear wind-direction was defined. The wind data has a measurement time of once every hour. To make the data more suitable for comparison with the wave data, which has a measurement time of once every 10 min., the wind data was re-indexed to every 10 min.

Same as for the wave data, to ensure a higher accuracy UNIBEST model for the sediment transport and for verification of the model, the wind data was further differentiated per period. The wind data for these various periods can be found in more detail in Appendix B. The wind roses in Figure 5.8 clearly show that the wind speeds, directions and chance of occurrence can differ significantly between years, with for example 2015Q2 - 2016Q2 showing higher extreme wind speeds from the south-west than the average. Combined with a variation in wave heights and -directions, this further increase the total variability of the wave climate on the alongshore sediment transport.




(1997 - 2020) (2015Q2 - 2016Q2)

Figure 5.8: Wind roses for 2014-2015 and 2015-2016. Location Europlatform.

## 5.3.2. FLAWS, ASSUMPTIONS AND ACKNOWLEDGEMENTS

Although the wind is not likely to change significantly during an hour, having it re-indexed from every 60 min. to every 10 min. causes an averaging-out of any extreme values. These extremes are less likely to occur, since the wind is averaged over 10 min., with the number of these averaged wind speeds further multiplied by 6. Alternatively, the wave data could be reduced from once every 10 min. to once every 60 min. and averaged, however this causes a significant reduction in resolution for the wave data. A higher resolution in wave data has a larger impact on hydrodynamics and sediment transport than a higher resolution in wind data, thus the choice was made for the re-indexing of the wind data. Apart from this, the wind data from the KNMI has been measured by 2 separate instruments for the majority of all the measured data. Differences between the 2 instruments is small and as such, the average of these values was taken for each measurement. If only one sensor registered data, data from a single sensor was used. Furthermore, the directional resolution of the wind only has an accuracy of 10 degrees, which is significant less than the directional resolution of the wave data. The wind speed has a resolution of 1 dm/s. Finally, the wind data was matched to the same time domain as the wave data. If any measurement (either wave height, wave period, wave direction, wind speed or wind direction) was unavailable, the entire measurement would be rejected, such that only fully represented wave conditions are used. This also means that the period 1991 to 1997 was cut, as this data was unavailable in the wave data-set.



## 5.4. BATHYMETRY

### 5.4.1. BATHYMETRY EXTENT AND PROCESSING

The bathymetry used in the models in this thesis is a combination of several separate bathymetries. The first set is bathymetry from Rijkswaterstaat, which covers the entire Dutch coast up until the -20m NAP contour line and has a resolution of 20x20m, retrieved directly from the Rijkswaterstaat geoservices server. The second is bathymetry from the European Marine Observation and Data Network (EMODnet), retrieved directly from the geoservices server. This bathymetry covers the entire European continent with a varying resolution, with a maximum resolution of 125x125m at the Dutch coast. The last bathymetry was obtained via PUMA and consists of maintenance data for the Maasvlakte 2 area for the period 2013 to 2020 and includes the beach- and dune area. This data consists of the entire Maasvlakte 2 western coast section with a resolution of 2.5x2.5 meter.

All bathymetries were processed and altered in ArcGIS to make them suitable for comparison and usage in the models. Where needed, the separate bathymetry files were combined to create a single bathymetry in which the RWS and PUMA bathymetry was governing and filled with the EMODnet bathymetry, to create the highest resolution bathymetry possible.

Lastly, while the EMODnet bathymetry covers both land and water, the RWS bathymetry stops at -0m NAP and as such is not usable for accurate coastline modelling in UNIBEST above this line and for comparison between coastal profiles for certain years. The EMODnet bathymetry however has a low resolution, and unworkable for coastline modelling. Rijkswaterstaat also provides a high resolution coastal monitoring dataset, the so-called 'Hoogtebestand DSM kust', which has a resolution of 2x2 meter, with data that includes the beach- and dune area. However, since Maasvlakte 2 is outside the monitoring and maintenance scope of Rijkswaterstaat, there is only data from the nearby coasts, which are outside the research area. Extensive maps of these bathymetry files can be found in Appendix A. Here we can see that the EMODnet bathymetry covers the entire Dutch coast with a coarse resolution while the RWS covers the Dutch coast in high detail from Schouwen-Duiveland up until Katwijk aan Zee until the blue NAP -20m line. Lastly, the PUMA bathymetry from 2013Q2 is shown, which covers the entire extended Maasvlakte 2 area, including the newly constructed harbours in high resolution. The separate bathymetry files and extensive maps of the bathymetry used can be found in the Appendix.

### 5.4.2. BATHYMETRY DIFFERENCE

The difference between various depth-surveys over the years can also be calculated and plotted on a map. This gives an clear overview of the locations where sediment accretion and -erosion occurs and can also indicate how any coastal nourishments disperse over time. An example of this can be seen in Figure 5.9. This Figure, along with the bathymetric difference between all other years, can also be seen in higher detail in Appendix A. It can be seen that across most of the years for the majority of the areas along Maasvlakte 2 there is a general erosion at the beach-zone, accretion around the innershelf and again accretion below the -10m NAP line. This can be seen even more clearly along coast normal transects over various years. This means that after construction of the soft coastal protection for Maasvlakte 2, the design profile has changed, under the influence of the hydrodynamics, to a more stable equilibrium profile. The way that these coastal profiles have changed over the years can be assessed more clearly when looking at the individual profiles per ray, as seen in section 5.6. With these coastal profiles, a better prediction of the profile-changes for Delta21 can be made.

5

### 5.4.3. BATHYMETRY DELTA21

For the bathymetry of the Delta21 area for the model 1 modelling, it is assumed that the future design parameters such as the design profile and required stability will be held similar to those for the design of the Maasvlakte 2 soft sea defence. This means that the design profile of the Maasvlakte 2 soft sea defence will also be applied to the Delta21 dunes.

The soft sea defence on the western and southwestern end of Maasvlakte 2 and the eastern side of the dune area of Maasvlakte 2, which will on the inside, and part of, the Energy Storage Lake (ESL), are therefore not modelled. These soft sea defences have little wave impact as they are sheltered and only small fetch waves generated on the ESL itself will generate. These dunes are however subject to rapid withdrawal of water due to the pumping and filling of the ESL, which can cause instabilities. This has been researched by another student on the project.

The layout of the Delta21 dunes is changing constantly and as such the (future) bathymetry of the area is too. Major and minor tweaks are constantly done, for example based on performed studies by students working on the project. For this study, only one layout will be looked at, which is the 2020 layout. The bathymetry for this layout can also be found in more detail in the Appendix. The exact location and method that Delta21 will connect to Maasvlakte 2 is explained in Section 6.3.2.

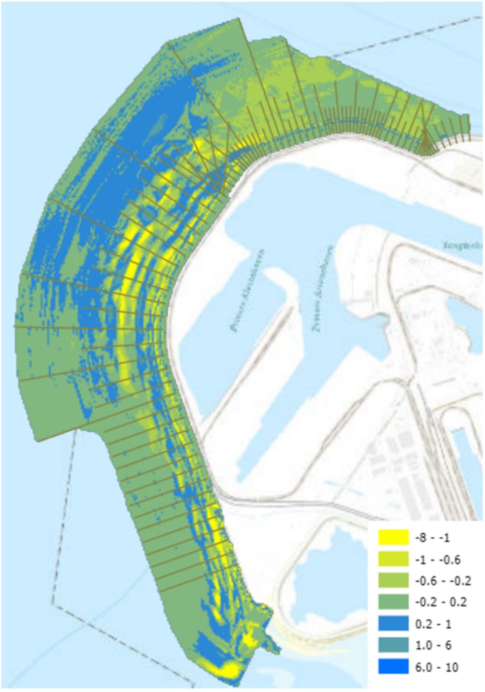



Figure 5.9: Difference in bathymetry between measurements 2016Q2 and 2017Q2. Location Maasvlakte 2. Processed and visualised in ArcGIS, data-source; PUMA.

### 5.4.4. FLAWS, ASSUMPTIONS AND ACKNOWLEDGEMENTS

Both the EMODnet and RWS bathymetry are very complete and little to no interpolation was required to fill any gaps inside their extent. Even though both are from the same year (2020), when combining the bathymetries in a single bathymetry, there are small local variations at the locations where they meet. This can have various reasons, such as a local steep variation in depth, which was visible around the Euro-Maasgeul or a different time period in which the measurement was taken, compared to one another or even within the data set itself. Especially for the RWS bathymetry there can be a certain time period between the first and last measurement, even within a same year. Attempts were made to account for these changes at the location where they intersect, however this was deemed too cumbersome, as it would shift the problem to a different location. Since the location of intersection between the bathymetry files was largely at the -20m NAP line, the shift in bathymetry, with a maximum order of 10cm, was seemed insignificant and was thus neglected.

In the dataset from PUMA, there were also flaws and errors. The measured area didn't always line up correctly and the rays were sometimes outside of the measured bathymetry. Artifacts at the locations of the rays are clearly visible, presumably from interpolation between the measured near-shore depth with a high accuracy and measured off-shore depth with a low accuracy. Since this was mostly occurring at the end of the rays and not at the near-shore, these effects were discarded.

## 5.5. COASTLINE CHANGES

Every year, Rijkswaterstaat measures the position of the Dutch coastline, where it retreats or where it expands in correlation to the BKL (Basis Kustlijn). A similar approach can be done for Maasvlakte 2. Using the various depth measurements from PUMA, the coastal changes for certain depths within the transects can also be calculated. For this, the alongshore transects are divided by the coast-normals, as defined and seen in Figure A in the Appendix. For the cross-shore dividers, the +3m NAP and -4m NAP depths are used. Figure 5.11 then shows for each section whether or not the average bathymetry for this range has increased or decreased between the period 2013Q2 and 2014Q and to what extent. The graphs for all other periods can be seen in Appendix A. Note that the method for calculating the coastline changes are slightly different than those of Rijkswaterstaat, and that no comparison to the base coastline is made, only a calculation whether the bathymetry in the area has increased or decreased *(RIKZ, 1995) (Rijkswaterstaat, 2020)*

After this analysis and comparison, it was found that the coastal profiles and coastline changes of Maasvlakte 2, combined with the coastal maintenance and wave climate could only yield a mere qualitative comparison to Delta21. Many of the interactions that are visible are due to processes and factors specifically for Maasvlakte 2, such as the interaction between the soft- and hard coastal defence. It was therefore decided that no decisive conclusions or validation for the design profile or bathymetry of Delta21 can thus be made based on just these results and that numerical modelling was needed to get more representative results.



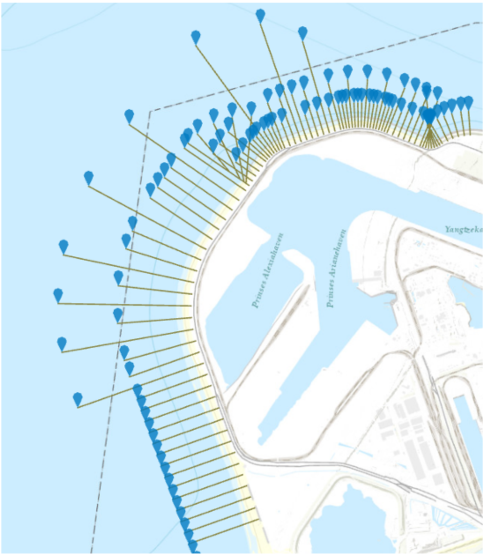


Figure 5.10: Map showing the rays (coastal normals) for a section of Maasvlakte 2. The blue pins indicate the end of the rays for which the Output locations were defined in SWAN. See Appendix A for a large scale map. Visualisation in ArcGIS. Data-source: PUMA.

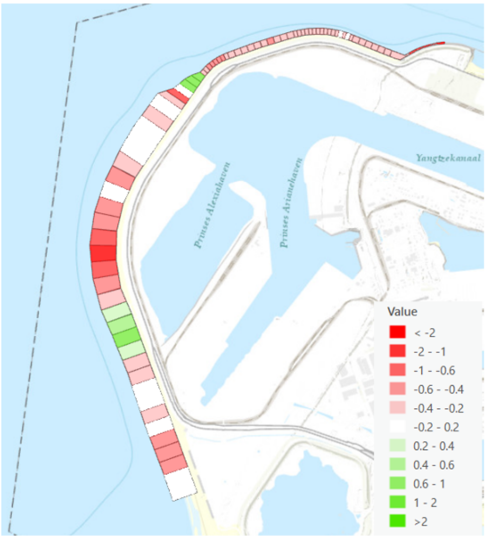



Figure 5.11: Bathymetry changes in meters between 2013Q2 and 2014Q2 for the profile between +3m NAP and -4m NAP. Red indicates a bathymetric decrease of the bottom profile, green indicates an increase. Visualisation in ArcGIS. Data-source: PUMA

## 5.6. PROFILES

For a clearer view of coastal movement over the years, profiles are made from the PUMA bathymetry of 2013 to 2020. The bathymetry point data was rasterised in ArcGIS, after which the profiles are interpolated through this raster at points every 5 meter along the different coast normals. This can be done with any arbitrary coast normal lines, but for comparative reasons, the same transects that were initially used in the design and maintenance of Maasvlakte 2 were used. These are indicated by the brown lines in Figure 5.9. A high detail map of these coast normals can also be found in Appendix A.

It should be noted that the data for these profiles start from 2013, the year Maasvlakte 2 was officially taken into use. Some characteristics, such as subtidal sandbars can already be seen in the cross-shore profile at various locations, such as the sub-merged sandbar seen in Figure 5.14, which was already present at the start of the available measurements.

For comparison reasons, one section of the hard coastal defence is studied, the transition between the soft and hard coastal defence is studied and two sections of soft coastal defence. The general profile changes across the years for various sections and cross sections along the coastal sea defence for Maasvlakte 2 and its comparison to Delta21 are then looked at in further detail in the following sections.



### 5.6.1. NORTHERN SIDE

The hard coastal section at the northern side of Maasvlakte, although not studied in detail in this study, is visualised by the coast normals 1450 - 1700, see Figure 5.12. These can also be seen in higher detail in Figure C.1 in Appendix C.

The Figures show a comparatively slow changing coastal profile at the hard coastal protection at the northern side of Maasvlakte 2. A clear initial change of the foreshore between 2013Q2 and 2014Q2 can be seen around the 0m NAP mark. The cubes at 170 meter distance furthermore slight movements across the years, however no distinct continuous movement further on- or offshore. The zone at 230 meter up until 400 meter shows slow, but steady accretion. The relative steeper breaker zone of the hard coastal protection is furthermore visible in comparison to the soft coastal protection at the other rays. The cubes are therefore protecting the coastline quite well and could offer a similar solution for Delta21, should the need and situation for it arise.

### 5.6.2. TRANSITION SOFT- AND HARD SEA DEFENCE.

The transition between the soft & hard sea defence is visualised by Figure 5.13 and Figure C.2 in Appendix C. These figures show a very dynamic coastal profile. Around the breakerzone, the profile is slowly retreating at rays 2850 and 2900 at first, while in the foreshore there is a small gradual trend of accretion over the years. A distinct initial change in the foreshore between 2013Q2 and 2014Q2 shows a relatively quick change immediately after construction. However, the most significant changes are from the 180 meter distance mark. Here is a very clear accretion at the northern side of the transition at the ray 2850, 2900 and 2950 over the years with up to a 10 meter accretion in less than 8 years. At ray 3100, at the start of the transition, this process of accretion slowly starts, while further north the image is mostly the same for all rays. In the current Delta21 design, the dunes

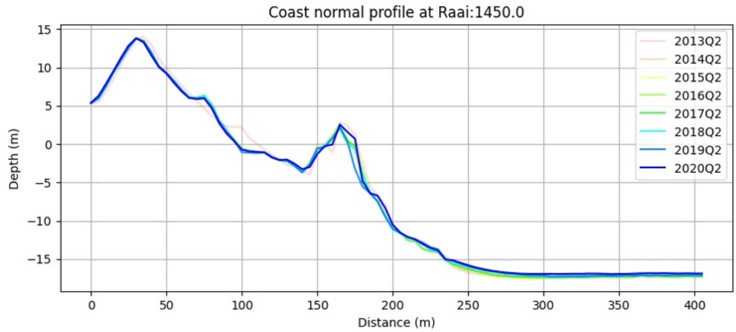



Figure 5.12: Profile changes over the years 2013-2020 for ray 1450, the northern hard sea defence at Maasvlakte 2.

of the Energy Storage Lake will connect to the existing dunes of Maasvlakte 2, around the transition between the soft & hard coastal defence. Although the angle of attachment of this dune to Maasvlakte 2 is not yet fully set in stone yet, the current trend of a northern-bound transport in combination with the transition of soft- to hard coastal defence will results in a expected similar process of accretion just northward of the transition for Delta21 as well. The numerical model can shed more light on whether this is in fact the case.



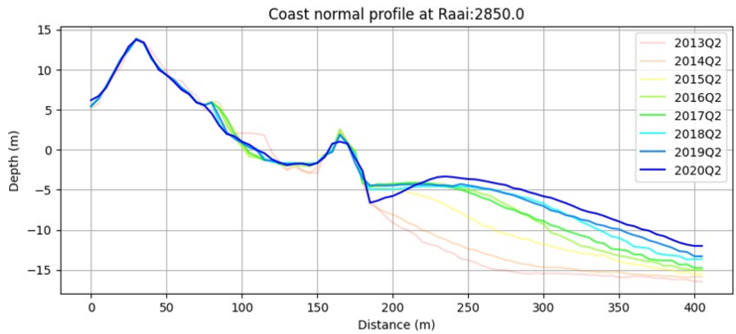



Figure 5.13: Profile changes over the years 2013-2020 for ray 2850, the transition of the soft- and hard sea defence at Maasvlakte 2.

### 5.6.3. WESTERN BEND

For the analysis of the western bend, the rays 5200, 5600, 6000 and 6400 are analysed. For ray 5200, this is visualised in Figure 5.14. These rays are spaced out further apart (400 meters) and have a longer length (1250 compared to 400) than the other rays looked at, such that the entire western bend can be compared, up until a larger depth for the analysis of tidal contraction. These rays show a similar behaviour. A foredune growth is seen over the years with a steady rate of up to half a meter per year. In the foreshore, a gradual erosion in all four profiles, with large initial decreases in the first years of up to 2 meters and slowing down slightly over time. In the breaker zone then, a general erosion pattern is also visible across all profiles and all years. The subtidal bar, most clearly visible at ray 5200 and ray 5600, is seen to gradually move towards onshore over time. From these observations, a similar process of erosion can be expected for the bend in the current dune design for Delta21, which has similar modelled wave conditions. Furthermore, the erosion due to tidal contraction that is present at the western bend at Maasvlakte 2 is also present at Delta21, as modelled by other students. In chapter 7 a quantification of these sediment transports that will occur is attempted.

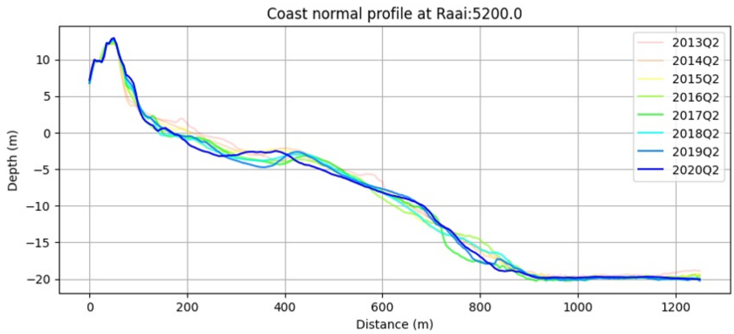



Figure 5.14: Profile changes over the years 2013-2020 for ray 5200, at the western bend of Maasvlakte 2.

### 5.6.4. SOUTH-WESTERN SIDE

Lastly, for the analysis of the south-western side of Maasvlakte 2, the representative rays 9000 - 9600 were used, as visualised in Figure 5.15 and seen in more detail in Figure C.4 in Appendix C. These profiles show a similar behaviour as those at the western bend, namely that the foredune and dune experience accretion between the +1m NAP and +5m NAP line, while the backshore and foreshore experience mostly erosion. The subtidal sandbar is moving more towards the offshore in all four profiles and from the -7m depth up until the local depth, the profile is very stable and no significant changes can be seen. The profile is more stable though than that at the western bend and in general a small accretion is shown across the entire profile over the years. The somewhat sheltered location of this site is due to this, as can also be seen in the wave heights and directions in Section 7.1. The south-western side of Delta21 will be similarly sheltered and show the same process, although the numerical model will have to quantify this.

## 5.7. SEDIMENT

The sediment characteristics and settings used for the modelling will be similar to those used in the original modelling of Maasvlakte 2. The transport formula of Bijker (*Bijker 1967, 1971*) is used with a $D_{50}$ of 370 $\mu m$ and a $D_{90}$ of 555 $\mu m$. For a full overview of all the

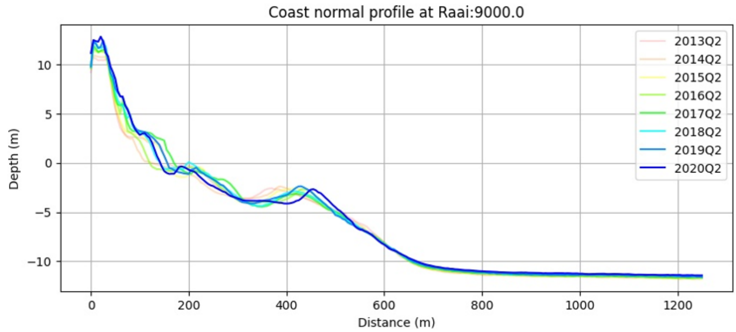



Figure 5.15: Profile changes over the years 2013-2020 for ray 9000, at the south-western side of Maasvlakte 2.

sediment characteristics used, please see Appendix F. For the creation of the dunes of Delta21, there has been a desire to re-use the available sediment from the Energy Storage Lake, as this will require excavation up until 17 meters depth, generating large amount of available sediment. From drilling samples and soil-sediment gradings present at the location of the energy storage lake, an average $D_{50}$ of 140 $\mu m$ and a $D_{90}$ of 200 $\mu m$ was taken across several samples. These were used to model the effects for the alongshore sediment transport when this sediment would be used to create the profiles and dunes of Delta21. Due to a somewhat lack of drilling samples and data across a larger depth, it has been assumed that this grading occurs throughout the entire depth and over the entire surface area of the Energy Storage Lake, up until the level that is required for excavation. In reality, a somewhat larger grain size is found at larger depths, as seen from the grain distribution graphs in the Appendix as well as larger grain sizes further north of the Energy Storage Lake.

## 5.8. TIDAL MODELLING

The tides used in this study for the modelling of the maintenance requirements come from a previously performed Delft3D model by Jelmer IJntema, another student that has worked on the Delta21-project. An example of an tidal time series used can be seen in Figure 5.16 for ray 3600. For the model 0 scenario in UNIBEST and thus the verification of the model, the tides come from the Delft3D model performed for the original design of the Maasvlakte 2 soft coastal protection. An excerpt can be seen in the Appendix. This data consists of a 15 day time-series from the Delft3D model, of which the spin-up time (1 day) has been removed.

From Figure 5.17, one can see that at ray 3600, at the western bend, the peak tidal velocity and peak water level occur almost simultaneously and the tidal velocities are rather high, up to 1.4 m/s. Compared to ray 9600, the tidal velocities at ray 3600 during low tide are also much more irregular. As expected due to the tidal squeeze in the bend, the tidal velocities at ray 3600 at also 2-3 times higher than those at ray 9600. The tide is slightly asymmetrical and water level elevation is in the range of -0.8m to +1.3m for both locations.

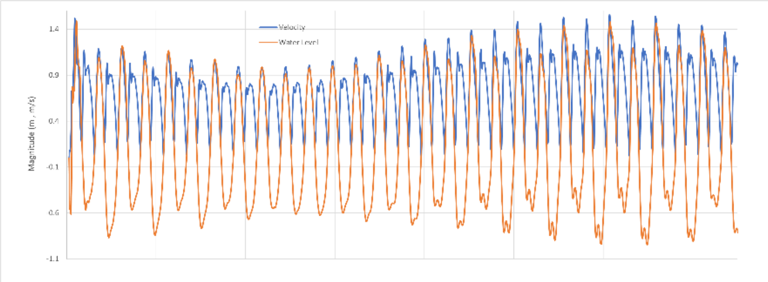



Figure 5.16: Tidal time series, showing the velocity and water level elevation at Ray 3600, at the western bend of Maasvlakte 2.

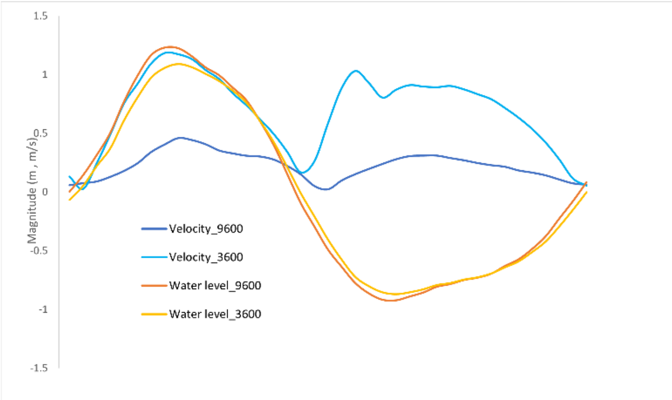



Figure 5.17: Tidal elevation and velocity of ray 3600 (west) compared to ray 9600 (south-west) at Maasvlakte 2 at a depth of around NAP -20m.

This schematisation of the model has been validated by means of comparison to the water level measurements in Hoek van Holland and thus is assumed to represent the tidal conditions at Maasvlakte 2 accurately. Subsequently, the modelled tidal conditions for Delta21 can also be assumed reliable data and thus no further validation for this data has been performed. For the model 1 scenario in UNIBEST, the tides come from the same Delft3D model in which the Delta21 bathymetry was included in a different run.

## 5.9. DISCHARGES

The literature review showed that the sluices at the Haringvliet and their flushing-regiment had little to no impact on the coastal maintenance at Maasvlakte 2 and only limited impact on the sedimentation in the Euro-Maasgeul *(S. Boer and Roukema, 2004)*. Furthermore, modelling done for the Delta21 Voordelta (IJntema, 2021) and tidal delta (Pina, 2020) showed that the Delta21 project's layout and the subsequent opening of the Haringvliet sluices had only limited impact on the sediment balance at the dunes of Delta21 and virtually no impact on the area of research, northwards of Maasvlakte 2 and at Delta21. The exact layout, size and orientation of the pumps and sluices and the presence of any protection or structures hereby, such as erosion-mats or breakwaters, near the sluices is not yet determined. As such, the current modelling of the discharge of the Haringvliet in the Delft3D-model will therefore not be adjusted and no specific alterations will be made to account for this in the SWAN or UNIBEST models. Discharges and currents from the rivers, which were modelled as a yearly-averaged discharge in the different Delft3D models, are not taken into account in both the SWAN or UNIBEST modelling.

# 6

# MODEL SETUP

## 6.1. INTRODUCTION

In this chapter, the models used will be introduced, explained and the actual setup and input parameters of the different models will be discussed. In principle, all computational models used will be executed twice; once for an area where the outcome has been pre-determined by means of measurements or calculations to validate and calibrate the model (Model 0), and once to model the actual impact of Delta21 on the area of interest (Model 1). Once the model 0 proves to provide an accurate representation of the conditions present, Model 1 will be ran. The setup between these models do not differ much, as only the bathymetry is assumed to have changed between Model 0 and Model 1, while other input, parameters and settings are maintained mostly the same.

## 6.2. WAVE-MODELLING

### 6.2.1. INTRODUCTION

SWAN (Simulation of Waves in Nearshore Areas) is used to model the transformation of the reduced representative off-shore wave conditions (Europlatform) at deep water to the surf zone at Maasvlakte 2 and the Delta21-dunes *(Ris et al., 1999, Booij et al. 2004)*. SWAN is wave-modelling software for wind-generated surface gravity waves, based on the spectral action balance equation with sources and sinks, representing the effects of spatial propagation, refraction, shoaling, generation, dissipation and nonlinear wave-wave interactions *(SWAN Team, 2020)*. In short; energy growth occurs due to wind input, energy is transferred due to wave-wave interactions and energy is dissipated due to white-capping, bottom friction and depth induced wave breaking *(SWAN Team, 2020)*. The version of SWAN used in this study is 41.20, released in May 2019.

### 6.2.2. COMPUTATIONAL GRIDS

An important choice in the setup of SWAN is the computational grid. It is a weigh-up of computational time on the one hand and the desired accuracy on the other hand. Having a high resolution grid provided greater accuracy measurements at the cost of

| Grid | Origin X | Origin Y | Rotation | M-cells | N-cells | Resolution |
|---|---|---|---|---|---|---|
| A | 26000 | 390000 | 45 ° CCW | 480 | 240 | 250x250m |
| B | 50000 | 414500 | 45 ° CCW | 400 | 200 | 150x150m |
| C | 52000 | 433000 | 45 ° CCW | 320 | 120 | 50x50m |

Table 6.1: Computational grids used for the SWAN wave modelling.

larger computational effort and time. In order to achieve both a high resolution model and accurately model waves from various offshore locations, nested grids are used. With nested grids, you first compute the waves on a coarse grid for a large region, then move to a finer grid for a smaller region. Each finer grid uses boundary conditions generated by the larger grid, while the outer most grid has the offshore wave conditions applied on its borders, as seen in Section 5.2.3. The finer grids are applied further towards the nearshore, where higher bottom gradients are present and a higher spatial resolution is required.

The computational grids used in the wave-modelling are summarised in Table 6.1 and a full page map can be found in the Appendix. All grids are rectangular grids with their coordinates in the Cartesian notation. The grids' origin, extent and resolution can be seen in Table 6.1. All grids are rotated in a 45 degree angle counter clockwise, similar to the natural orientation of the Dutch coast. All coordinates are in the Cartesian projection, with the Rijksdriehoek (RD new) / Amersfoort as the geodetic coordinate projection. The grid cells themselves are square.



Grid A & B were chosen such that the Dutch closure dams are also included in the model and waves from the south-side of the computation grid do not have to be imposed. Grid C was chosen in such a way that a high resolution grid of the entire Delta21 project-area and Maasvlakte 2 was obtained. However, after initial modelling, grid C proved to have a very large computational time, and thus it was chosen that its size was reduced to only cover the northern section of Maasvlakte 2 and the Delta21 dunes. The grids have an increasingly higher resolution for each subsequent grid and are spaced apart sufficient wave lengths to allow for resolving between the grid boundaries, which is a requirement for accurate wave resolving in SWAN.

For the creation of the depth files for the SWAN input, the different bathymetries were altered to coincide with the computational grid. This means that for the 150x150 grid, the .dep depth-files were created in this same 250x250m resolution and likewise for the 150x150m and 50x50m grids. This means that any coarser bathymetry, such as the EMODnet bathymetry, with a bathymetry of 250x250m will have to be interpolated, while any finer bathymetry than the computational grid, such as the 20x20m bathymetry will require grid cell averaging to get the desired resolution.

A Python script was used to populate the base-files for each of the grids A,B and C. For grid C, the reduced wave climate of 100 wave conditions was applied on all four borders of the grid. The nested grid output was applied on the borders of B and vice versa for grid B on grid C.

Furthermore, the spectral resolution is defined as a full circle divided per 72 sections, such that a spectral directional resolution of $\Delta\Theta = 360°/72 = 5°$ is obtained. The lowest (flow) and highest (fhigh) discrete frequency is defined as 0.03 and 1.50 respectively.

### 6.2.3. WAVE MODELLING PARAMETERS

#### PHYSICAL & NUMERICAL SETTINGS

The precise physical and numerical settings for SWAN that have been applied can be found in Appendix D. For most settings, the default options for accurate modelling of North Sea waves have been used, although some settings have been altered to acquire a more stable and higher accuracy model. For the used settings for each grid and an example of the SWAN input files, the reader is referred to Appendix D.

#### OUTPUT & OTHER SETTINGS

The output of the SWAN-model differs per computational grid. While for grid A & B only a nested 'out'-grid is outputted, for grid C the output was defined as a .tab-file for the required raaien and a .mat (MATLAB) file for each computational grid cell. With the .tab-file the exact coordinates for the start of the raaien can be retrieved, which are the input location for the UNIBEST model. These files are only suitable for exact coordinates and have interpolation to calculate between grid cells. While the MATLAB file is more convenient to use for data per grid-point and has a significant smaller size, it can not be used for exact coordinates. A Python script was made which can interpolate the values in the .mat files, based on the characteristics, such as size, number of grid cells and orientation of the computational field. This can be found in Appendix **??**. The data is then converted to .SCO-files, which serve as input for the UNIBEST-LT Module. For the models which require tidal conditions, these are then added to the same .SCO-file



### 6.2.4. ACKNOWLEDGEMENTS

Firstly, there are several shortcomings with the model. For the SWAN model, the water level increase for each different wave condition has not been modelled. Each wave condition will have a certain increase in water level compared to the mean sea level, however, due to lack of consistent data at the Europlatform and the expected limited impact that this will have on the wave transition to the nearshore, this has not been included in the model. The expected water level increase is in the order of several decimetres at most and compared to the water depth at the Europlatform, this was deemed insignificant to yield any large impacts on the wave transition. Additionally, tidal-, wave-, and wind-induced currents have not been included in the model. These can be provided as input to SWAN from a circulation model in an iterative process, but this was seemed irrelevant for the goal of this model. Storm surges have also not been included in all the models.

Secondly, during the SWAN modelling, several problems and bugs were encountered which hindered and delayed the modelling progress. The first type of error encountered was due to the waves set on the boundaries of the model. Since the waves were set for the entire length of the boundary, including the part which touches the coastal zone, unrealistic waves were imposed at these areas. This had to be solved by disabling the boundary check within SWAN. Several of these errors were due to convergence problems, wherein the iteration steps (spatial propagation of waves, spectral propagation and wave-induced setup), no convergence can be achieved. This errors were mostly caught by either reducing the convergence requirements or the convergence limits for the specific wave condition. This does however limit the accuracy of the results. Errors due to the immediate calculation of subsequent grids are caused due to SWAN not having properly processed and synced the output of previous grid before executing the next one.

## 6.3. COASTLINE MODELLING

### 6.3.1. INTRODUCTION

For the coastline modelling, the coastline modelling software package UNIBEST-CL+ is used. UNIBEST-CL+ is a tool for simulating longshore sediment transport and coastal morphodynamics and consists of the modules UNIBEST-LT and UNIBEST-CL *(Deltares, 2011)*. The UNIBEST-LT module firstly calculates longshore transports caused due to tidal- and wave induced alongshore currents for various cross-shore trans sects. Shoreline migration is then calculated using gradients in alongshore transports estimated at specified points along the coast in the UNIBEST-CL module. The $S-\varphi$ curve, which is the relation between the orientation of the coast and longshore transport, serves as the foundation for the shoreline modelling in UNIBEST-TL *(Walstra, 2000)*. It provides details on transport gradients produced by coastline curvature, as well as the longshore transport's time-dependent reaction to changes in coast-orientation across time. UNIBEST-CL+ can evaluate the longshore transport and its distribution using various sediment transport formulae. Throughout this thesis, the process based formulation by *Bijker (1971)* is used, which is an accurate total load formula for the sediment characteristics present in the study area and which is available in UNIBEST-CL+ *(Camenen and Larroudé, 2003)*.



### 6.3.2. CONNECTION TO MAASVLAKTE 2

For the effect of the Delta21-project on Maasvlakte 2, the method, angle, location and characteristics of the 'attachment' will certainly influence the behaviour. Since exact design specifications are not yet determined for this connection, this connection is modelled in UNIBEST-LT and UNIBEST-CL as a direct connection from ray 58 of Delta21 to ray 3800 of Maasvlakte 2. Here, the design profile and bathymetry of Delta21 meets up with the bathymetry of Maasvlakte 2, half-way at the soft sea defence of the north-western section. In Figure 6.1, this connection is visualised. From this default location, there are two options:

- A connection to, or closer at, the transition between the soft- and hard sea defence at Maasvlakte 2 can negatively impact the gravel profile of the hard coastal profile. A sudden influx of sand caused by the connection and sudden change in coastline orientation can cause washing in of sand and destabilisation of the profile.
- A connection more to the western side of Maasvlakte 2 will likely have a positive effect on current development of the scour hole at Maasvlakte 2, since the point of tidal contraction will be moved further to the south-west. On the long term, this can however lead to a significant sediment deposit, dependent on the exact specifications and coastline orientations of the attachment.

Based on the aforementioned two consequences, a location further south/south-west thus appears more beneficial. The final position of the connection in the design will have to be based on a combination of the aforementioned two consequences along with criteria such as costs and long term consequences for both the wash-in of sediment at the hard sea defence, the tidal contraction and the impact on the Euro-Maasgeul.

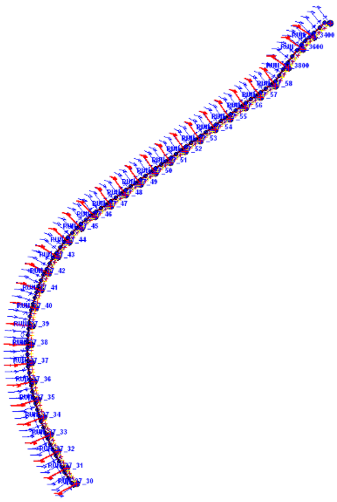


Figure 6.1: Visualisation of the Delta21 coastline, as represented in UNIBEST-CL. The connection of Delta21 to Maasvlakte 2 is modelled at Ray 3800 at the north-western side of Maasvlakte 2. For each run, the distinct wave conditions present at every ray are modelled, summarised in the UNIBEST-LT .RAY-files. These are visible by the differently numbered .RAY conditions at each coast normal



Figure 6.2: Visualisation of the connection and the location of each of the calculated rays, as represented in UNIBEST-CL (see Figure 6.1 and overlaid on the map of the research area.

### 6.3.3. OUTPUT

The output of the UNIBEST-LT models contain all information regarding the sediment transport, such as the calculated total transports per coastline orientations. Furthermore, they contain the current- and equilibrium coastline angle, active height of the profile, the shape (factor) of the profile, parameters describing the $S - \Phi$-curve and the way the sediment is distributed in the cross-shore direction. The individual RAY-files can then be fed into the UNIBEST-CL model, yielding the coastline changes and modelled erosion volumes. In UNIBEST-CL, these RAY-files are then applied at the various shore-normal ray locations along the Maasvlakte 2 and Delta21 coastline, as visualised in Figure 6.1. This created the most accurate model, as each location in the model has its own distinct wave-climate.

The output from the UNIBEST-CL models will then mostly consist of these visualised erosion rates, alongshore sediment transport and calculated erosion volumes for various periods and locations.

### 6.3.4. ACKNOWLEDGEMENTS

In order to minimise the model errors, preliminary models have been set up before executing the actual models to understand the shortcomings, restraints and requirements of the input data. To further minimise user errors and inconsistencies, great effort was put into various Python scripts, which were used to populate the model with the required data and files. Since no extensive documentation on the data-requirements exists, this was mostly done by trial and error. In addition, the latest version of the UNIBEST software is written for operating systems which are currently outdated and dates back to 2010, which at the time of writing is 11 years ago. Several errors and crashes of UNIBEST related to the programming can occur, especially while working with a large amount of rays (up to 100) and their corresponding combined wave- and tidal calculative conditions (up to 3000 per ray).

In regards to the connection of Delta21 to Maasvlakte 2; since UNIBEST assumes an almost uniform alongshore coast, the sharp bend at the attachment near ray 3800 cannot be modelled accurately. For the determination of whether a wave is shore-directed for a ray in this shadow-zone, only the corresponding coastline orientation is used, while the nearby coastlines are not taken into account. This will likely cause a slight overestimation of the waves in this shadow-zone at the connection.

To be usable in the UNIBEST model, the tidal cycles have to be schematised as a table in which the tidal elevation, tidal velocity, tidal angle in relation to the coastal angle and chance of occurrence are summarised. Due to the limitations of UNIBEST, this tidal schematisation has to be limited to 30 conditions, as with 100 wave conditions, this leads to a maximum total of 3000 calculative conditions, which is the maximum of UNIBEST per cross section. Similarly to the schematised tidal conditions for Maasvlakte 2, a threshold of 0.4 m/s was maintained, such that all tidal conditions below this threshold will not be modelled. An example of the tidal schematisation for ray 3600 can be found in Figure B.8

6

| **Velocity** | **Occurence** | **Ref. Depth** | **Elevation** |
|---|---|---|---|
| 1.052838 | 0.018831 | 20.03032 | -0.84328 |
| 0.984143 | 0.031715 | 20.03032 | -0.84703 |
| -0.70386 | 0.031715 | 20.03032 | 0.756167 |
| -0.83515 | 0.021804 | 20.03032 | 0.75784 |
| -0.90472 | 0.063429 | 20.03032 | 0.923882 |
| -1.00292 | 0.030723 | 20.03032 | 0.910332 |
| -1.08217 | 0.046581 | 20.03032 | 1.070753 |
| -1.20831 | 0.022795 | 20.03032 | 1.070073 |
| -1.14134 | 0.02775 | 20.03032 | 1.220865 |
| -1.39015 | 0.00892 | 20.03032 | 1.214588 |
| -1.32053 | 0.019822 | 20.03032 | 1.381387 |
| -1.49611 | 0.005946 | 20.03032 | 1.373335 |
| 0.943718 | 0.03667 | 20.03032 | -0.714 |
| 0.863813 | 0.046581 | 20.03032 | -0.69996 |
| 0.843063 | 0.054509 | 20.03032 | -0.53339 |
| 0.782738 | 0.111001 | 20.03032 | -0.53797 |
| 0.846947 | 0.052527 | 20.03032 | -0.38593 |
| 0.664525 | 0.081269 | 20.03032 | -0.39236 |
| 0.417948 | 0.023786 | 20.03032 | -0.21614 |
| -0.45837 | 0.021804 | 20.03032 | 0.431447 |
| -0.52167 | 0.017839 | 20.03032 | 0.441904 |
| -0.57135 | 0.026759 | 20.03032 | 0.593567 |
| -0.70136 | 0.017839 | 20.03032 | 0.584979 |
| 0 | 0.179386 | 20 | 0 |

Table 6.2: Schematised tidal conditions for Ray 3600, at the western bend of Maasvlakte 2, at a depth of around NAP -20m. This location has one the largest number of modelled tidal conditions of all rays, as tidal velocities here are larger and the majority surpass the 0.4 m/s threshold. The last tidal condition has no contribution, but is due to the tidal requirements in UNIBEST, which requires a total of 100% for multiplication with the number of wave conditions for each calculative condition.

# 7

# MODEL RESULTS

In this chapter, the results from the individual SWAN and UNIBEST models ran will be displayed and compared with the initial PUMA models and measured data. The actual results from both the models are quite limited, as SWAN merely translates waves from the offshore to the nearshore, while UNIBEST will only yield the alongshore sediment transports and erosion along the cross-shore transects. Python scripts were primarily used to process and visualise the output data and making it suitable for usage in the other models.

## 7.1. WAVE FORECASTS

### 7.1.1. WAVE NORMALISATION

The output from each individual SWAN run is stored in a .tab file for each of the 100 wave conditions in a wave climate. A Python script (see Appendix **??**) was used to then extract the wave conditions for each individual location from each SWAN output file and is then combined with the tidal-current data from the external Delft-3D model to create an wave and current input file for UNIBEST-LT. The data required the removal of the off-shore directed waves, primarily caused by off-shore wind, as these wave conditions cannot be imported in UNIBEST-LT. Therefore each wave condition is checked against the coast normal orientation and calculated whether it is within +/- a normalised 90 degrees. The percentage of shore-directed waves that are remaining is then normalised with the total amount of waves present and visualised by the percentage of shore-directed waves, as seen in the example in Figure 7.2.

### 7.1.2. ANALYSIS NEARSHORE WAVES

In Table 7.1, the 10 largest occurrences of transformed waves (not excluding any offshore directed waves) for the period 2013-2014 from the offshore to the nearshore can be seen for several locations along the Maasvlakte coast, namely the northern-, western- and south-western side of the soft sea defence. It can be seen that the vast majority of the high occurrence waves for all three locations are coming from the WSW to NW side (330 °- 15 °), dependent on the location. This can be see in more depth in the table on page

| | Occur. (%) | Dir. (°) | Hm0 (cm) | Tper (s) | Wind (°) | Wind (.1m/s) | Location 2000 Hsig (m) | Location 2000 Tper (s) | Location 2000 Dir (°) | Location 5000 Hsig (m) | Location 5000 Tper (s) | Location 5000 Dir (°) | Location 7000 Hsig (m) | Location 7000 Tper (s) | Location 7000 Dir (°) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 7,94% | 90,00 | 77,51 | 3,79 | 114,48 | 74,72 | 0,34 | 2,45 | 65,81 | 0,31 | 4,45 | 72,03 | 0,21 | 2,03 | 146,99 |
| 50 | 7,20% | 235,49 | 96,90 | 4,20 | 228,07 | 73,24 | 0,64 | 4,87 | 261,26 | 0,73 | 4,88 | 249,98 | 0,69 | 4,86 | 252,33 |
| 90 | 6,70% | 337,57 | 83,27 | 4,61 | 232,90 | 51,87 | 0,85 | 5,43 | 323,93 | 0,88 | 5,43 | 322,07 | 0,79 | 5,43 | 315,23 |
| 95 | 6,03% | 354,07 | 64,89 | 4,69 | 173,85 | 41,87 | 0,60 | 5,48 | 347,34 | 0,62 | 5,49 | 347,19 | 0,52 | 5,48 | 333,49 |
| 0 | 5,18% | 5,57 | 65,24 | 4,56 | 158,76 | 45,17 | 0,60 | 5,39 | 352,26 | 0,63 | 5,39 | 352,22 | 0,49 | 5,39 | 332,09 |
| 5 | 4,58% | 20,05 | 70,48 | 4,09 | 91,43 | 57,69 | 0,58 | 4,88 | 14,18 | 0,56 | 4,89 | 9,32 | 0,40 | 4,87 | 353,02 |
| 55 | 3,33% | 249,57 | 78,86 | 4,04 | 230,06 | 63,64 | 0,55 | 4,85 | 264,43 | 0,61 | 4,85 | 253,70 | 0,58 | 4,84 | 256,18 |
| 85 | 2,82% | 319,52 | 102,22 | 4,54 | 266,02 | 63,56 | 0,90 | 5,40 | 312,03 | 0,93 | 5,40 | 310,46 | 0,87 | 5,40 | 307,64 |
| 45 | 2,71% | 227,97 | 121,06 | 4,44 | 223,92 | 83,85 | 0,93 | 5,26 | 264,74 | 1,04 | 5,26 | 255,92 | 0,98 | 5,22 | 257,96 |
| 35 | 2,32% | 223,05 | 116,71 | 4,35 | 220,25 | 86,29 | 1,10 | 4,54 | 265,87 | 1,21 | 4,60 | 258,47 | 1,12 | 4,55 | 260,50 |

Table 7.1: SWAN Model 0 - Largest 10 occurrences (total ≈ 50%) of reduced wave conditions for the period 2013-2014, transformed by SWAN to nearshore for the locations 2000, 5000 and 7000.

116 in Appendix E for the full wave climate of 100 wave conditions.

For the Model 0 - Maasvlakte 2 modelling, waves from the north/north-east are more dampened at the south-western side of Maasvlakte 2 and waves from the west/south-west are more damped out at the hard coastal protection, as seen in the decrease in wave height. Some waves, such as wave number 90, are measured quite low at the Europlatform and under the governing wind increase in height towards the shore. Furthermore, waves have the tendency to get more perpendicular towards the coast due to wave refraction caused by the change in bottom elevation. This can be seen in the difference in measured wave angles between the Europlatform and Maasvlakte 2. Off-shore directed waves, generally having a lower wave height, are impacted more heavily due to the wind having a larger impact on this, seen in the more present change in wave direction.



These wave directions measured at each of the location do however not entirely coincide with the spectral directions from the majority of waves coming from the Europlatform. If these incoming waves at Maasvlakte 2 are plotted as a wave-rose, as seen in Figure 7.2, a more clear understanding is gained and even more so when comparing these to the wave-rose from the same period at the Europlatform, as seen in Figure 7.3. Firstly, the 'onshore' wave rose at each of the locations show more distinct wave directions in comparison to the one from the Europlatform. While there are gaps in between the waves at Location 5000, the wave spectrum at the Europlatform is much 'fuller'.

Looking at each individual wave rose on the map in Figure 7.1 shows there are two main wave directions that are present at most locations that do not precisely match the concentration of waves shown for the Europlatform. This is due to the method of wave input reduction. Since the reduced wave climate was based on the sediment transport proxy, and thus on the wave height and wave angle in relation to the coast normals, there is a bias in these wave roses for the waves with the highest sediment transport contribution, which causes this exaggeration of specific waves. These wave roses are thus representing more a sort of 'morphological wave climate', meant to reproduce annual sediment transport and not the full wave climate.

### 7.1.3. MODEL VALIDATION

The results from the SWAN Model 0 have to be validated to check whether they are an accurate representation of the wave conditions present at the nearshore of Maasvlakte 2. If so, these offshore conditions can then also be used for the SWAN Model 1 trans-

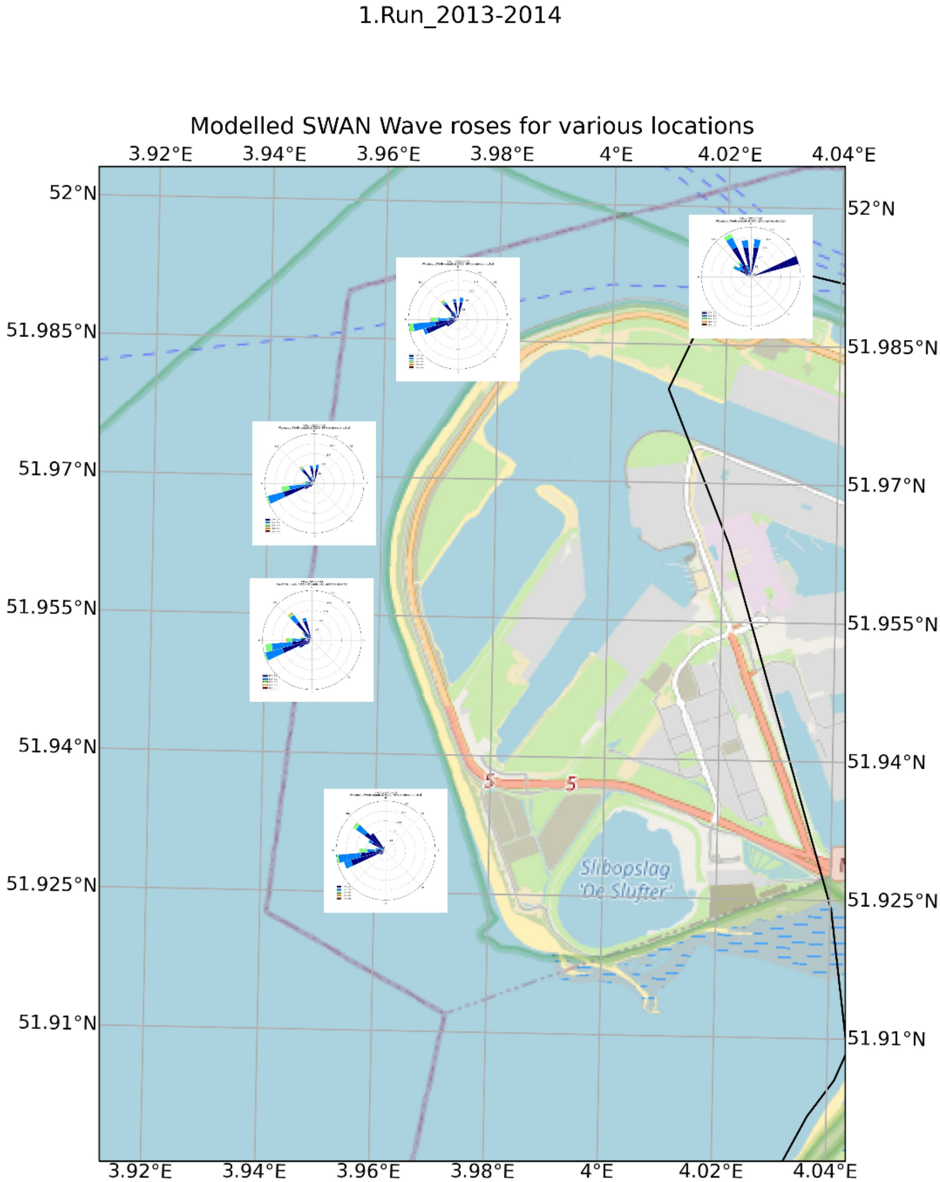



Figure 7.1: Wave rose map for various locations along the coastal defence Maasvlakte 2 for the period 2013-2014.

formation to the nearshore at Delta21. However, this appeared to be challenging. As previously shown in Chapter 5 and in the aforementioned Section, due to the usage of a reduced wave climate, there is a bias towards waves with a higher wave height and from specific directions. This makes the comparison of a reduced wave climate transformed to the coast to a full-scale near-shore wave climate somewhat skewed. Besides this, there is a lack of usable near-shore wave data for Maasvlakte 2. Although there is a wave measuring station close to Maasvlakte 2, upon closer inspection the data there proved to be inconsistent and not suitable for comparison.

The SWAN Model 0 results were therefore compared to the PUMA model results and general coarse wave data available for Maasvlakte 2. This limited comparison, showed that the wave heights, -periods and -directions for the Maasvlakte 2 coast are within the expected range. This then served as a validation of the Model 0 SWAN results. Additionally, as a means of validation, for the Model 1 - Delta21 modelling, similar observations are made in comparison to those of Model 0. More of these results can be found in the Appendix. Some previously observed processes are amplified. The larger shadow zone for the northern-side of Maasvlakte 2 due to the location and extent of Delta21 will have a larger impact on waves from the west to south-west.

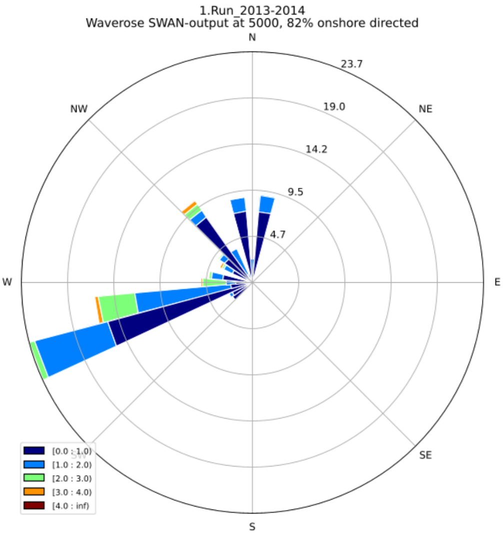



Figure 7.2: SWAN wave rose for Location 5000 at the western bend of Maasvlakte 2. Period 2013-2014.

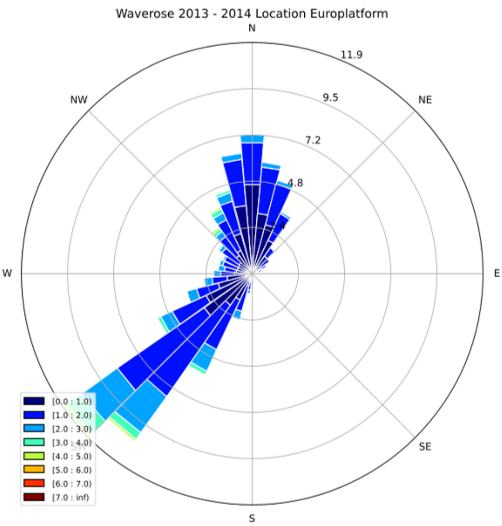



Figure 7.3: Wave rose for 2013 - 2014 for Europlatform.

## 7.2. COASTLINE DEVELOPMENT MODEL 0

For the Model 0 modelling and the validation of the model, for each of the available years (2013-2020), a UNIBEST-LT model has been set up. The results of which are then presented in this section. For each of these models, the corresponding SWAN wave climate specific for that specific year has been used, while for the yearly average the averaged wave climate of 1997-2020 has been used.

Firstly, the results from the input wave reduction using the sediment transport proxy are compared to the results from the wave energy flux reduction. These can be seen in Figure 7.4. Comparing these to the modelled results by PUMA, a better fit is found with the sediment transport proxy than with the wave energy flux, as the southward directed transports with the latter are too high in comparison to the north-ward directed transports. The sediment transport proxy is therefore chosen as the most promising wave input reduction method and will be used for the modelling hereafter.

Using this wave reduction, Figure 7.5 shows the modelled alongshore sediment transport above -8m NAP per year for each of the rays along Maasvlakte 2 coastline. For all the years, the behaviour is consistent; around ray 6000 to 9600 there is a southward directed transport, while for the other rays, there is a more northward directed transport. The south-ward transport in the range of 250.000-450.000 $\mathrm{m}^3$/year, while the north-ward transport has a much wider range of 80.000-500.000 $\mathrm{m}^3$/year. Compared to the modelled sediment transports in the PUMA report, the ratio of the north-bound and south-bound sediment transports is slightly different. However in the PUMA report, the north-bound transports from ray 7400 have been multiplied by a factor of 2 due to a underestimation of the north-bound tidal current in UNIBEST compared to their Delft3D model. Moreover, year 2016-2017 is somewhat of an outlier, in which the northward directed transports are significant lower than average, while also the southward directed transports are lower. This seems to however correspond to the observation made in the PUMA nourishment volume report, where they remark that the second planned nourishment in 2016 was significant less than originally planned due to decreased wave action in that year *(PUMA, 2018)*. This is also visible in the decreased erosion pattern for 2016-2017 on page 88 in the Appendix.

7

The erosion- and sedimentation behaviour shown is matching to that modelled by PUMA. Similarly to the PUMA modelling, the previously observed accretion between rays 6800-8000 and erosion between rays 8200-9600, discussed in Section 4.6 and seen in Figure 4.2, does not coincide with the modelled alongshore sediment transport. It therefore remains unclear whether a similar effect and erosion pattern for Delta21 can be expected at similar locations.

### 7.2.1. INFLUENCE OF TIDAL CURRENTS

Following Section 5.8 for the setup of the tidal modelling and the characteristics of the tide, the effect of the tidal currents and -elevation on the alongshore sediment transport has also been modelled. In Figure 7.6, the mean alongshore sediment transport per year over the period 1997-2020 has been plotted. The difference between the two models is small and almost insignificant compared to the wave-induced sediment transports. The modelled absolute net differences in alongshore sediment transport range between 1.000 and 22.000 $\mathrm{m}^3$/year. The differences are lowest at the south side, between ray

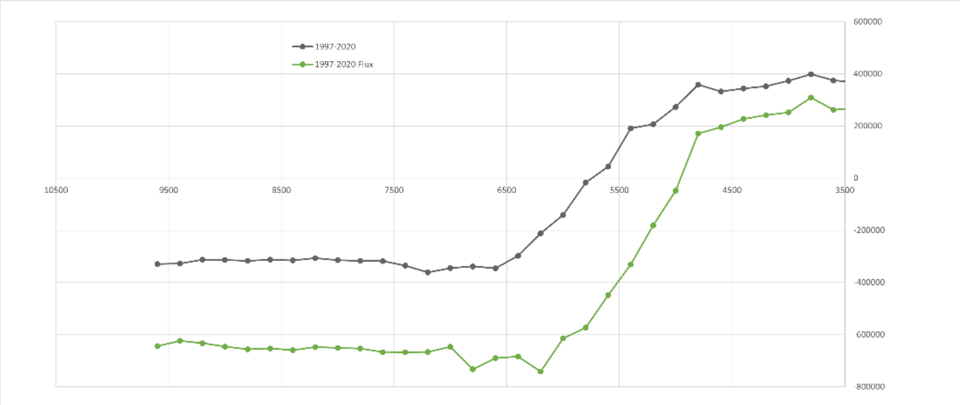



Figure 7.4: UNIBEST modelled net sediment transports per year, per ray in $m^3$/year above -8m NAP for the Sediment Proxy-reduced wave climate (black) and the Wave Energy Flux-reduced wave climate (green), excluding tides.

7

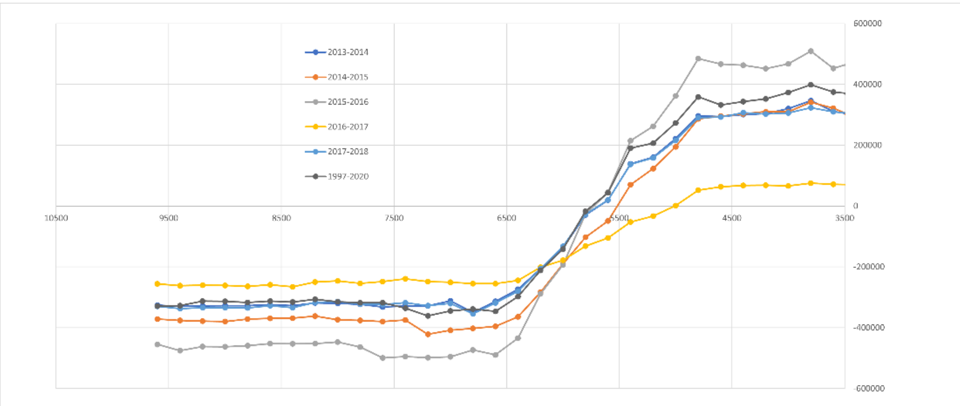



Figure 7.5: UNIBEST modelled net sediment transports above -8m NAP for Maasvlakte 2 per year, per ray in $m^3$/year. Wave climate per year, excluding tides.

7000-9600, while at the bend and the northern side they are much higher. This is to be expected, as the tidal velocities at these points are larger. As only the area above -8m NAP is modelled, the effect of the tide on the lowest section of the profile and the area at which the tidal contraction and scour hole is most present can not be accounted for in this model. These effects are best studied with the usage of a more specialised morphological model. In the initial PUMA model of the tidal currents and contribution to the alongshore sediment transport for Maasvlakte 2, the values in UNIBEST-LT also seemed to be under-represented close to the coast *(PUMA, 2018)*. This is mainly a consequence of the modelling of tidal velocities in UNIBEST-LT, which are significantly reduced in shallow water (Chézy). The tidal velocities are retrieved from the Delft3D modelling depth of around 20 meter, which UNIBEST translates inaccurately to the nearshore. In the PUMA modelling, the effect of the tides was therefore compared to the Delft3D results and multiplied by a factor of 2. Since the used Delft3D model does not allow for a more accurate description of the tidal data closer to the coast and no exact data is available on the contribution of the tide to the measured erosion or performed nourishments, the tidal contribution to the alongshore sediment transport can not be accurately validated. Thus, while inaccurately modelled, the decision was therefore made that the contribution from the tidal currents was still insignificant compared to the wave-driven contribution and that the tidal currents will not be modelled in the model 1 results for Delta21.

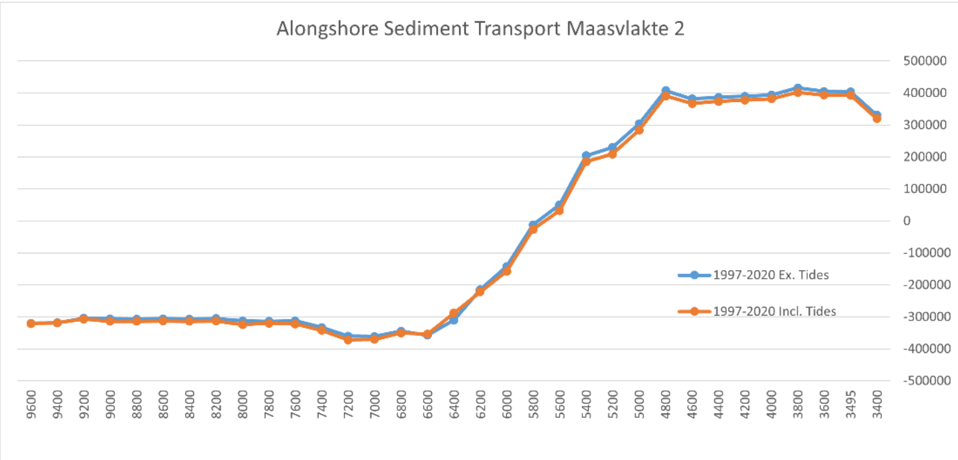



Figure 7.6: Maasvlakte 2: difference in mean alongshore sediment transport per year between a wave climate excluding tides (blue) and including tides (orange) for the period 1997-2020. Per ray, for the section above -8m NAP. Quantities in $m^3$/year.

### 7.2.2. MODEL VALIDATION

To validate and compare the Model 0 results, initially a comparison was made to the PUMA model for Maasvlakte 2. These results, as previously shown in Chapter 5, show the various modelled sediment transports above -8m NAP for each ray along the soft sea defence of Maasvlakte 2. The modelled transports were however not according to the actual occurring erosion volumes and required coastal nourishments in the first years, In the PUMA Suppletie-plan 2014, the choice was made to not use the model data as a guidance for the maintenance requirements, but the actual occurring morphological behaviour and erosion volumes *(PUMA, 2018)*.

For the results shown in Section 7.2, the decision is therefore made to match the results to those of the actual coastal nourishments and erosion, as mentioned in Section 4.6. Based on the modelled 1997-2020 yearly alongshore sediment transport in UNIBEST-LT for Maasvlakte 2, an average yearly total sediment loss of 750.000 $m^3$/year is modelled, of which around 400.000 $m^3$/year northward and 350.000 $m^3$ southward.

In Figure 7.7 and Figure 7.8, the modelled average sediment transport rate and modelled average yearly erosion rate in UNIBEST-CL for Maasvlakte 2 are shown, respectively. A total volumetric sediment loss of 770.000 $m^3$ was then calculated. In Figure 7.8, showing the erosion along the coastline of Maasvlakte 2, the distinct erosion along the western bend is visible. As expected, the graph however does not show the occurred erosion along the recreational beach, between ray 8.200 - 10.000, and at the northern section, between ray 3.400 - 4.200, as previously shown and discussed in section 4.6. The interaction between the soft- and hard sea defence in the north is not included in this model, while the erosion at the recreational beach is hard to model and not yet fully understood. Since the total erosion volumes between the two graphs are within the same order of magnitude, there is thus an overestimation of erosion at the western bend.

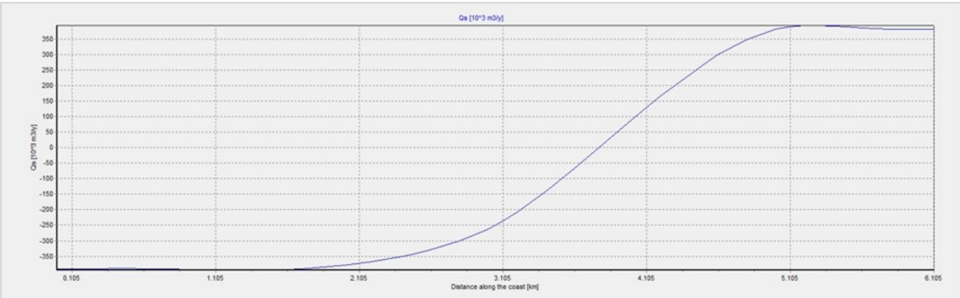



Figure 7.7: Modelled alongshore sediment transport rate of Maasvlakte 2 in UNIBEST-CL after one year. From ray 9600 (left) to ray 3400 (right), total length 6200 meter, for the reduced wave climate of 1997-2020, excluding tides.

For these transports, no interaction with the surroundings & transports are assumed at the most southern- and northern transects, such that a net zero boundary condition is applied. Also enough sediment was assumed available at the boundaries. This is then compared with both the yearly averaged measured erosion volume of 0.9 million $m^3$/year and the yearly average nourishment volume of 0.7 million $m^3$/year for the profile above -8m NAP. The difference between the UNIBEST model and these figures is then in the ballpark of max. 150.000 $m^3$/year. This difference is seemed insignificant to require a correctional factor to the modelled transports to correct these to the actual nourishment- and erosion losses.

It should also be noted that this validation, based on the erosion- and nourishment volumes above -8m NAP, assumes that all erosion above -8m NAP is due to wave-induced

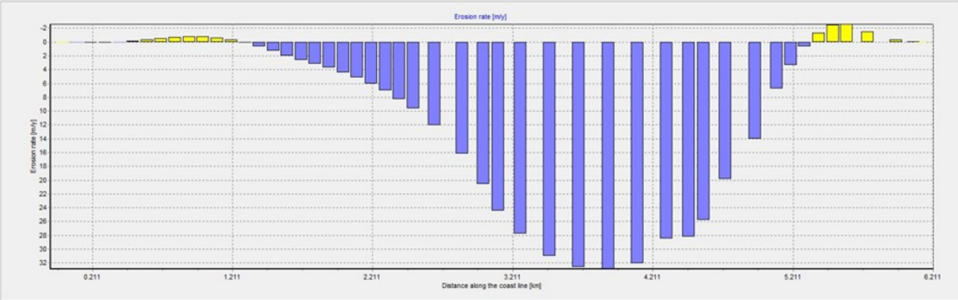



Figure 7.8: Modelled erosion rate in UNIBEST-CL per year of Maasvlakte 2 coast from ray 9600 (left) to ray 3400 (right) after one year, for the reduced wave climate of 1997-2020, excluding tides.

sediment transport and all erosion below -8m NAP is due to tidal-current induced sediment transport. In reality, although the majority of the transport below -5m NAP was shown to be due to tidal currents in the PUMA model, there is still a small contribution of the tidal currents above -8m NAP. Cross-currents and sediment redistribution across the profile also create a more diverse behaviour than assumed.

In addition, this validation is based on the averaged sediment loss for the entire soft sea defence of Maasvlakte 2 and thus can be an over- or underestimation for the local differences in specific areas and rays, which can be quite significant. From the nourishment volumes, no distinction is visible from the sediment losses that are due to north- or southbound transport. Moreover, the distribution of the modelled erosion does not fully match the erosion measured. The precise distribution of sediment losses for Delta21 is therefore subject to discussion. However, the ballpark figures, shape and distribution of sediment going north and south are plausible and close to that modelled and measured by PUMA. The model is therefore deemed as a good enough representation for modelling the initial effects of Delta21 in the modelling of Model 1.

# 7.3. COASTLINE DEVELOPMENT MODEL 1

## 7.3.1. ALONGSHORE SEDIMENT TRANSPORT

Following the setup for the Model 1, as seen in Chapter 6, the results of the UNIBEST-LT model for Delta21 for each ray can be seen in Figure 7.9.

For comparison, both the equidistant binning and the sediment transport proxy binning were calculated. The results of both models are very close to one another, meaning that although the binning method influences the outcome, it does not show entirely different results for Delta21. The equidistant binning shows around 20-25% more conservative calculations. Since the sediment proxy was already proven to be the most accurate option at Maasvlakte 2, this method will therefore continue to be used in the further modelling of Delta21.

On first sight, it can be seen that the shape of the figure is similar to that for the sediment transport at Maasvlakte 2. There is a similar separation at the western bend; the sediment transport is northward directed north of ray 39 and southward directed south of ray 39, alike to the behaviour at Maasvlakte 2. Due to the larger extent of Delta21 and the larger bend (5 kilometres) that is present, the length over which the transport changes from southward directed (-) to northward directed (+) is also longer than that at Maasvlakte 2. This also means that the gradient in the alongshore sediment transport is lower and thus a lower average erosion per meter along the bend.

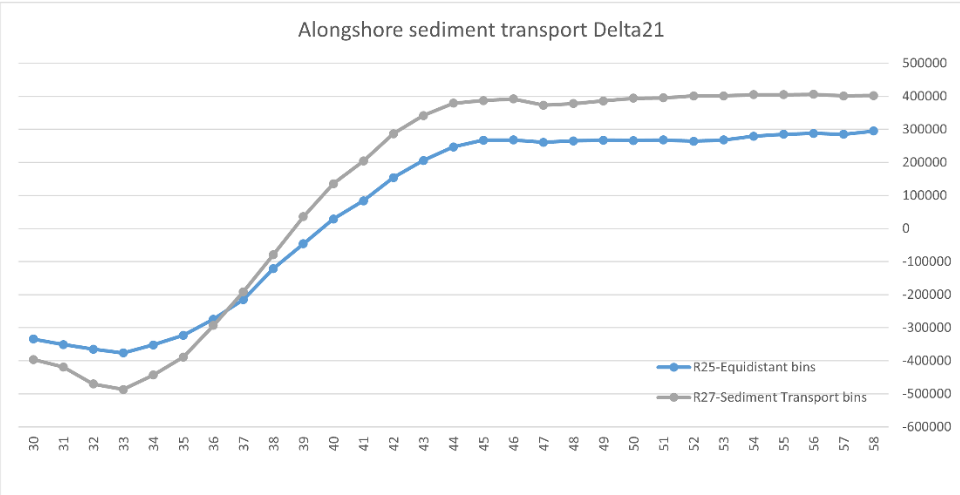



Figure 7.9: Modelled mean alongshore sediment transport per ray for Delta21 using the Equidistant bins (blue) and Sediment Transport bins (grey) wave input reduction methods for the period 1997-2020. Quantities in $m^3$/year.

The modelled alongshore sediment transport numbers seem to correlate well with those from Maasvlakte 2. Northward directed transport is an very continuous 400.000 $m^3$/year, while southward directed is around 400.000 $m^3$/year, with a small dip at Ray 33 to 500.000 $m^3$/year. The results for the northern side of Delta21, where the orientation of the coastline is slightly more western than that of Maasvlakte 2, might be somewhat lower than expected given the main wave orientations and comparison to transports at north side of Maasvlakte 2. Overall, given the similarity in orientation, wave climate, location and governing conditions between Maasvlakte 2 and Delta21, these results are deemed reliable. From these alongshore sediment transport results, a total erosion in the order of 0.8 $\mathrm{Mm}^3$/year is obtained.

### 7.3.2. MAINTENANCE REQUIREMENTS

The actual maintenance requirements stem from the gradients in the previously calculated alongshore sediment transports. The UNIBEST-TL results and .RAY files for the alongshore transports were fed into the UNIBEST-CL model, the setup of which can be seen in Figure 6.1. The results of this UNIBEST-CL model after one year are visualised as the alongshore sediment transport rate in Figure 7.10 and the erosion rate in Figure 7.11. This is then also overlaid on the map of the area in Figure 7.12.

From the sediment transport graph in UNIBEST-CL, the same separation is visible between Ray 38 and Ray 39. The rays south of here have a southward directed transport, the ones north of here a northward directed transport. Just south and north of the extent of the bend, at 1250 and 8000 metres respectively, there is a drop in these transports after which they remain rather stable up until the connection point at Maasvlakte 2. At this transition, there are some small variations in alongshore transport caused by the change in coastline orientation.

Consequently from the sediment transport graph, prominent erosion is visible along almost the entirety of the western bend with an erosion rate up to 20 meter per year. As expected, due to the lower gradient in the sediment transport graph compared to that of Maasvlakte 2, this erosion rate is lower. Directly south and north then are locations of accretion. The same observations, albeit with a lower gradient in sediment transport and smaller accretion- and erosion volumes, are then also visible at the connection to Maasvlakte 2. Since no boundary conditions are assumed and the transition of hard- to soft coastal defence is not modelled, it should be noted that the left side near the pumping stations, and the right side near the transition are therefore not modelled accurately.

In the Appendix, the erosion- and alongshore sediment transport rates after 5 and 10 years can also be found. From these figures, the erosion volume per year has been calculated in UNIBEST-CL at 850.000 $\mathrm{m}^3$/year. This number remains consistent throughout the first 10 years. Compared to the Model 0 erosion volumes from Maasvlakte 2, this number is thus very similar.

### 7.3.3. INFLUENCE OF SEDIMENT CHARACTERISTICS

As seen in Section 5.7, the planned sediment for the construction of the Delta21 soft coastal defence is from the Energy Storage Lake, however this will likely have a large impact on the sediment transport- and erosion rates. In Figure 7.13 the impact of the reduction of the grain size on the alongshore sediment transport is shown. It is clear that the usage of a smaller $\mathrm{D}_{50}$ of 140 µm significantly amplifies the sediment transport to both the south and the north. Both the northbound and southbound sediment transports went up from 0.4 $\mathrm{Mm}^3$/year to around 1.0 $\mathrm{Mm}^3$/year. This will therefore also result in a much larger maintenance requirement for the Delta21 dune area, especially since the gradients in the alongshore sediment transport in the bend at Delta21 are significantly

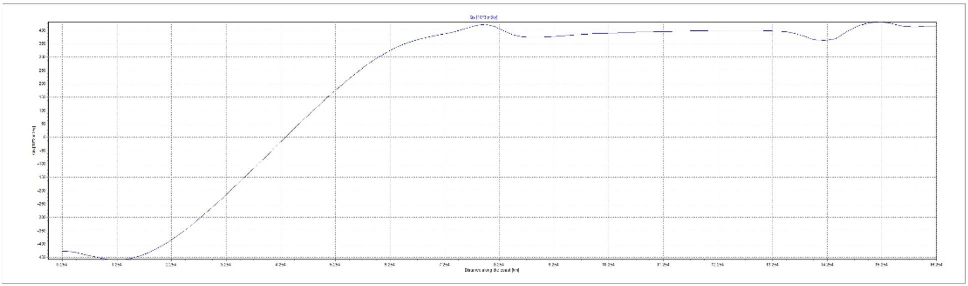


Figure 7.10: Alongshore sediment transport after 1 year for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

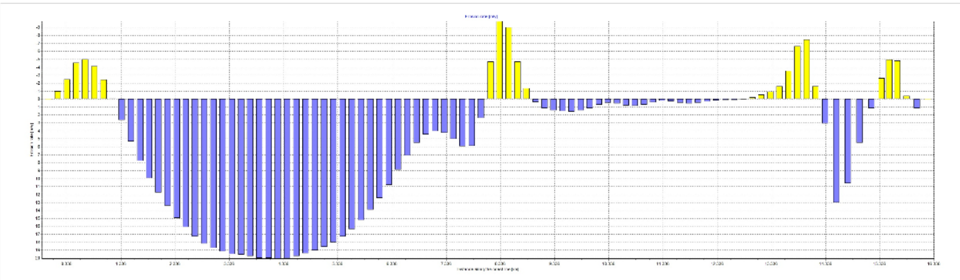


Figure 7.11: Erosion rates after 1 year for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

Figure 7.12: Location of erosion and accretion after 1 year for Delta21 connection to Maasvlakte 2. As seen in Figure 7.11 and overlaid on map of the area.

larger compared to the usage of 370 µm.

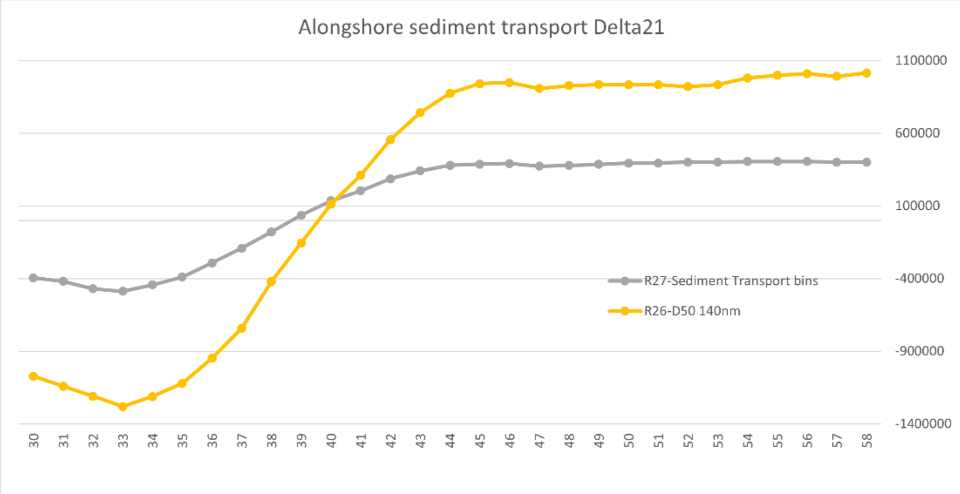



Figure 7.13: Modelled mean alongshore sediment transport per ray for Delta21 for using the default $D_{50}$ of 370 µm (grey) and for the usage of decreased grain size, $D_{50}$ of 140 µm (yellow), present at the location of the ESL. Reduced wave climate 1997-2020, excluding tides. Quantities in $m^3$/year.

### 7.3.4. VARIABILITY

Estimating and putting a number or bandwidth to the expected variability for the alongshore sediment transport and erosion has proved to be difficult. From Sections 4.5, it was already clear that substantial differences in the wave-climate could occur between years. Section 4.6 furthermore shows that in the sediment transport and erosion a significant difference can also occur between the models and the actual measurements. For the latter, between different years, the amount of variability in the measured erosion and required nourishments is then also significant.

In the PUMA modelling of Maasvlakte 2, the bandwidths for the mean alongshore sediment transport per ray were based on the variability in wave climate over the modelled years and the inaccuracy of the models. For the variability of the alongshore sediment transport and erosion in this study is therefore chosen for a similar approach. Using Figure 7.5, the bandwidth is calculated by the differences between the minimum, maximum and average of the alongshore sediment transports and consequent erosion of Model 0 for the years 2013-2019 to create a bandwidth. Since the variation per year seems to be mostly in the total amount of sediment transport in the system and not in the way that it is distributed north- and southbound, the conditions at which the minimum and maximum occur for both the south- and northbound transport are almost identical. This means that for the total erosion, the sum of the north- and southbound transport can be used.

The bandwidths for the north-bound and south-bound sediment transport respectively for the Delta21-project and the total erosion, based on variability in alongshore sediment transport, are then:

- North-bound alongshore sediment transport: 0.1 - 0.6 $\mathrm{Mm}^3$/year.
- South-bound alongshore sediment transport: 0.3 - 0.5 $\mathrm{Mm}^3$/year.
- Total erosion due to alongshore sediment transport: 0.4 - 1.2 $\mathrm{Mm}^3$/year.

The bandwidth for the north-bound transport can be seen to be much larger, as the variability in wave climate seems to have a larger effect here. This observation was also visible in the initial PUMA modelling of the variability in alongshore transport. Given the amount of assumptions, lack of data and limited modelling present in this study, this number should however not be seen as absolute, but more an initial qualitative estimation for the bandwidth and behaviour.

# 8 CONCLUSIONS

From the literature and site study, it became apparent that the bathymetry and coastal profile at Maasvlakte 2 have varied significantly. Some of the visible local interactions are due to processes and factors specifically for Maasvlakte 2, such as the interaction between the soft and hard coastal defence at the northern part of the beach. From this analysis and comparison, it was found that the coastal profiles and coastline changes of Maasvlakte 2, combined with the coastal maintenance and wave climate can yield a qualitative comparison to Delta21. Numerical modelling was then needed to get better representative quantitative results for the maintenance requirements for the Delta21-project.

Along with the wave input reduction method, which was based on a sediment transport proxy, the SWAN Model 0 was validated. The wave-transformations by SWAN showed that the nearshore waves for the soft sea defence at Delta21 were comparable in wave height, period and direction to those found at the north and west side of Maasvlakte 2.

In the UNIBEST Model 0, a total volume loss of 770.000 $\mathrm{m}^3$/year was modelled, which matched well with the measured actual erosion volumes of PUMA. The model was then compared with the actual Maasvlakte 2 coastal nourishment volumes and was shown to be a good representation of the occurring alongshore transports and erosion at Maasvlakte 2. The model was thus validated and applicable to be used for the modelling of Delta21.

The results from the Delta21 - Model 1 showed that the characteristics of alongshore transport are similar to those of Maasvlakte 2. There is a clear separation at the western bend, with a north and southward directed transport of around 0.4 million $\mathrm{m}^3$/year in both directions. Erosion was visible along the entirety of the western bend, with a total erosion volume of 0.85 million $\mathrm{m}^3$/year and a subsequent erosion rate up to 20 meters per year.

In UNIBEST, due to the imposed depth of the tides in Delft3D and the way UNIBEST translates these to the nearshore, the effects of the tidal currents on the alongshore sediment transport have a lower accuracy. During the implementation of the Delft3D tidal data in the UNIBEST model, the effect of the tidal velocities and elevations were however shown to be limited for the area above -8m NAP. The literature study also concluded a mostly current-driven transport below -8m NAP and a wave-driven transport above -

8m NAP. As a consequence, no definitive quantification could be made for the effect of tidal currents on the alongshore sediment transport and erosion above -8m NAP, but the effect that it does have is limited in comparison to the wave-driven transport.

The proposed usage of sediment from the ESL, with a $D_{50}$ of $140\mu$ showed that the grain size can have a significant impact on alongshore sediment transport and total erosion. Both are a factor 2.5 higher compared to the 370 $\mu m$-model. This is in line with previous studies for Maasvlakte 2, where a factor of 2.0-2.5 was found for a grain size of 160 $\mu m$.

The data study furthermore has shown that these results contained a large uncertainty due to the natural variability in the yearly wind and wave climate, wave energy flux and consequently, the sediment transport and erosion. Based on the modelled years and variability in alongshore sediment transport, the total erosion for the Delta21 coast was estimated to be between 0.4 and 1.2 million $m^3$/year for a grain size of 370 $\mu m$.

Evaluation of the results from the models, confirms the null hypothesis that the Delta21-project will show comparative morphological behaviour, alongshore sediment transport and erosion characteristics to those found at Maasvlakte 2.

# 9

# Discussion and Recommendations

## 9.1. Discussion

Delta21 is a project that has the potential to solve future issues regarding flood safety and offer a reliable renewable energy storage solution. When built, this project would be the first of its kind, potentially changing the way flood protection is tackled. However, it does have some major issues in its current approach, mainly in regards to the environmental impact it can have on the area. As a consequence, it will be challenging to align all stakeholders on the definitive location, layout and characteristics of the Delta21-project. Municipalities, the Port of Rotterdam and environmental agencies raise questions on the extent of the potential negative impacts of this project for them.

Taking Maasvlakte 2 as an example, the time frame it took from concept to construction was of several decades. And while for Maasvlakte 2 there was an actual demand and necessity, the sense of urgency for large-scale coastal interventions like Delta21 is currently insufficiently felt. Nevertheless, the Delta21-project offers a lot of potential as a novel flood protection approach. This study aimed at solving one more piece of the puzzle, more specifically, the expected alongshore sediment transport and coastal maintenance.

The current models used in this study are based on the available data, various assumptions and a limited time frame. SWAN was used for the transformation of offshore waves and UNIBEST for the alongshore sediment transport and consequent erosion. Additionally, the models used, and coastal modelling in general, are prone to numerous uncertainties, which can also include form- or function errors. This study did not take into account many interactions with external factors, such as the pumping regime of the Energy Storage Lake, the Haringvliet discharge and an extreme-wave pumping event. Additionally, it also did not take into account the exact location and characteristics of the connection between Delta21 and Maasvlakte 2. While all these parameters can have a large impact on the model results, they have yet to be fully determined and were therefore not considered for this study.

## 9.2. RECOMMENDATIONS

In the case of the continuation of the used models and data by future students, it is recommended to put further strive towards models with a more extended validation and calibration. Validation of the Model 0 results proved difficult under the current conditions, methods and available data, but is a requirement to accurately model the consequences for Delta21. In addition, for future models, it is advised to increase the resolution of these models to acquire a higher accuracy. In particular for the tidal modelling, the accuracy of the data proved insufficient.

the scales used in this study are quite coarse. For Delta21, alongshore wise every 500 meters a ray was placed for analysis while the SWAN computational grid had a resolution of 50 meters for the smallest grid used. For continued modelling, it is advised to increase the resolution of these models to acquire a higher accuracy.

Lastly, the Delta21-project is still in its early stage and subject to many changes. Based on the results of this study, a start can be made for determining the best maintenance strategy for Delta21. The exact location, layout, size and characteristics of the Delta21-project are yet to be fully determined and as such, an in-depth study regarding coastal maintenance in its current form and state is ill-advised. However, this study has given an initial insight and paved the way for future studies. More research regarding the cross-shore distribution of sediment, the influence of the tidal contraction and the connection with - and interaction to - Maasvlakte 2 are recommended as future approaches.

# REFERENCES

Andrijanovits, A., Hoimoja, H., & Vinnikov, D. (2012). Comparative review of long-term energy storage technologies for renewable energy systems. *Electronics and Electrical Engineering, 118*(2).

Arcadis Nederland B.V. (2017). *Mer bestemmingsplan maasvlakte 2* (Rep.).

Berke, L., & Lavooij, H. (2017). *Delta21 en energie - delta21: Rotterdam als duurzame energie hub* (tech. rep.).

Berke, L., & Lavooij, H. (2018a). *Delta21 en natuurherstel - delta21: Herstel van natuur, waaronder de vismigratie in en rond het haringvliet* (tech. rep.).

Berke, L., & Lavooij, H. (2018b). *Delta21 en waterveiligheid - delta21: Kostenbesparend alternatief voor dijkverhogingen* (tech. rep.).

Boer, S. (2004). *Landaanwinning t.b.v. aanleg tweede maasvlakte, doorsteek alternatief. morfologische berekeningen t.b.v. kustonderhoud zachte zeewering, ontgronding vooroever en aanzanding euro-maasgeul* (tech. rep.). Infram.

Boer, S. [S.], Roelvink, J. A., & Vellinga, T. (2006). Large-scale scour of the sea floor and the effect of natural armouring processes, land reclamation maasvlakte 2, port of rotterdam.

Boer, S. [S.], & Roukema, D. (2004). *Landaanwinning t.b.v. aanleg tweede maasvlakte onderhoudsaspecten doorsteekvariant* (tech. rep.).

Booij, N., Holthuijsen, L., & Ris, R. (1996). The "swan" wave model for shallow water. *Coastal Engineering, 1*.

Borsje, B. W., van Wesenbeeck, B. K., Dekker, F., Paalvast, P., Bouma, T. J., van Katwijk, M. M., & de Vries, M. B. (2011). How ecological engineering can serve in coastal protection. *Ecological Engineering, 37*(2), 113–122.

Camenen, B., & Larroudé, P. (2003). Comparison of sediment transport formulae for the coastal environment. *Coastal Engineering, 48*(2), 111–132.

Commission, E. (2007). *Guidelines for the establishment of the natura 2000 network in the marine environment. application of the habitats and birds directives* (tech. rep.).

de Boer, A. M., Castells, M. D., Fournier, A., Overdijk, S., Schäfer, J., Stoorvogel, M., & Troost, J. (2019). *Building with nature in the dutch delta* (tech. rep.).

Deltares. (2011). Unibest-cl+ manual.

de Queiroz, B., Scheel, F., Caires, S., Walstra, D.-J., Olij, D., Yoo, J., Reniers, A., & de Boer, W. (2019). Performance evaluation of wave input reduction techniques for modeling inter-annual sandbar dynamics. *Journal of Marine Science and Engineering, 7*(5), 148.

de Vriend, H. J., van Koningsveld, M., Aarninkhof, S. G. J., de Vries, M. B., & Baptist, M. J. (2015). Sustainable hydraulic engineering through building with nature. *Journal of Hydro-environment Research, 9*(2), 159–171.

European Commission. (2000). *Managing natura 2000 sites - the provisions of article 6 of the 'habitats' directive 92-43-cee* (tech. rep.).

IJntema, J. (2021). *Initial morphodynamic changes in the voordelta in response to the delta21 interventions* (tech. rep.). Delft University of Technology.

IPCC. (2013). *Climate change 2013: The physical science basis. contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

Jonkman, S. N., Kok, M., & Vrijling, J. K. (2008). Flood risk assessment in the netherlands: A case study for dike ring south holland. *Risk Analysis*, *28*(5), 1357–74.

Kuijper, E. (1998). *Het effect van een zandwinkuil op de stroomcontractie door maasvlakte 2* (tech. rep. RIKZ/AB-98.1O7X). RIKZ.

Li, Z. (2020). *Large-scale and local morphological impact along the northern side of delta 21* (tech. rep.). Delft University of Technology.

Mann, M. (2019). *Unravelling the sediment transport mechanisms in an artificial lagoon* (tech. rep.). Delft University of Technology.

Ministry of Economic Affairs and Climate Policy. (2019). Climate agreement.

PUMA. (2018). Samenvatting keuringen en ervaringen instelperiode: Volume morfologische schillen.

Rijke, J., van Herk, S., Zevenbergen, C., & Ashley, R. (2012). Room for the river: Delivering integrated river basin management in the netherlands. *International Journal of River Basin Management*, *10*(4), 369–382.

Rijkswaterstaat. (2020). Kustlijnkaarten 2021.

RIKZ, F. M. (1995). *Jaarlijkse kustmetingen - richlijnen voor de inwinning, bewerking en opslag van gegevens van jaarlijkse kustmetingen* (tech. rep. rapport RIKZ-95.022).

Steijn, R. (2000). *Morfologisch onderzoek maasvlakte 2 - onderhoud zachte zeewering, grootschalige ontgronding en aanzanding maasgeul* (tech. rep. A579R1M).

Steijn, R. (2002). *Zachte zeeweringen maasvlakte 2 - vervolgstudie kustonderhoud maasvlakte 2* (tech. rep.). WL | Delft Hydraulics, Alkyon, Arcadis.

SWAN Team. (2020a). Swan - user manual.

SWAN Team. (2020b). *Swan scientific and technical documentation* (tech. rep.).

Van Adrichem, S. (2021). *Influence of rapid draw down on dike stability* (tech. rep.). Delft University of Technology.

Van De Graaff, J., & Van Overeem, J. (1979). Evaluation of sediment transport formulae in coastal engineering practice. *Coastal Engineering*, *3*, 1–32.

van Leeuwen, S. (2009). *Natuurcompensatie in de voordelta bij de aanleg van de tweede maasvlakte. achtergronddocument bij de natuurbalans 2008* (tech. rep.).

Vrancken, J., Van den Berg, J., & Dos Santos Soares, M. (2008). Human factors in system reliability: Lessons learnt from the maeslant storm surge barrier in the netherlands. *International Journal of Critical Infrastructures*, *4*(4), 418.

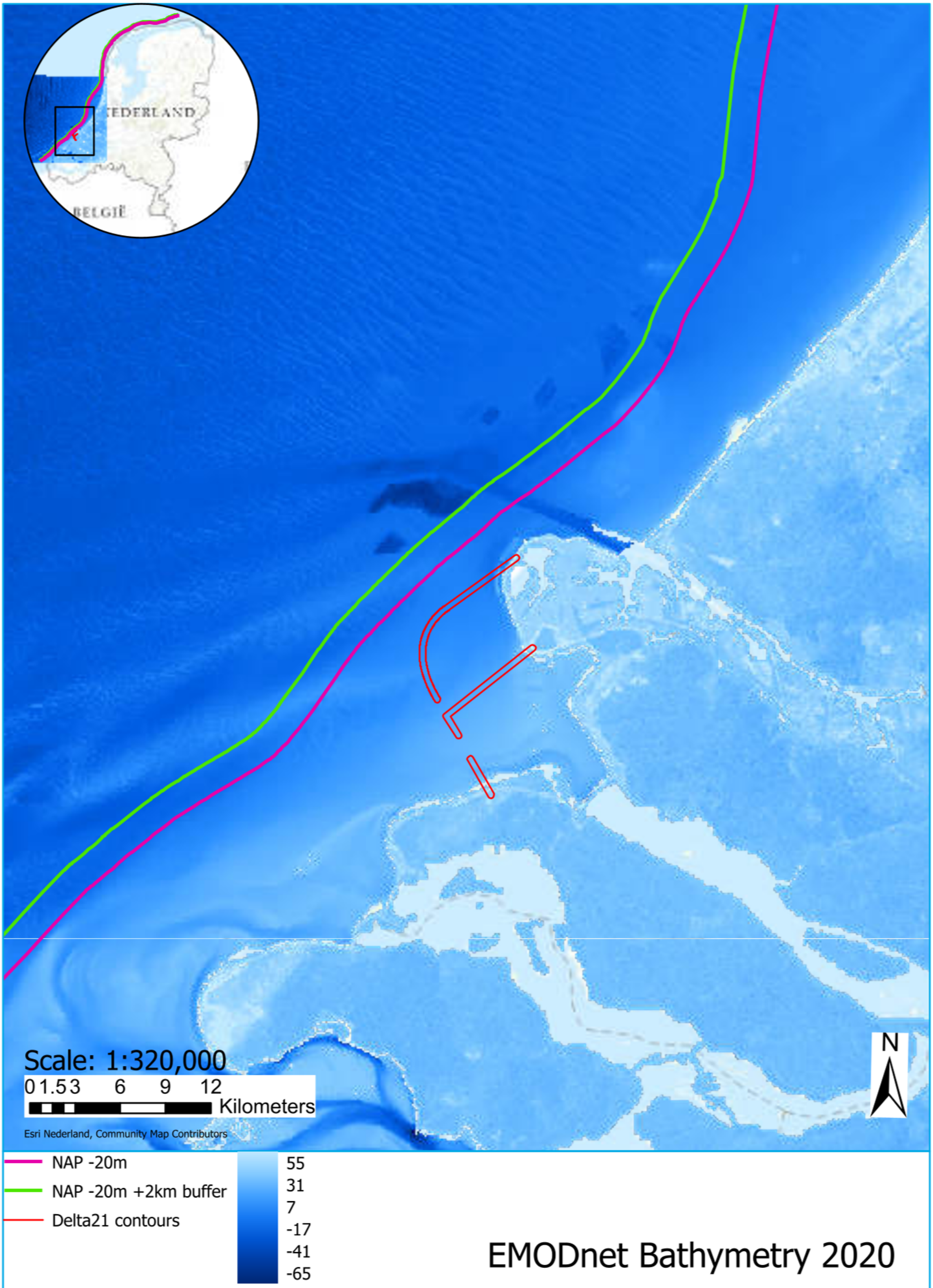
Walstra, D. (2000). Unibest-tc userguide.

Zaldivar Piña, M. (2020). *Stability of intertidal and subtidal areas after delta21 plan: Evaluating the consequences for the morphological development produced by the intervention* (Msc Thesis). Delft University of Technology.

# A

# MAPS AND OVERVIEWS

In this appendix, various maps on the extent and difference of the used bathymetry data used in the modelling and the computational grids of SWAN can be found.

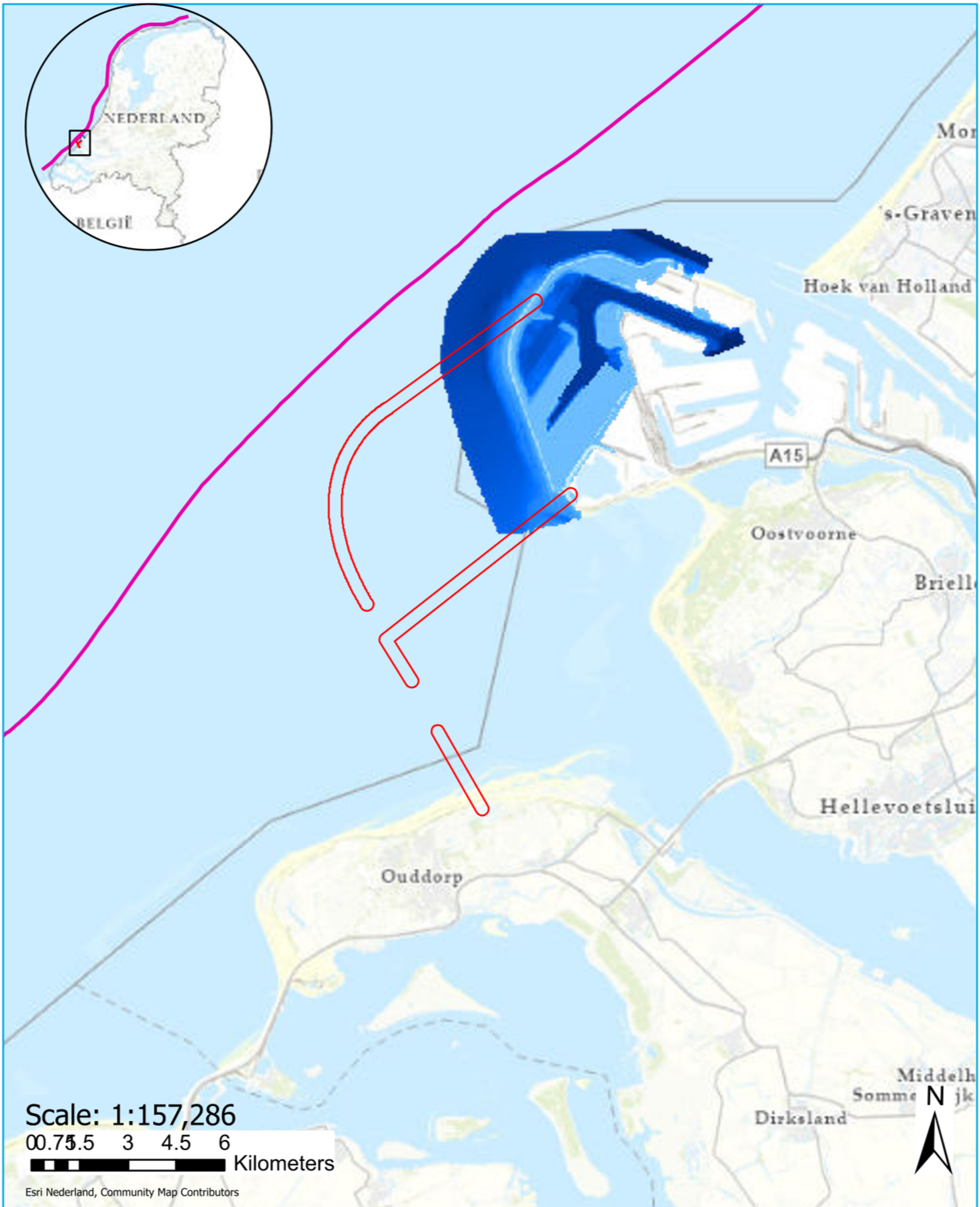



EMODnet Bathymetry 2020

Msc thesis Detmar Dieleman

Date Exported: 26-2-2021 14:58


NEDERLAND
BELGIË
Den Haag
Delf
A15
A20
Sch
Vlaarding
Spijkenis
Scale: 1:320,000
0 1.5 3 6 9 12
Kilometers
N
Esri Nederland, Community Map Contributors
NAP -20m
NAP -20m +2km buffer
Delta21 contours
4963
2706
448
-1809
-4067
-6324
RWS Bathymetry 2020
Msc thesis Detmar Dieleman
Date Exported: 26-2-2021 14:17




NAP -20m

Delta21 contours

Value

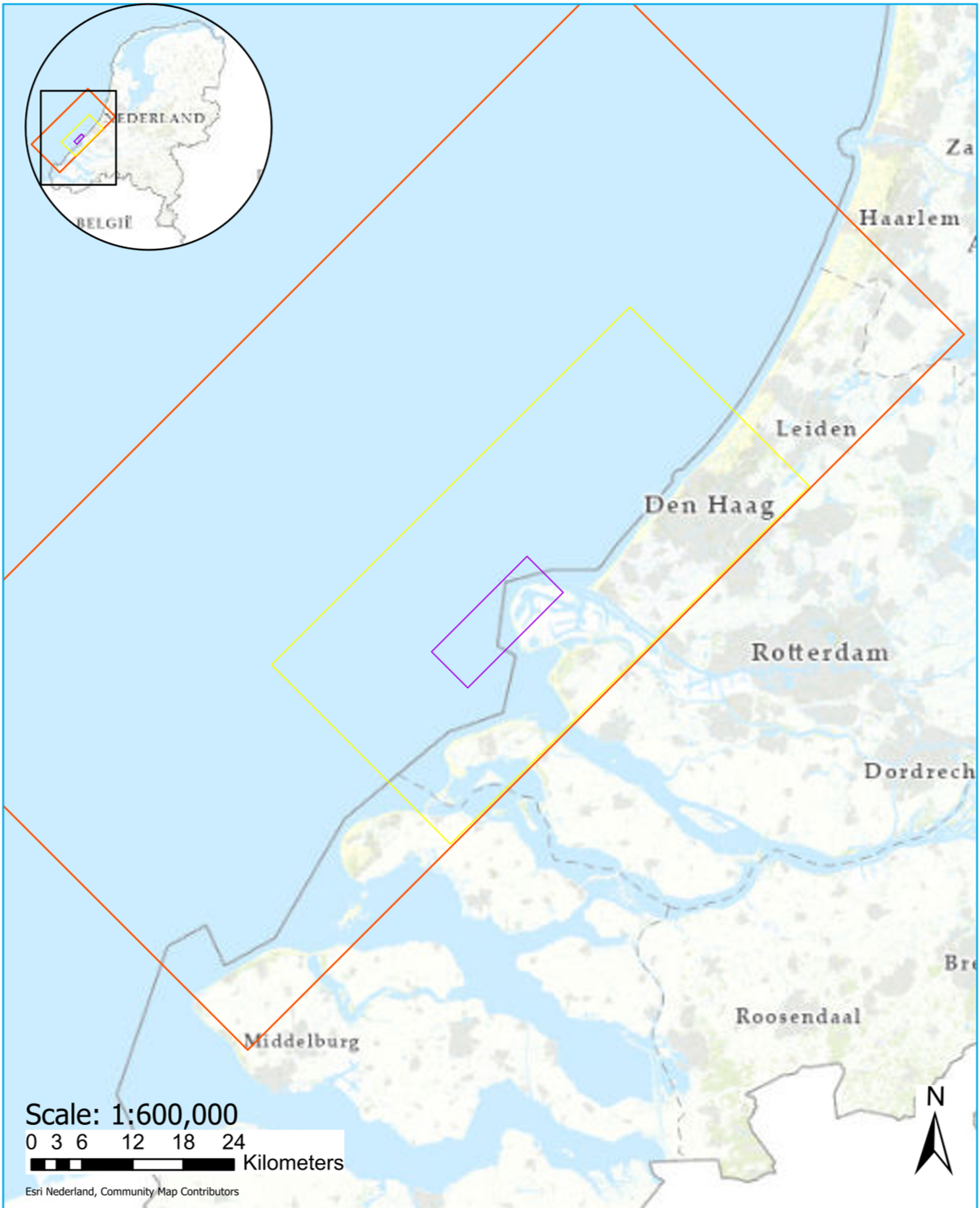
27.433

-28.95

# Extent bathymetry PUMA (Showing: 2013Q2)

Msc thesis Detmar Dieleman

Date Exported: 26-3-2021 14:57

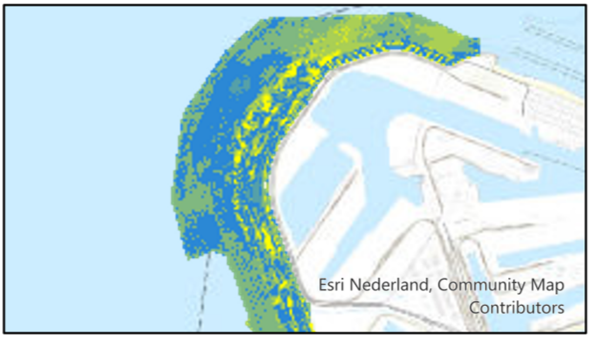



Grid 250x250m
Grid 150x150m
Grid 50x50m

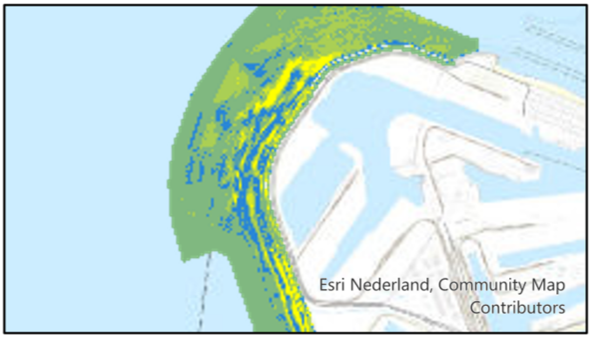
## Computative grids SWAN

Msc thesis Detmar Dieleman

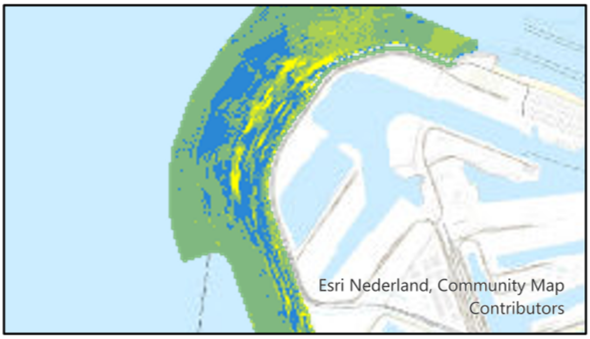
Date Exported: 1-3-2021 15:57



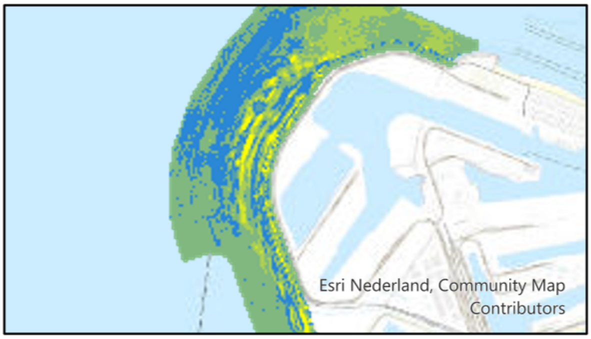

Bathymetric difference 2013-2014



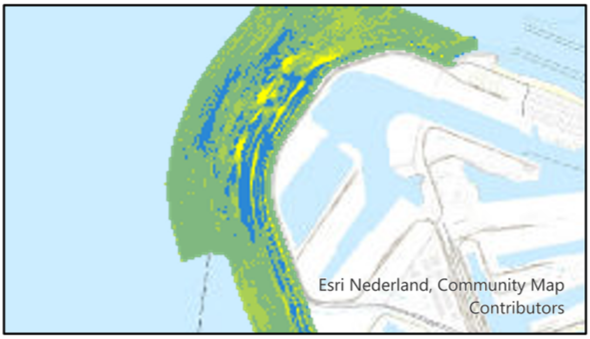

Bathymetric difference 2014-2015



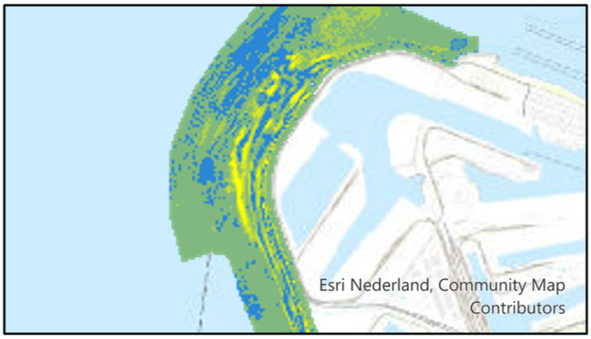

Bathymetric difference 2015-2016



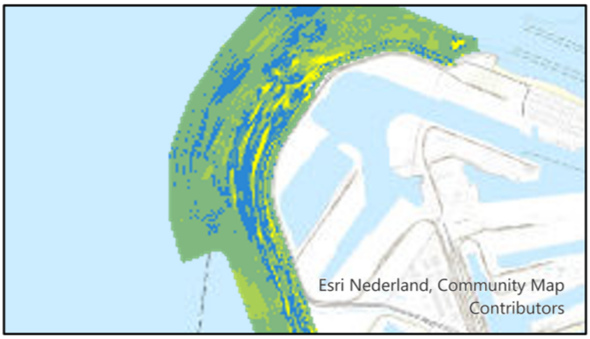

Bathymetric difference 2016-2017



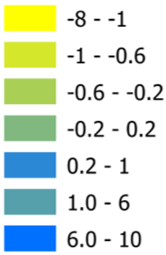

Bathymetric difference 2017-2018

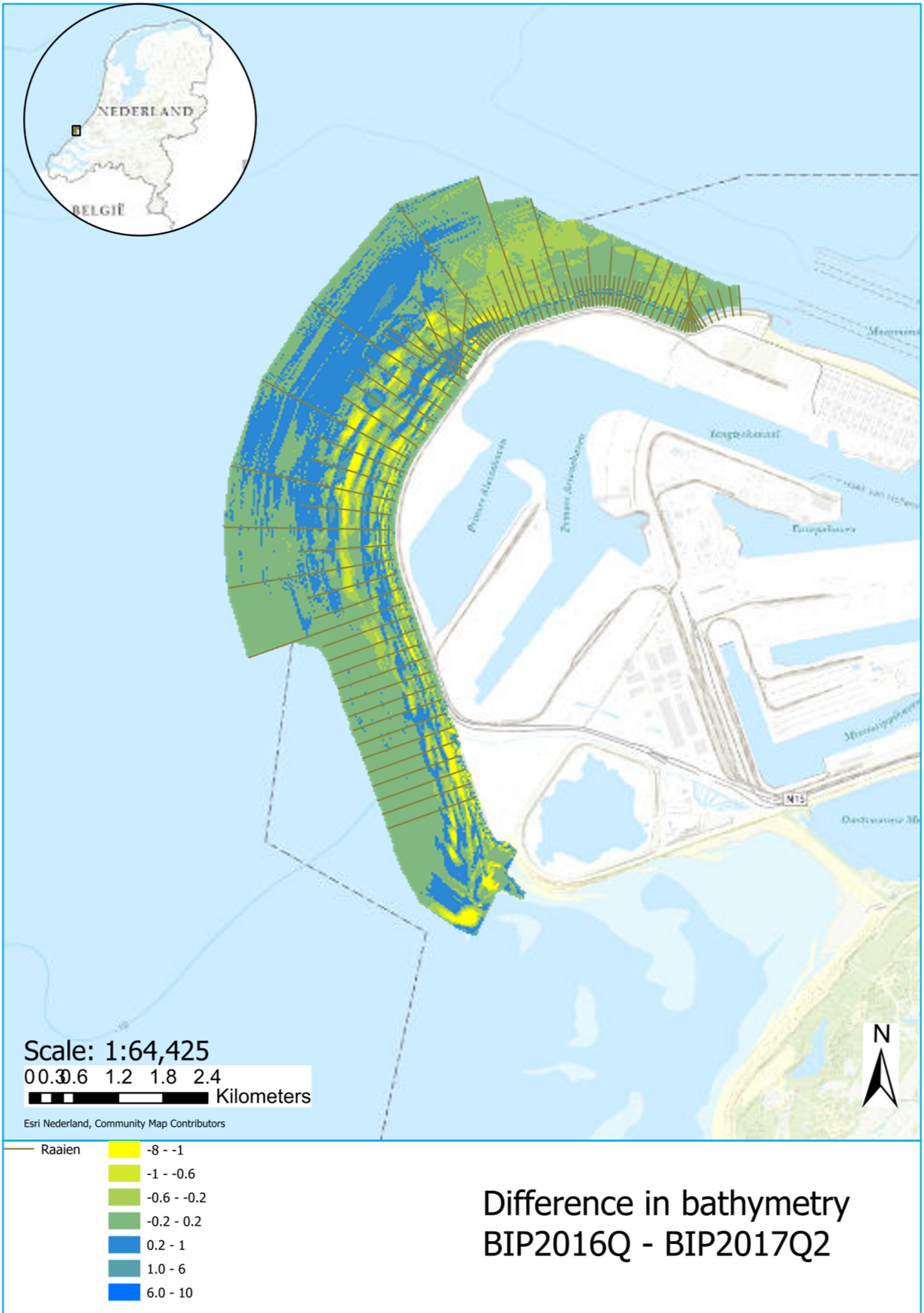



Bathymetric difference 2018-2019




Bathymetric difference 2019-2020

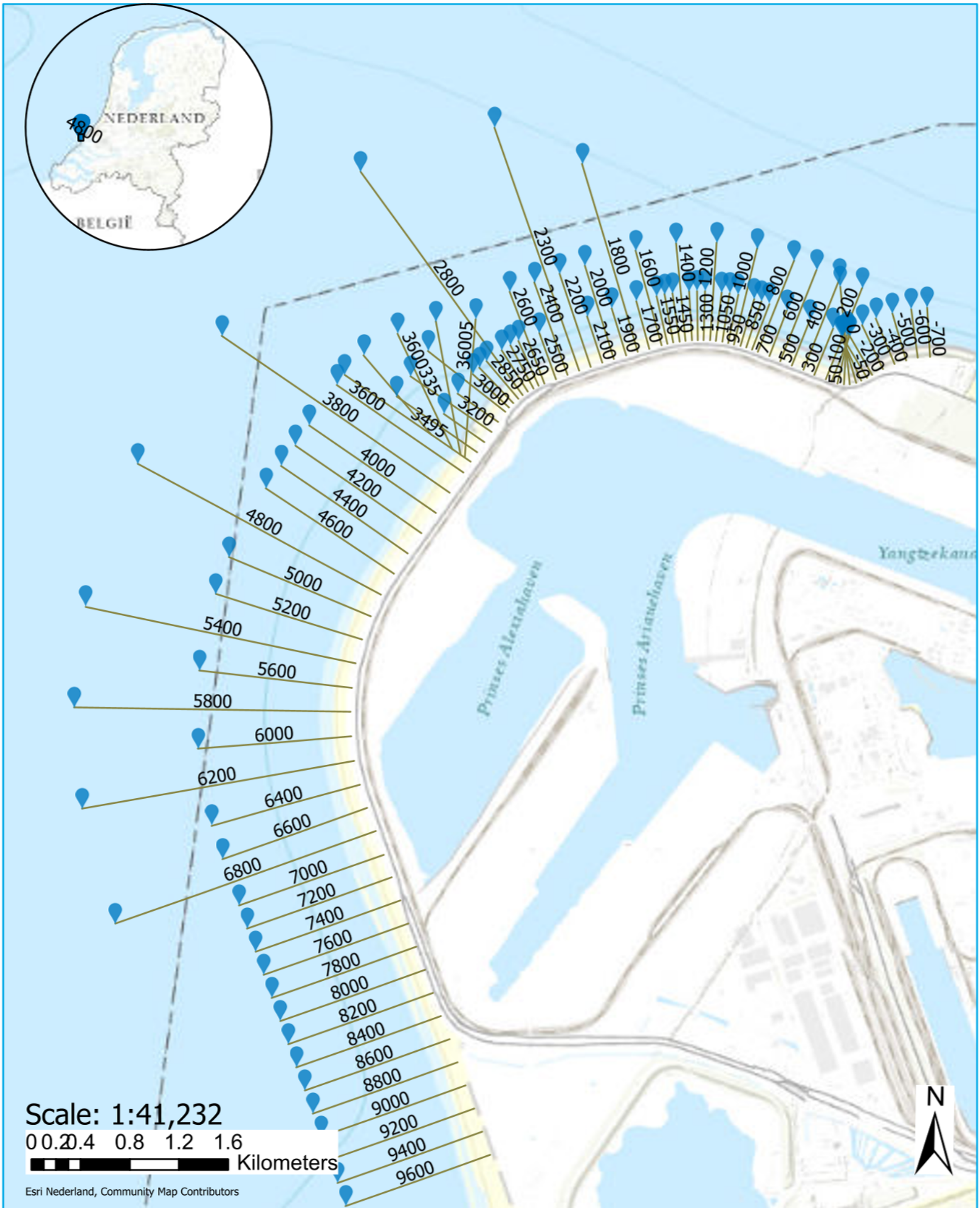





Difference in bathymetry
BIP2016Q - BIP2017Q2

Msc Thesis 08-04-2021

Date Exported: 9-4-2021 14:04



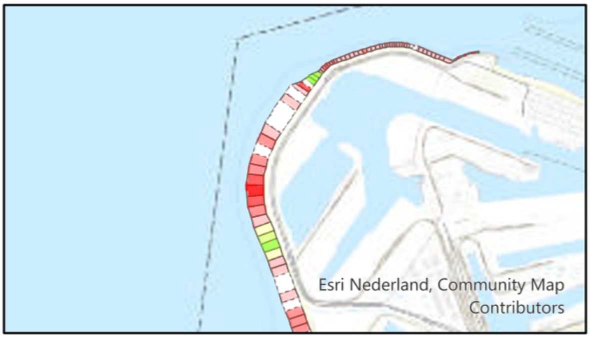

Raaien End Points

Raaien

# Raaien transects (UNIBEST) and Raaien Endpoints within calculative grid SWAN

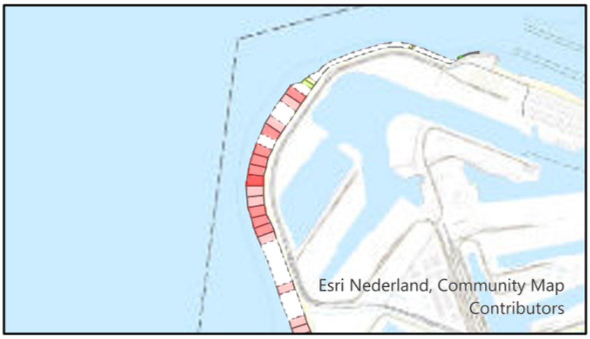
Msc Thesis - Detmar Dieleman

Date Exported: 16-4-2021 13:51

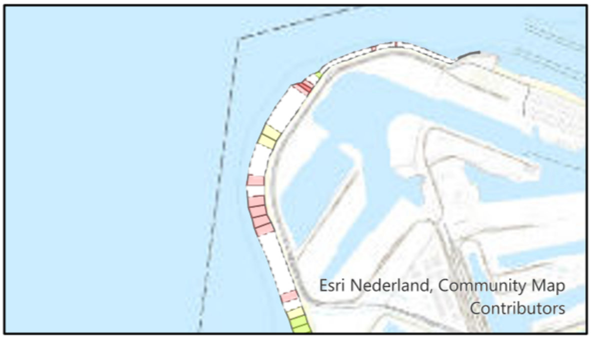



Difference 2013-2014


Difference 2014-2015



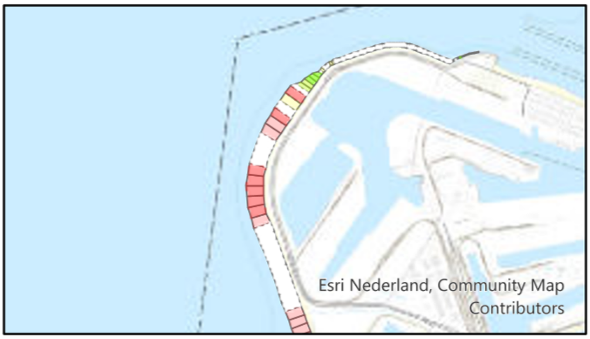

Difference 2015-2016




Difference 2016-2017


Difference 2017-2018


Difference 2018-2019

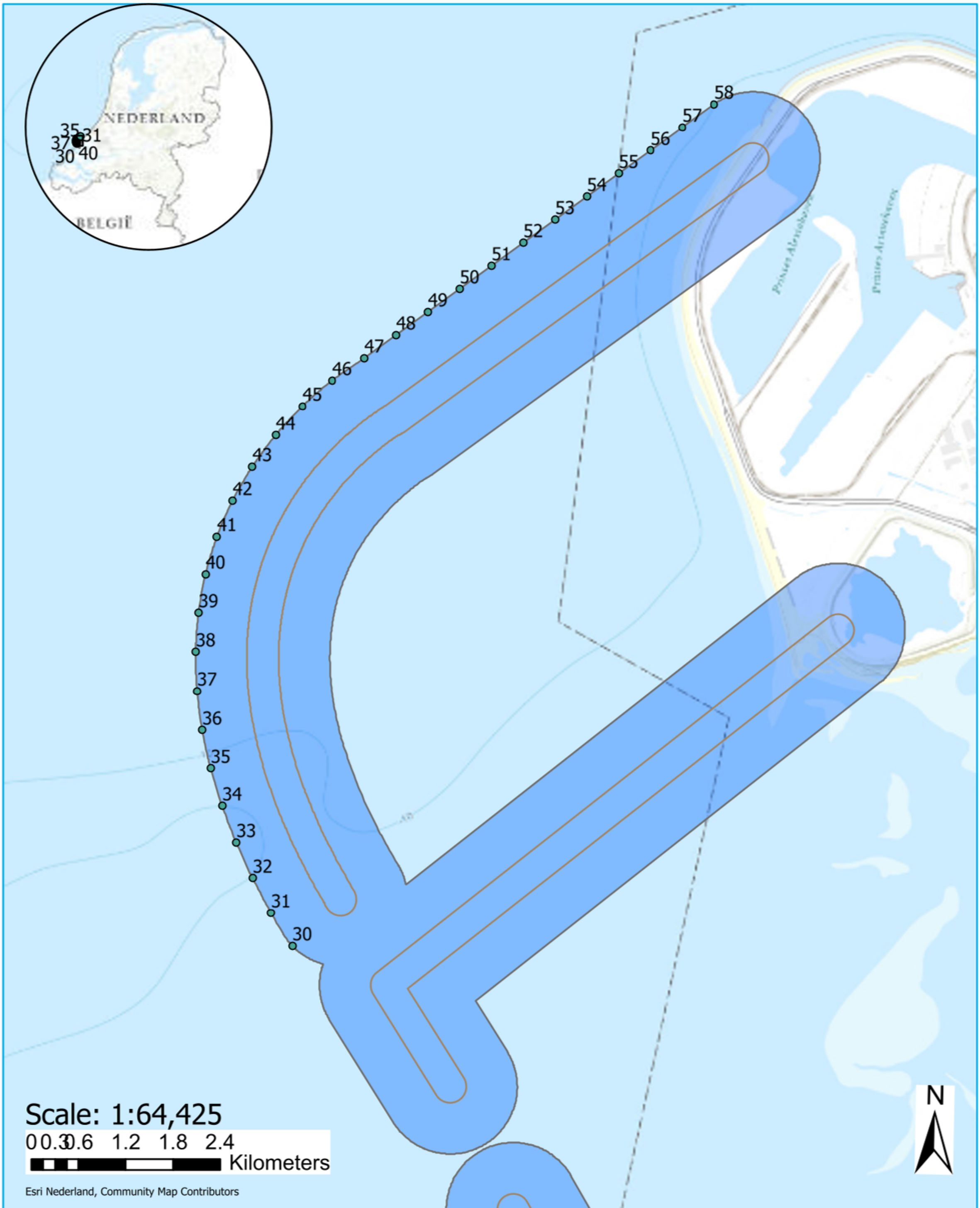



Difference 2019-2020

Average difference between raaien for depths between +3m NAP and -4m NAP for various periods (m).

Value

- < -2
- -2 - -1
- -1 - -0.6
- -0.6 - -0.4
- -0.4 - -0.2
- -0.2 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 1
- 1 - 2
- >2




Buffer around contour of Delta21 and location of studied Ray transects.

Msc Thesis - Detmar Dieleman

Date Exported: 9-6-2021 21:08

| File | Resolution |
|---|---|
| zhol20SKtt20.asc | 20m |
| walc20JKtt20.asc | 20m |
| vrne20JKtt20.asc | 20m |
| schw20JKtt20.asc | 20m |
| osch20JKtt20.asc | 20m |
| msvl20JKtt20.asc | 20m |
| maasmnd20tt20.asc | 20m |
| havliet18TT20.asc | 20m |
| goer20JKtt20.asc | 20m |
| delf20JKtt20.asc | 20m |
| EMODnet Bathymetry | 125m |
| PUMA BIP2013Q2 | 2.5m |
| PUMA BIP2014Q2 | 2.5m |
| PUMA BIP2015Q2 | 2.5m |
| PUMA BIP2016Q2 | 2.5m |
| PUMA BIP2017Q2 | 2.5m |
| PUMA BIP2018Q2 | 2.5m |
| PUMA BIP2019Q2 | 2.5m |
| PUMA BIP2020Q2 | 2.0m |

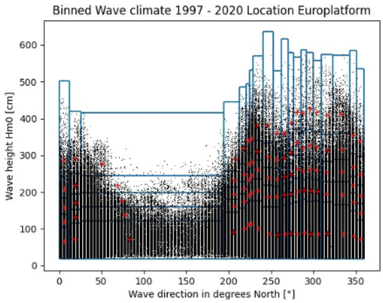
Table A.1: Bathymetry data used

# B

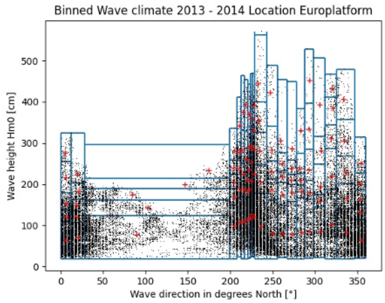
# WAVE-, WIND- AND TIDAL DATA

In this appendix, the various graphs and tables regarding the wave-, wind and tidal conditions and wave variability can be found, including wave- and wind roses for the Europlatform location.

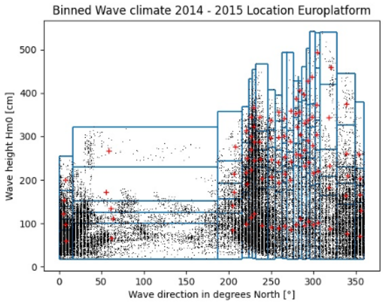
B



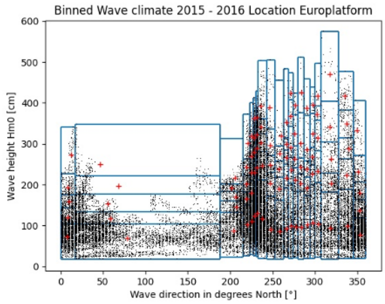

(1997-2020)



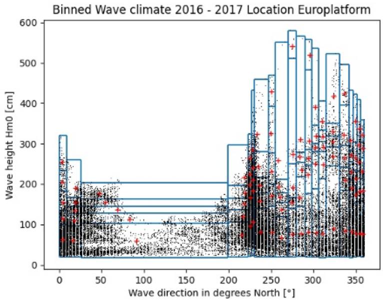

(2013Q2 - 2014Q2)



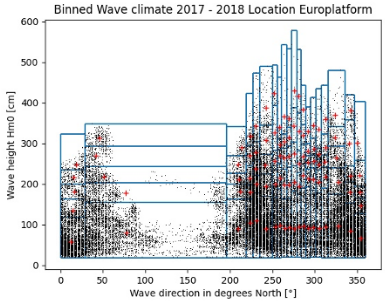

(2014Q2 - 2015Q2)



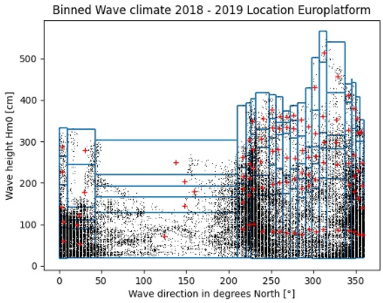

(2015Q2 - 2016Q2)



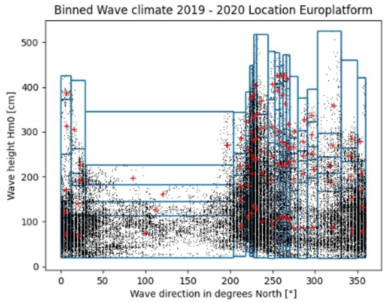

(2016Q2 - 2017Q2)




(2017Q2 - 2018Q2)

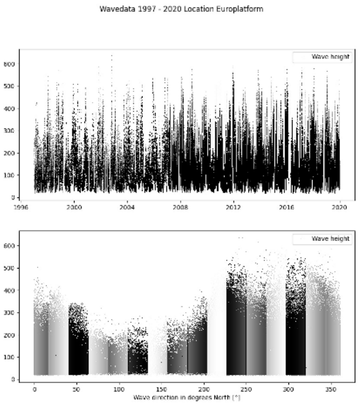



(2018Q2 - 2019Q2)

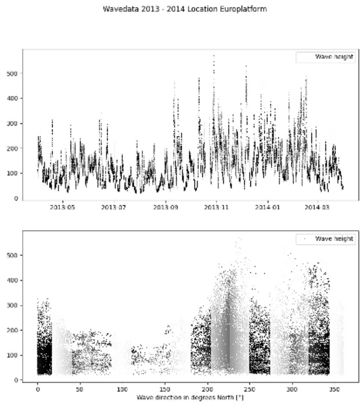



(2019Q2 - 2020Q2)

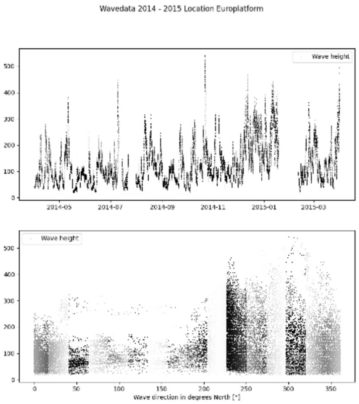
Figure B.1: 2D binned wave climates for various years. Wave reduction based on Sediment Transport proxy.



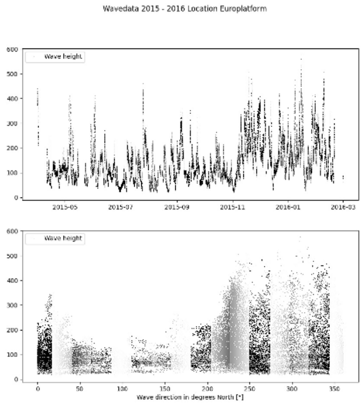

(1997-2020)




(2013Q2 - 2014Q2)



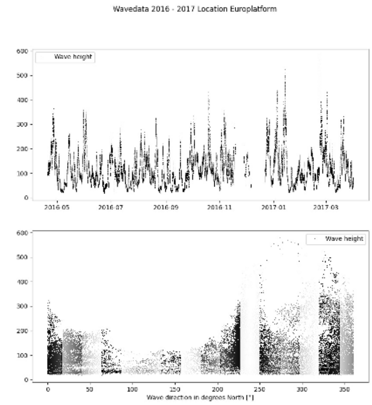

(2014Q2 - 2015Q2)



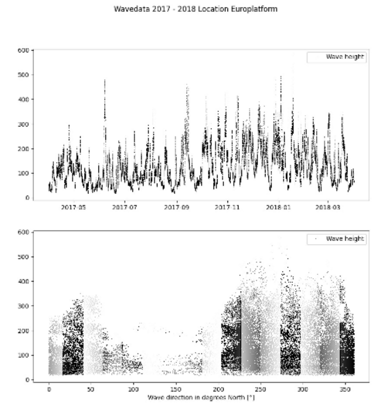

(2015Q2 - 2016Q2)

Figure B.2: Wave climates for various years.

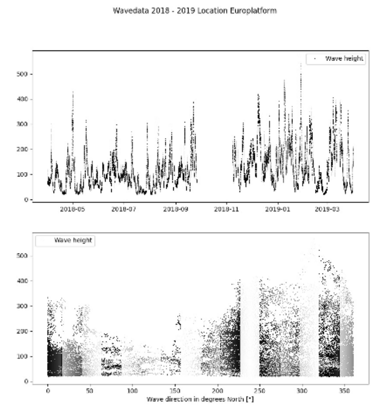
B



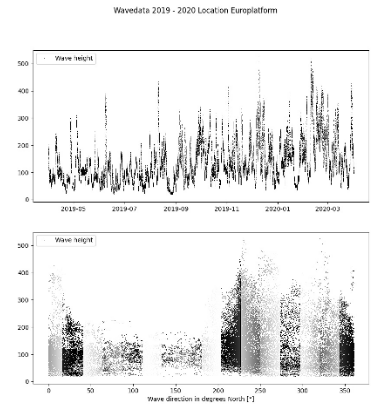

(2016Q2 - 2017Q2)




(2017Q2 - 2018Q2)

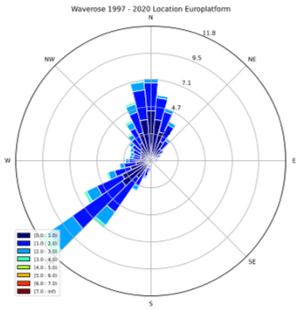



(2018Q2 - 2019Q2)

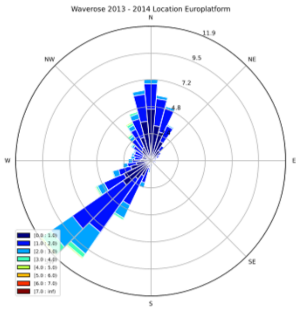



(2019Q2 - 2020Q2)

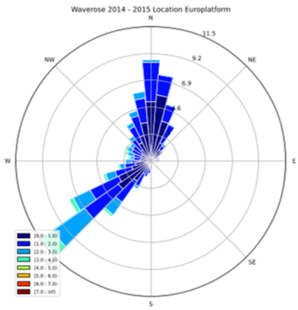
Figure B.3: Wave climates for various years.



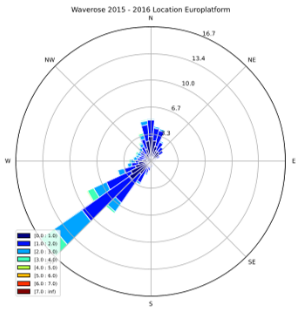

(1997-2020)



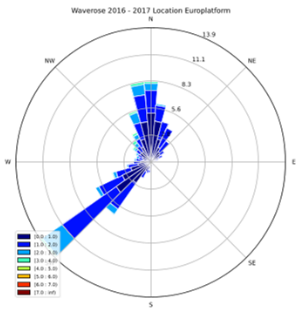

(2013Q2 - 2014Q2)



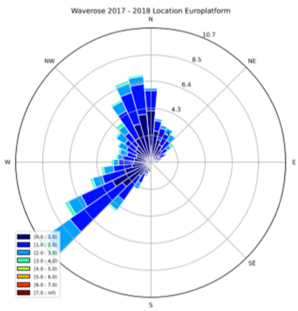

(2014Q2 - 2015Q2)



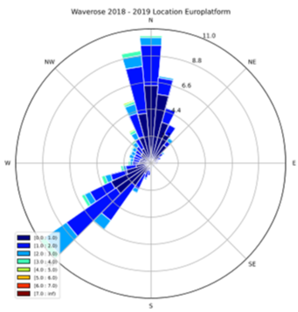

(2015Q2 - 2016Q2)



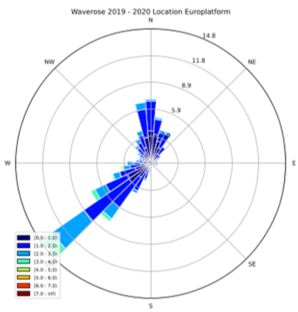

(2016Q2 - 2017Q2)




(2017Q2 - 2018Q2)

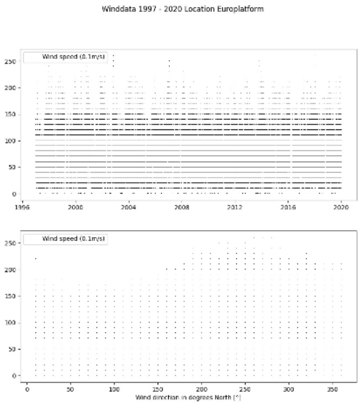



(2018Q2 - 2019Q2)

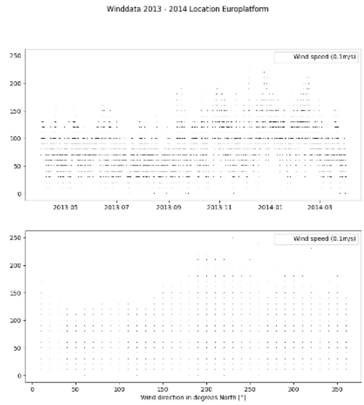



(2019Q2 - 2020Q2)

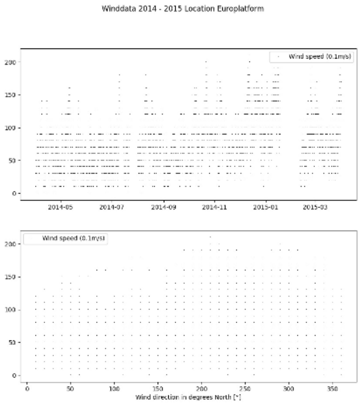
Figure B.4: Wave roses for various periods. Location Europlatform



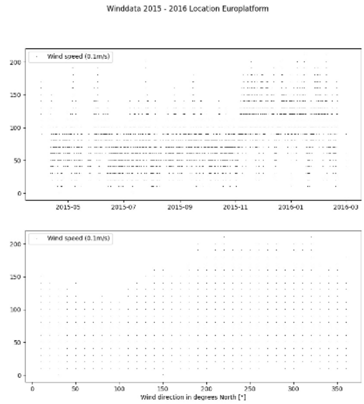

(1997-2020)




(2013Q2 - 2014Q2)

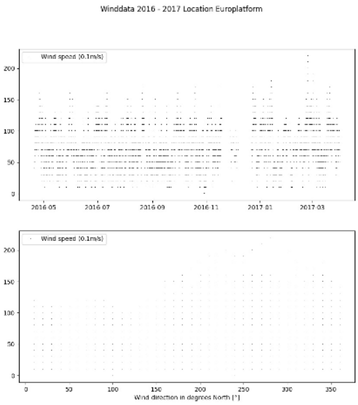



(2014Q2 - 2015Q2)

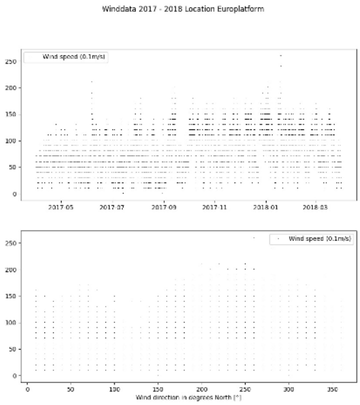



(2015Q2 - 2016Q2)

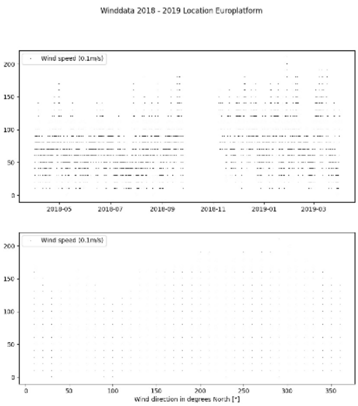
Figure B.5: Wind data for various periods. Location Europlatform.



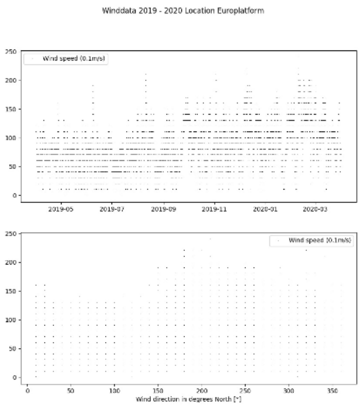

(2016Q2 - 2017Q2)




(2017Q2 - 2018Q2)

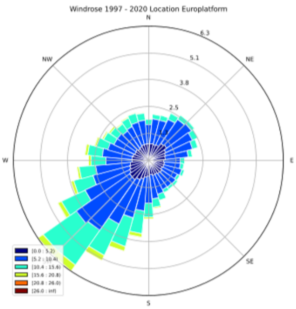



(2018Q2 - 2019Q2)

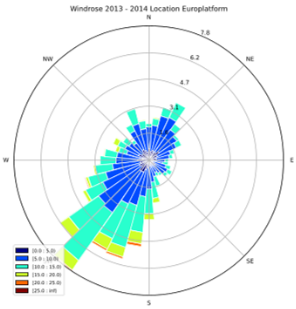



(2019Q2 - 2020Q2)

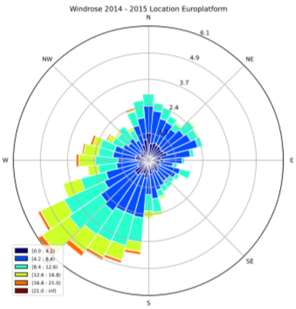
Figure B.6: Wind data for various periods. Location Europlatform.



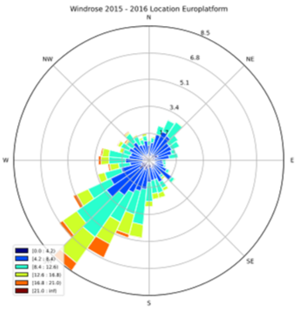

(1997-2020)



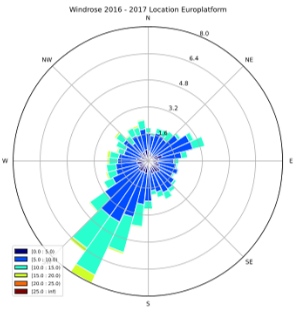

(2013Q2 - 2014Q2)



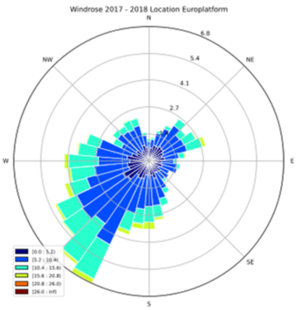

(2014Q2 - 2015Q2)



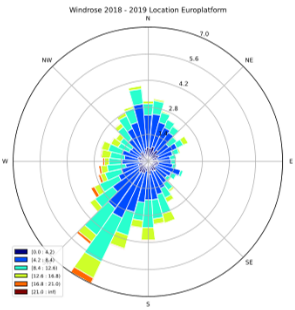

(2015Q2 - 2016Q2)



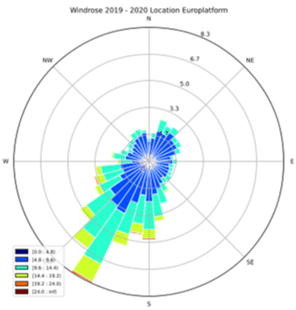

(2016Q2 - 2017Q2)




(2017Q2 - 2018Q2)




(2018Q2 - 2019Q2)




(2019Q2 - 2020Q2)

Figure B.7: Wind roses for various periods. Location Europlatform.

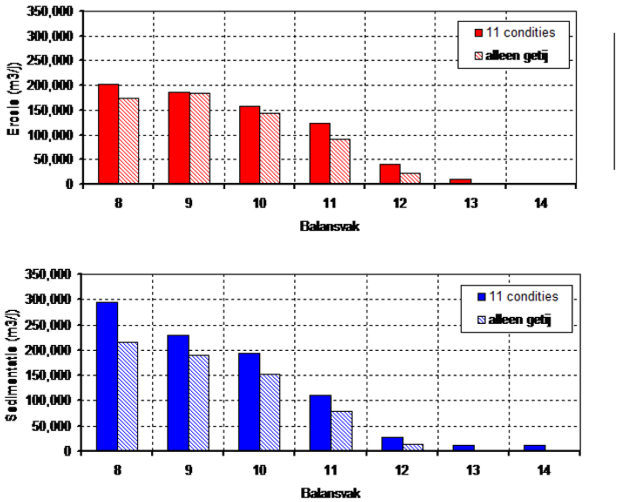



Figure B.8: PUMA modelled sedimentation- and erosion rates due to waves and tides per modelled section. From: PUMA Kenmerk puma-p-mo-onb07

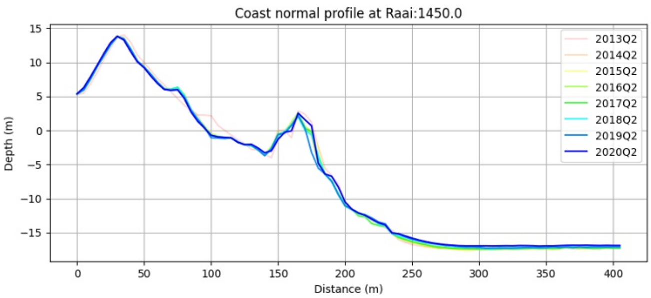
| | Wave Dir. | Hm0 | Tm01 | Wind Dir. | Wind Speed | Chance of occurrence (p) |
|---|---|---|---|---|---|---|
| **1** | 5.361 | 123.316 | 5.042 | 143.295 | 64.130 | 0.01319522 |
| **3** | 5.513 | 224.687 | 5.771 | 147.381 | 99.860 | 0.00293379 |
| **4** | 5.526 | 323.270 | 6.524 | 136.827 | 132.656 | 0.00116340 |
| **2** | 5.643 | 165.823 | 5.288 | 135.572 | 80.089 | 0.00627908 |
| **0** | 5.756 | 65.316 | 4.602 | 138.686 | 45.871 | 0.05304200 |
| **9** | 18.254 | 292.348 | 6.195 | 61.639 | 126.696 | 0.00155166 |
| **5** | 18.419 | 71.378 | 4.226 | 94.549 | 57.621 | 0.04351606 |
| **7** | 18.465 | 170.762 | 5.109 | 58.896 | 93.417 | 0.00606581 |
| **8** | 18.563 | 219.053 | 5.558 | 51.518 | 108.662 | 0.00326053 |
| **6** | 18.659 | 132.464 | 4.762 | 62.299 | 80.679 | 0.01146994 |
| **14** | 47.266 | 277.921 | 5.928 | 71.494 | 137.712 | 0.00302949 |
| **13** | 62.880 | 217.361 | 5.352 | 82.789 | 123.546 | 0.00572540 |
| **12** | 66.705 | 175.127 | 4.934 | 86.848 | 109.672 | 0.01125668 |
| **11** | 72.195 | 137.469 | 4.520 | 91.523 | 95.878 | 0.02218662 |
| **10** | 79.182 | 71.761 | 3.802 | 109.423 | 68.723 | 0.09903934 |
| **15** | 204.657 | 89.498 | 3.914 | 180.953 | 82.282 | 0.02635490 |
| **18** | 205.007 | 226.607 | 5.261 | 188.740 | 145.352 | 0.00309101 |
| **17** | 205.437 | 190.933 | 4.970 | 187.190 | 131.185 | 0.00478757 |
| **16** | 205.542 | 158.741 | 4.648 | 183.992 | 117.715 | 0.00757919 |
| **19** | 206.116 | 286.399 | 5.745 | 194.777 | 166.778 | 0.00171434 |
| **24** | 217.157 | 316.631 | 6.041 | 208.159 | 167.137 | 0.00168563 |
| **23** | 217.861 | 246.550 | 5.521 | 206.708 | 145.344 | 0.00331794 |
| **20** | 218.027 | 100.994 | 4.138 | 203.041 | 82.316 | 0.02623049 |
| **22** | 218.037 | 210.566 | 5.226 | 205.616 | 132.007 | 0.00495846 |
| **21** | 218.046 | 174.383 | 4.906 | 204.609 | 117.042 | 0.00791686 |
| **29** | 223.380 | 336.249 | 6.257 | 219.351 | 166.365 | 0.00191804 |
| **28** | 223.593 | 277.184 | 5.836 | 219.089 | 147.676 | 0.00318260 |
| **25** | 223.601 | 111.531 | 4.316 | 214.043 | 83.404 | 0.02608148 |
| **26** | 223.616 | 192.508 | 5.135 | 217.803 | 117.616 | 0.00789499 |
| **27** | 223.665 | 234.746 | 5.509 | 217.075 | 133.540 | 0.00484226 |
| **34** | 226.878 | 355.143 | 6.431 | 222.500 | 171.217 | 0.00206705 |
| **33** | 227.297 | 285.045 | 5.982 | 222.349 | 147.716 | 0.00374174 |
| **31** | 227.435 | 199.948 | 5.252 | 222.576 | 117.727 | 0.00914314 |
| **32** | 227.449 | 244.615 | 5.675 | 222.794 | 134.233 | 0.00555862 |
| **30** | 227.499 | 113.320 | 4.372 | 217.807 | 81.761 | 0.03171118 |
| **39** | 232.853 | 382.797 | 6.709 | 232.249 | 174.796 | 0.00288184 |
| **38** | 233.030 | 314.689 | 6.265 | 232.298 | 153.995 | 0.00478347 |
| **37** | 233.635 | 267.267 | 5.888 | 232.833 | 138.749 | 0.00756141 |
| **36** | 233.950 | 209.617 | 5.378 | 232.773 | 119.003 | 0.01423148 |
| **35** | 234.473 | 103.248 | 4.297 | 221.517 | 76.202 | 0.06752639 |
| **44** | 244.952 | 383.837 | 6.694 | 250.458 | 171.888 | 0.00146279 |
| **41** | 245.790 | 193.164 | 5.191 | 247.764 | 110.924 | 0.00747255 |
| **43** | 245.990 | 297.016 | 6.122 | 251.605 | 145.235 | 0.00250452 |
| **42** | 246.009 | 243.344 | 5.644 | 250.136 | 127.471 | 0.00413000 |
| **40** | 246.023 | 87.497 | 4.160 | 225.190 | 66.951 | 0.03955969 |
| **49** | 255.890 | 381.038 | 6.698 | 260.867 | 169.662 | 0.00064664 |
| **47** | 256.260 | 236.734 | 5.545 | 257.786 | 125.636 | 0.00210533 |
| **48** | 256.355 | 295.268 | 6.064 | 255.532 | 143.541 | 0.00120851 |
| **46** | 256.708 | 183.277 | 5.082 | 255.014 | 106.958 | 0.00389623 |
| **45** | 256.738 | 84.494 | 4.160 | 226.604 | 64.447 | 0.01982837 |
| **54** | 264.241 | 377.127 | 6.605 | 266.275 | 165.854 | 0.00048805 |

| | Wave Dir. | Hm0 | Tm01 | Wind Dir. | Wind Speed | Chance of occurrence (p) |
|---|---|---|---|---|---|---|
| **53** | 264.498 | 302.891 | 6.094 | 264.134 | 146.979 | 0.00085990 |
| **52** | 264.724 | 252.579 | 5.694 | 261.587 | 129.593 | 0.00134386 |
| **51** | 264.750 | 204.937 | 5.297 | 260.091 | 113.965 | 0.00225161 |
| **50** | 264.946 | 88.972 | 4.221 | 231.559 | 65.637 | 0.01291223 |
| **58** | 271.762 | 301.374 | 6.088 | 268.603 | 141.960 | 0.00075327 |
| **59** | 271.942 | 383.580 | 6.601 | 273.492 | 165.763 | 0.00040329 |
| **57** | 272.142 | 243.948 | 5.615 | 267.876 | 125.107 | 0.00127413 |
| **56** | 272.328 | 193.091 | 5.187 | 261.629 | 107.109 | 0.00226528 |
| **55** | 272.401 | 84.797 | 4.195 | 232.350 | 63.211 | 0.01263061 |
| **64** | 279.277 | 417.442 | 6.871 | 280.580 | 167.545 | 0.00030623 |
| **63** | 279.418 | 331.701 | 6.327 | 276.044 | 152.039 | 0.00055641 |
| **62** | 279.797 | 267.718 | 5.859 | 272.756 | 127.316 | 0.00094740 |
| **61** | 279.981 | 205.897 | 5.305 | 266.234 | 110.189 | 0.00181140 |
| **60** | 280.330 | 85.629 | 4.230 | 233.910 | 62.796 | 0.01134554 |
| **68** | 286.950 | 315.610 | 6.225 | 278.874 | 145.628 | 0.00063160 |
| **67** | 287.063 | 255.791 | 5.760 | 277.458 | 124.776 | 0.00107044 |
| **69** | 287.130 | 408.313 | 6.870 | 285.798 | 162.269 | 0.00032537 |
| **66** | 287.425 | 203.341 | 5.313 | 270.829 | 107.404 | 0.00189616 |
| **65** | 287.932 | 89.171 | 4.284 | 238.457 | 63.654 | 0.01040498 |
| **72** | 294.388 | 265.198 | 5.851 | 278.448 | 125.188 | 0.00105677 |
| **73** | 294.537 | 327.598 | 6.324 | 284.978 | 144.934 | 0.00062340 |
| **74** | 294.665 | 426.720 | 6.997 | 290.348 | 163.609 | 0.00031443 |
| **71** | 294.889 | 210.697 | 5.397 | 275.353 | 107.956 | 0.00187976 |
| **70** | 295.457 | 86.861 | 4.287 | 239.409 | 61.875 | 0.01189921 |
| **78** | 302.802 | 317.894 | 6.291 | 286.142 | 135.042 | 0.00080795 |
| **79** | 302.813 | 410.803 | 6.903 | 294.230 | 159.180 | 0.00041696 |
| **77** | 303.097 | 257.097 | 5.838 | 278.947 | 118.100 | 0.00138897 |
| **76** | 303.176 | 202.008 | 5.363 | 280.518 | 101.641 | 0.00253323 |
| **75** | 303.446 | 89.069 | 4.343 | 243.556 | 61.175 | 0.01360672 |
| **82** | 314.133 | 245.805 | 5.816 | 289.822 | 109.811 | 0.00260979 |
| **81** | 314.671 | 189.322 | 5.329 | 282.501 | 93.233 | 0.00517173 |
| **80** | 314.842 | 85.713 | 4.389 | 243.306 | 57.681 | 0.02718336 |
| **83** | 314.868 | 306.674 | 6.252 | 297.526 | 131.324 | 0.00158036 |
| **84** | 314.921 | 406.607 | 6.933 | 301.589 | 158.214 | 0.00076557 |
| **89** | 331.304 | 413.024 | 7.168 | 312.776 | 155.620 | 0.00199459 |
| **88** | 331.853 | 316.797 | 6.495 | 310.488 | 127.557 | 0.00386752 |
| **87** | 332.340 | 256.896 | 6.033 | 302.416 | 109.617 | 0.00635974 |
| **86** | 333.151 | 196.975 | 5.601 | 292.147 | 87.455 | 0.01183222 |
| **85** | 333.177 | 87.331 | 4.697 | 238.903 | 52.510 | 0.06686745 |
| **94** | 345.377 | 361.084 | 6.901 | 300.417 | 133.455 | 0.00134522 |
| **93** | 346.399 | 268.831 | 6.246 | 293.762 | 107.250 | 0.00273966 |
| **92** | 347.033 | 215.692 | 5.830 | 292.128 | 89.903 | 0.00465223 |
| **90** | 347.226 | 78.077 | 4.905 | 208.020 | 44.740 | 0.04386331 |
| **91** | 347.238 | 168.504 | 5.594 | 274.260 | 69.242 | 0.00849514 |
| **99** | 354.752 | 338.447 | 6.729 | 260.502 | 134.064 | 0.00119758 |
| **98** | 355.026 | 250.633 | 6.078 | 228.629 | 103.830 | 0.00255237 |
| **97** | 355.510 | 193.282 | 5.640 | 233.840 | 82.650 | 0.00484499 |
| **96** | 355.710 | 144.404 | 5.378 | 237.597 | 63.249 | 0.00994836 |
| **95** | 355.847 | 71.412 | 4.868 | 177.578 | 41.982 | 0.04583056 |

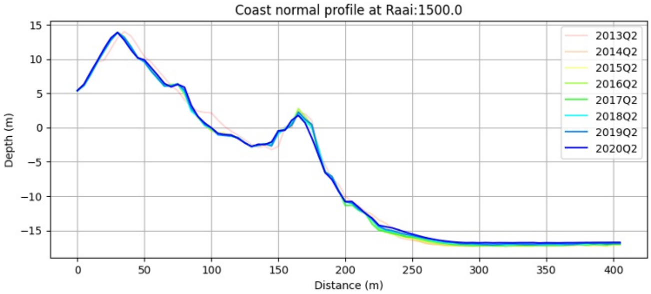
# C

# PROFILES

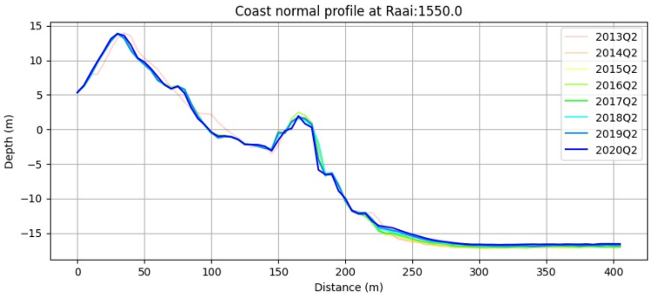
In this appendix, the calculated cross-shore profiles from the PUMA bathymetric data for various sections and year along the Maasvlakte 2 soft- and hard coastal protection are displayed. These cross-shore profiles are calculated by interpolating the XYZ bathymetric data on the coast-normal rays every 5 meter.



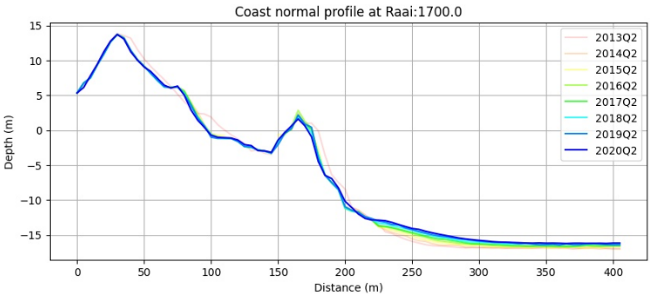

(Profile over the years 2013-2020. Raai 1450.)




(Profile over the years 2013-2020. Raai 1500.)

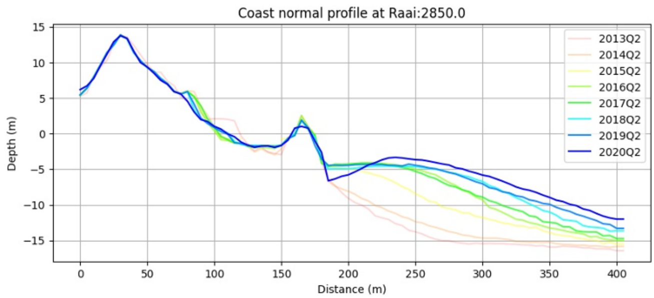



(Profile over the years 2013-2020. Raai 1550.)

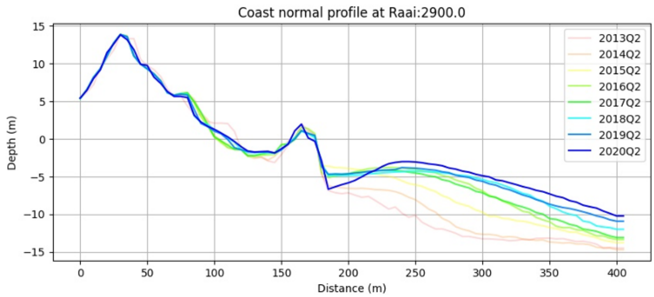



(Profile over the years 2013-2020. Raai 1700)

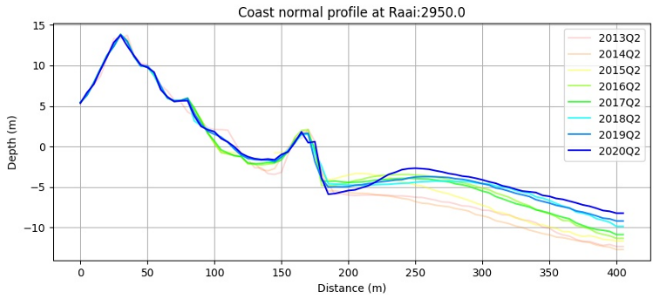
Figure C.1: Depth profiles for various coastal normals at northern side Maasvlakte 2



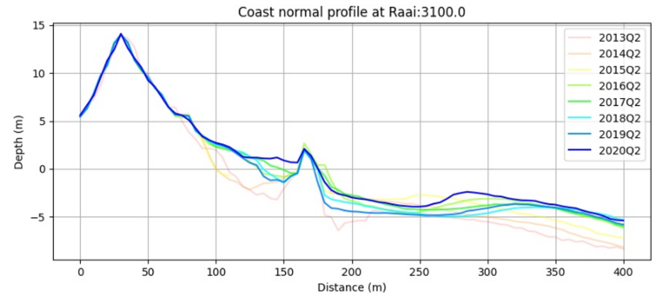

(Profile over the years 2013-2020. Raai 2850.)




(Profile over the years 2013-2020. Raai 2900.)




(Profile over the years 2013-2020. Raai 2950.)

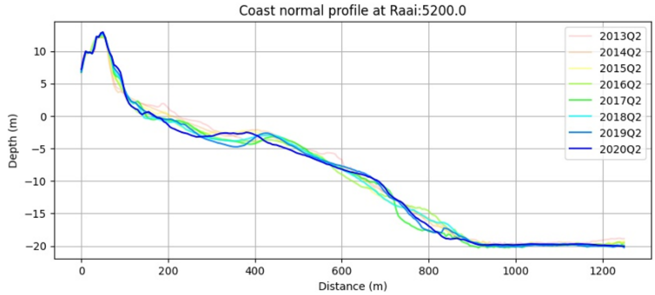



(Profile over the years 2013-2020. Raai 3100.)

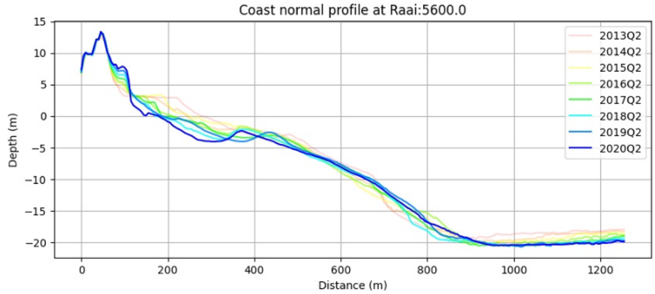
Figure C.2: Depth profiles various coastal normals at the transition between soft- and hard coastal defence, north-western side of Maasvlakte 2.

C

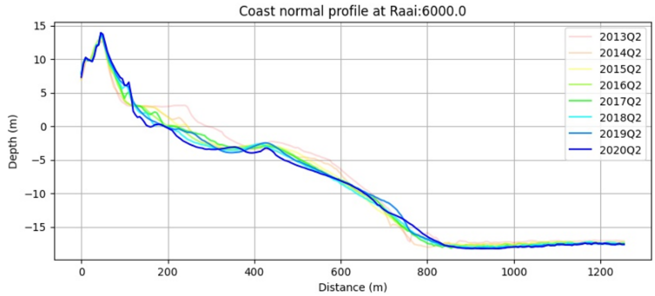
C



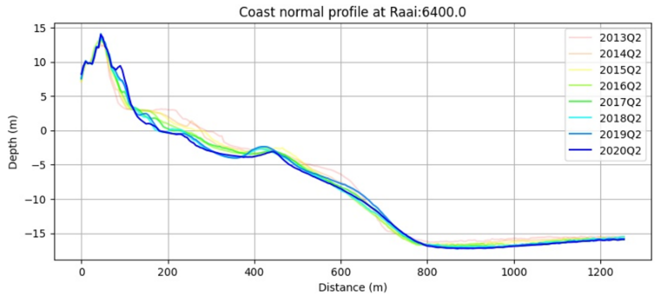

(Profile over the years 2013-2020. Raai 5200.)




(Profile over the years 2013-2020. Raai 5600.)

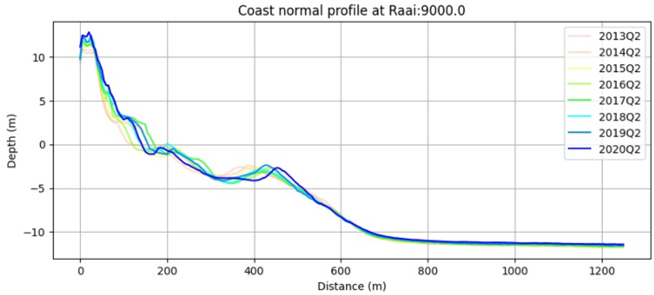



(Profile over the years 2013-2020. Raai 6000.)

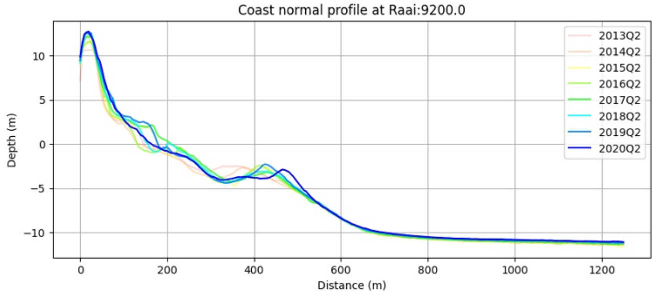



(Profile over the years 2013-2020. Raai 6400.)

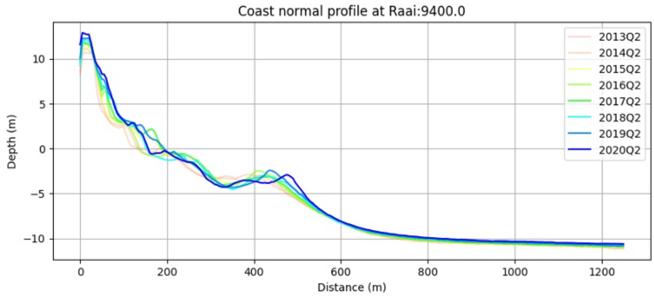
Figure C.3: Depth profiles for various coastal normals at the western bend along Maasvlakte 2.



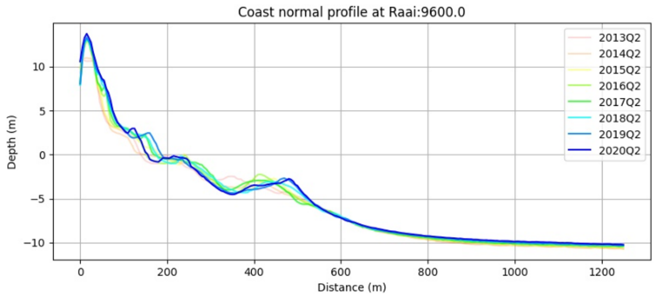

(Profile over the years 2013-2020. Raai 9000.)




(Profile over the years 2013-2020. Raai 9200.)




(Profile over the years 2013-2020. Raai 9400.)




(Profile over the years 2013-2020. Raai 9600.)

Figure C.4: Depth profiles for various coastal normals along the south-western side of Maasvlakte 2.

# D

# SWAN SETUP

In this appendix, a summary is given for the SWAN physical and numerical settings used and the .SWN input files for the three different grids are displayed.

## PHYSICAL SETTINGS

For the SWAN setup in the study, the following physical settings have been applied. These can also be seen in the .SWN base-files in the Appendix.

- GEN3 KOMEN AGROW
  With this command, the computations in SWAN are performed in third-generation mode (GEN3) for the wind input, quadruplet wave-wave interactions and white-capping. The Komen et al. (1984) formulation (KOMEN) for exponentional growth is used with a default rate of whitecapping dissipation, $C_{ds}$ of $2.36e-5$ and a default wave steepness. Furthermore, the wave growth term of Cavaleri and Malanotte (1981) is used (AGROW).

- WCAP KOM
  Include whitecapping, $S_{wc}(\sigma, \vartheta)$ according to the pulse-based model of Komen et al. (1984), using the default coefficients.

- BRE CON
  Wave breaking is applied using a constant default breaker index (wave height over depth) of $\gamma = 0.73$.

- FRIC JON
  Bottom friction, $S_{bot}(\sigma, \vartheta)$, is applied using the Hasselmann et al. (1973) semi-empirical expression derived from the JONSWAP results, with a default and constant JONSWAP coefficient for sandy bottoms of 0.038 $m^2s^{-3}$ (since 2013).

- TRI trfac=0.10
  Triad wave-wave interactions are accounted for using the default LTA method of Eldeberky (1996), with a proportionality coefficient of 0.10 and all other parameters set as default.

- LIM
  Sets a upper threshold for when quadruplets should be de-activated once the actual Ursell number reaches the threshold value of 10.0

Furthermore, non-linear quadruplet wave interactions are activated by default with all the default coefficients. Wave damping due to vegetation or mud and turbulent viscosity are both not activated and lastly, no currents were supplied.

### NUMERICAL SETTINGS

The following numerical settings (NUM) for the SWAN model used in this study have been applied:



- STOPC
  Tells SWAN that the iterative procedure in the SWAN computations can stop if a certain % of wet grid points have either a certain absolute- or relative change in the local significant wave height between iterations or the normalised iteration curve is less than a certain value.

- dabs=0.005
  The absolute change in local significant wave height at which the iterative procedure is stopped.

- drel=0.01
  The relative change in local significant wave height at which the iterative procedure is stopped.

- curvat=0.005
  The curvature of the normalised iteration curve $H_s$ at which the iterative procedure is stopped.

- npnts=98.0
  The percentage of wet grid points for which either one of the above criteria must conform.

- STAT mxitst=50, alfa=0.01 limiter=0.1
  The maximum number of iterations $(50)$, the proportionality constant used in the frequency-dependent under-relaxation technique $(\alpha = 0.01)$ and the maximum change per iteration of the energy density per spectral bin $(0.1)$.

## Base File Grid A

```
$************* HEADING ************************************
PROJECT  'Delta21'      '01'
 'Msc_Thesis_Detmar_Dieleman'
 'MV2_Run'
 'Grid: A Case: [runnumber]'

$*********** MODEL INPUT *********************************
TEST  ITEST= 0   ITRACE= 0

CGRID  REGULAR  26000.00    390000.00    45.00    120000.00    60000.00    480    240 &
     CIRCLE  72 0.03    1.50    41
INPGRID  BOTTOM  REGULAR 26000.00    390000.00    45.00    480    240    250.00    250.00 EXCEPT = 999.00
$*********** READ DEP FILE ********************************
READinp BOTTOM FAC=-1.0 'bottom\D21_A.dep'    IDLA= 3    FREE
$*********** SET GLOBAL WATER LEVEL **********************
SET LEVEL=0 NAUTical
$*********** WIND SETINGS ********************************
WIND [windspeed]      [windir]
$*********** INITIAL AND BOUNDARY CONDITIONS *************
$ Incident wave conditions
BOUnd SHAPE JON3.30 MEAN DSPR DEGR
BOUndspec SIDE North CCW CONST  PAR [hs]    [per]    [dir]    25.00
BOUndspec SIDE East CCW CONST  PAR [hs]    [per]    [dir]    25.00
BOUndspec SIDE West CCW CONST  PAR [hs]    [per]    [dir]    25.00
BOUndspec SIDE South CCW CONST  PAR [hs]    [per]    [dir]    25.00
$*********** PHYSICS *************************************
GEN3 KOMEN AGROW
WCAP KOM
BRE CON
FRIC JON
TRI trfac=0.10
LIM
OFF BNDCHK
$*********** NUMERICS ************************************
NUM STOPC dabs=0.005 drel=0.01 curvat=0.005 npnts=98.0 STAT mxitst=50 alfa=0.01 limiter=0.1
$************ OUTPUT REQUESTS ****************************
OUTPUT OPTIONS '%' TABLE 16 BLOCK 9 1000 SPEC 8

NGRID 'nst01'    50000.00    414500.00    45.00    60000.00    30000.00    400    200
NEST 'nst01'     '[runmap]\nests\NB[runnumber].rvw'
$************ LOCK UP ************************************
TEST  ITEST= 1   ITRACE= 0
COMPUTE
STOP
```

## BASE FILE GRID B

```
$************** HEADING ***********************************
PROJECT  'Delta21'     '01'
  'Msc_Thesis_Detmar_Dieleman'
  'MV2_Run'
  'Grid: B Case: [runnumber]'

$*********** MODEL INPUT ********************************
TEST  ITEST= 0  ITRACE= 0

CGRID  REGULAR  50000.00   414500.00   45.00   60000.00   30000.00   400   200 &
       CIRCLE  72  0.03   1.50   41
INPGRID  BOTTOM  REGULAR 50000.00   414500.00   45.00   400   200   150.00   150.00 EXCEPT = 999.00
$*********** READ DEP FILE ******************************
READinp BOTTOM FAC=-1.0 'bottom\D21_B.dep'   IDLA= 3   FREE
$*********** SET GLOBAL WATER LEVEL *********************
SET LEVEL=0 NAUTical
$*********** WIND SETINGS ******************************
WIND [windspeed]    [windir]
$*********** INITIAL AND BOUNDARY CONDITIONS ************
$ Incident wave conditions from parent grid
BOUndary  NEST  '[runmap]\nests\NB[runnumber].rvw'
$*********** PHYSICS ************************************
GEN3 KOMEN AGROW
WCAP KOM
BRE CON
FRIC JON
TRI trfac=0.10
LIM
$*********** NUMERICS ***********************************
NUM STOPC dabs=0.005 drel=0.01 curvat=0.005 npnts=98.0 STAT mxitst=50 alfa=0.01 limiter=0.1
$************ OUTPUT REQUESTS ***************************
OUTPUT OPTIONS '%' TABLE 16 BLOCK 9 1000 SPEC 8

NGRID 'nst02'    52000.00    433000.00    45.00    16000.00    6000.00    320    120
NEST 'nst02'     '[runmap]\nests\NC[runnumber].rvw'
$************ LOCK UP ***********************************
TEST  ITEST= 1  ITRACE= 0
COMPUTE
STOP
```

## Base File Grid C

```
$************** HEADING ************************************
PROJECT  'Delta21'    '01'
 'Msc_Thesis_Detmar_Dieleman'
 'MV2_Run'
 'Grid: C Case: [runnumber]'

$*********** MODEL INPUT *********************************
TEST  ITEST= 0  ITRACE= 0

CGRID  REGULAR  52000.00   433000.00   45.00   16000.00   6000.00   320   120 &
     CIRCLE  72  0.03   1.50   41
INPGRID  BOTTOM  REGULAR 52000.00   433000.00   45.00   320   120   50.00   50.00 EXCEPT = 999.00
$*********** READ DEP FILE *******************************
READinp BOTTOM FAC=-1.0 'bottom\D21_C.dep'   IDLA= 3   FREE
$*********** SET GLOBAL WATER LEVEL **********************
SET LEVEL=0 NAUTical
$*********** WIND SETINGS ********************************
WIND [windspeed]   [windir]
$*********** INITIAL AND BOUNDARY CONDITIONS *************
$ Incident wave conditions from parent grid
BOUndary  NEST  '[runmap]\nests\NC[runnumber].rvw'
$*********** PHYSICS *************************************
GEN3 KOMEN AGROW
WCAP KOM
BRE CON
FRIC JON
TRI trfac=0.10
LIM
$*********** NUMERICS ************************************
NUM STOPC dabs=0.005 drel=0.01 curvat=0.005 npnts=98.0 STAT mxitst=50 alfa=0.01 limiter=0.1
$************ OUTPUT REQUESTS ****************************
OUTPUT OPTIONS '%' TABLE 16 BLOCK 9 1000 SPEC 8

POINTS 'output'  FILE 'points\Raaien_RD_eind.dat'

TAB  'output'  NOHEAD  '[runmap]\output\[i].tab' &
HSign  DIR   TM01   TPS   TMM10   DSPR   DEPth   WATLev   BOTLev   WIND   &
WLENgth   DHSign   DRTM01   XP   YP

$************ LOCK UP ************************************
TEST  ITEST= 1  ITRACE= 0
COMPUTE
STOP
```

D

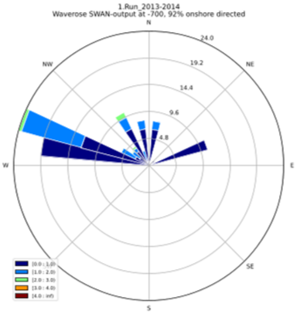
# E

# SWAN RESULTS

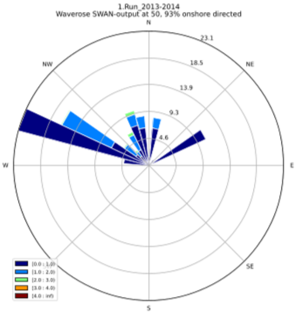
In this appendix, the offshore wave transformation for 2013-2014 for three locations is displayed, along with various wave roses for various locations in the same period.

| | | | | | | | Location 2000 | | | Location 5000 | | | Location 7000 | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | Occur. (%) | Dir. (°) | Hm0 (m) | Tper (s) | Wind (°) | Wind (.1m/s) | Hsig (m) | Tper (s) | Dir (°) | Hsig (m) | Tper (s) | Dir (°) | Hsig (m) | Tper (s) | Dir (°) |
| 0 | 5,18% | 5,57 | 65,24 | 4,56 | 158,76 | 45,17 | 0,60 | 5,39 | 352,26 | 0,63 | 5,39 | 352,22 | 0,49 | 5,39 | 332,09 |
| 1 | 1,37% | 6,94 | 120,95 | 4,98 | 116,19 | 65,06 | 1,02 | 5,90 | 359,56 | 1,04 | 5,90 | 359,00 | 0,77 | 5,90 | 344,34 |
| 2 | 0,75% | 6,01 | 153,85 | 5,17 | 155,73 | 73,10 | 1,30 | 6,04 | 350,44 | 1,36 | 6,04 | 351,12 | 1,05 | 6,04 | 331,79 |
| 3 | 0,32% | 5,58 | 215,38 | 5,77 | 99,75 | 87,30 | 1,65 | 6,78 | 355,84 | 1,67 | 6,77 | 355,84 | 1,26 | 6,79 | 342,62 |
| 4 | 0,17% | 5,06 | 277,30 | 6,62 | 74,20 | 82,50 | 1,95 | 7,88 | 351,67 | 1,96 | 7,88 | 353,24 | 1,52 | 7,88 | 341,36 |
| 5 | 4,58% | 20,05 | 70,48 | 4,09 | 91,43 | 57,69 | 0,58 | 4,88 | 14,18 | 0,56 | 4,89 | 9,32 | 0,40 | 4,87 | 353,02 |
| 6 | 1,43% | 18,47 | 120,91 | 4,66 | 70,41 | 76,91 | 0,90 | 5,47 | 12,39 | 0,88 | 5,48 | 7,44 | 0,61 | 5,46 | 349,69 |
| 7 | 0,86% | 18,99 | 148,21 | 4,70 | 41,13 | 91,13 | 1,09 | 5,50 | 11,81 | 1,06 | 5,52 | 8,07 | 0,74 | 5,51 | 348,52 |
| 8 | 0,53% | 21,29 | 182,51 | 5,10 | 45,07 | 97,41 | 1,24 | 5,99 | 11,59 | 1,22 | 5,99 | 7,92 | 0,83 | 6,00 | 349,16 |
| 9 | 0,30% | 19,18 | 223,85 | 5,64 | 53,33 | 97,91 | 1,43 | 6,64 | 7,21 | 1,41 | 6,63 | 4,57 | 0,97 | 6,63 | 347,75 |
| 10 | 7,94% | 90,00 | 77,51 | 3,79 | 114,48 | 74,72 | 0,34 | 2,45 | 65,81 | 0,31 | 4,45 | 72,03 | 0,21 | 2,03 | 146,99 |
| 11 | 2,09% | 102,51 | 142,96 | 4,48 | 116,91 | 105,91 | 0,48 | 2,79 | 71,82 | 0,44 | 2,68 | 88,73 | 0,34 | 2,35 | 150,58 |
| 12 | 1,09% | 83,81 | 174,67 | 4,89 | 99,03 | 115,21 | 0,82 | 5,50 | 48,76 | 0,73 | 5,63 | 39,96 | 0,33 | 2,21 | 121,51 |
| 13 | 0,50% | 146,51 | 199,22 | 5,01 | 141,60 | 133,70 | 0,65 | 3,97 | 240,22 | 0,78 | 3,41 | 216,24 | 0,78 | 3,21 | 209,50 |
| 14 | 0,29% | 174,41 | 233,19 | 5,17 | 162,18 | 145,92 | 1,38 | 6,46 | 265,97 | 1,63 | 6,46 | 251,13 | 1,52 | 6,39 | 250,83 |
| 15 | 1,99% | 204,59 | 99,39 | 3,97 | 191,63 | 88,20 | 0,59 | 4,82 | 245,78 | 0,76 | 4,85 | 228,30 | 0,71 | 4,77 | 228,56 |
| 16 | 0,62% | 205,04 | 168,84 | 4,69 | 187,02 | 126,77 | 1,42 | 6,29 | 265,76 | 1,66 | 6,25 | 253,47 | 1,53 | 6,13 | 255,05 |
| 17 | 0,38% | 204,26 | 205,97 | 5,16 | 186,24 | 142,32 | 1,64 | 6,71 | 266,79 | 1,93 | 6,72 | 254,65 | 1,76 | 6,58 | 256,21 |
| 18 | 0,26% | 204,06 | 240,21 | 5,41 | 191,98 | 153,21 | 1,85 | 6,96 | 267,78 | 2,17 | 6,97 | 256,30 | 1,98 | 6,92 | 257,87 |
| 19 | 0,17% | 204,98 | 281,52 | 5,60 | 196,14 | 166,14 | 1,91 | 5,40 | 262,53 | 2,22 | 5,35 | 248,68 | 1,99 | 5,34 | 249,40 |
| 20 | 1,83% | 211,13 | 106,59 | 4,14 | 195,56 | 88,80 | 0,91 | 5,05 | 263,03 | 1,06 | 5,03 | 251,17 | 0,99 | 4,96 | 253,04 |
| 21 | 0,53% | 210,74 | 187,57 | 5,02 | 196,51 | 127,96 | 1,43 | 4,95 | 261,45 | 1,65 | 4,91 | 248,50 | 1,49 | 4,91 | 249,83 |
| 22 | 0,29% | 210,62 | 236,79 | 5,37 | 196,40 | 148,20 | 1,32 | 6,80 | 255,46 | 1,64 | 6,30 | 237,62 | 1,48 | 6,26 | 237,56 |
| 23 | 0,20% | 210,01 | 278,14 | 5,57 | 198,30 | 169,70 | 2,16 | 7,28 | 268,51 | 2,53 | 7,28 | 257,90 | 2,30 | 7,23 | 260,08 |
| 24 | 0,11% | 210,31 | 342,69 | 6,04 | 198,62 | 188,62 | 2,31 | 5,89 | 264,17 | 2,66 | 5,73 | 250,40 | 2,35 | 5,49 | 251,37 |
| 25 | 1,87% | 215,51 | 111,32 | 4,25 | 203,23 | 89,77 | 0,71 | 4,99 | 251,91 | 0,86 | 4,97 | 236,38 | 0,80 | 4,89 | 237,74 |
| 26 | 0,59% | 215,23 | 188,58 | 5,09 | 202,81 | 124,92 | 1,76 | 6,28 | 267,68 | 1,97 | 6,21 | 259,25 | 1,79 | 6,15 | 261,63 |
| 27 | 0,37% | 215,09 | 225,05 | 5,35 | 202,77 | 135,45 | 1,72 | 6,71 | 267,43 | 2,00 | 6,72 | 257,51 | 1,82 | 6,62 | 259,80 |
| 28 | 0,21% | 214,55 | 282,42 | 5,61 | 198,95 | 158,57 | 2,33 | 6,99 | 269,39 | 2,62 | 6,94 | 260,91 | 2,35 | 6,89 | 263,30 |
| 29 | 0,10% | 214,87 | 375,77 | 6,40 | 204,81 | 184,81 | 2,00 | 7,81 | 261,30 | 2,41 | 7,82 | 246,03 | 2,18 | 7,70 | 247,72 |
| 30 | 2,13% | 219,63 | 113,16 | 4,31 | 212,83 | 87,64 | 0,74 | 5,01 | 255,48 | 0,88 | 4,99 | 241,55 | 0,82 | 4,91 | 243,43 |
| 31 | 0,74% | 219,67 | 182,51 | 5,00 | 214,71 | 117,59 | 1,46 | 4,92 | 263,65 | 1,64 | 4,92 | 253,77 | 1,48 | 4,91 | 255,83 |
| 32 | 0,51% | 219,70 | 211,63 | 5,32 | 211,07 | 127,56 | 1,87 | 6,49 | 268,18 | 2,09 | 6,47 | 260,71 | 1,89 | 6,43 | 263,26 |
| 33 | 0,29% | 219,10 | 261,39 | 5,63 | 205,20 | 147,53 | 2,20 | 6,80 | 269,16 | 2,47 | 6,79 | 261,44 | 2,23 | 6,77 | 264,06 |
| 34 | 0,10% | 218,69 | 393,54 | 6,62 | 204,23 | 181,15 | 2,41 | 7,83 | 265,51 | 2,75 | 7,85 | 253,94 | 2,45 | 5,47 | 256,36 |
| 35 | 2,32% | 223,05 | 116,71 | 4,35 | 220,25 | 86,29 | 1,10 | 4,54 | 265,87 | 1,21 | 4,60 | 258,47 | 1,12 | 4,55 | 260,50 |
| 36 | 0,79% | 222,70 | 187,56 | 5,13 | 216,38 | 113,23 | 1,15 | 6,00 | 260,19 | 1,34 | 5,92 | 247,46 | 1,23 | 5,87 | 249,79 |
| 37 | 0,43% | 222,14 | 235,64 | 5,51 | 214,55 | 133,56 | 1,42 | 6,57 | 261,35 | 1,67 | 6,50 | 248,48 | 1,53 | 6,46 | 250,58 |
| 38 | 0,27% | 222,21 | 288,04 | 5,85 | 211,84 | 153,97 | 2,40 | 7,12 | 269,73 | 2,68 | 7,12 | 262,62 | 2,41 | 7,11 | 265,49 |
| 39 | 0,14% | 222,21 | 369,42 | 6,53 | 212,25 | 177,32 | 2,88 | 7,75 | 270,91 | 3,23 | 7,78 | 264,34 | 2,91 | 7,77 | 267,97 |
| 40 | 2,03% | 225,43 | 127,85 | 4,49 | 222,15 | 88,82 | 0,83 | 5,30 | 259,74 | 0,95 | 5,29 | 247,63 | 0,89 | 5,23 | 249,91 |
| 41 | 0,70% | 224,98 | 207,35 | 5,28 | 218,38 | 119,27 | 1,76 | 6,32 | 268,21 | 1,95 | 6,30 | 261,36 | 1,77 | 6,25 | 263,97 |
| 42 | 0,43% | 224,97 | 253,16 | 5,67 | 212,06 | 138,49 | 1,83 | 5,36 | 265,12 | 2,07 | 5,34 | 255,37 | 1,84 | 5,31 | 257,51 |
| 43 | 0,30% | 224,94 | 292,38 | 6,01 | 216,95 | 151,13 | 2,09 | 7,11 | 266,27 | 2,34 | 5,41 | 257,20 | 2,10 | 5,39 | 259,86 |
| 44 | 0,17% | 224,64 | 358,86 | 6,41 | 220,23 | 172,53 | 2,50 | 7,54 | 267,52 | 2,79 | 7,60 | 258,66 | 2,50 | 7,34 | 261,88 |
| 45 | 2,71% | 227,97 | 121,06 | 4,44 | 223,92 | 83,85 | 0,93 | 5,26 | 264,74 | 1,04 | 5,26 | 255,92 | 0,98 | 5,22 | 257,96 |
| 46 | 0,69% | 227,87 | 225,62 | 5,45 | 222,06 | 122,46 | 1,37 | 6,49 | 263,78 | 1,58 | 6,45 | 252,57 | 1,44 | 6,43 | 255,14 |
| 47 | 0,38% | 227,70 | 285,37 | 5,91 | 219,69 | 143,47 | 2,01 | 7,05 | 266,85 | 2,25 | 5,40 | 258,35 | 2,01 | 5,38 | 261,00 |
| 48 | 0,25% | 227,34 | 331,34 | 6,34 | 229,85 | 157,69 | 2,66 | 7,45 | 271,62 | 2,94 | 7,55 | 266,40 | 2,65 | 7,60 | 269,93 |
| 49 | 0,17% | 227,58 | 391,41 | 6,62 | 223,72 | 185,00 | 2,91 | 7,93 | 271,71 | 3,29 | 7,94 | 265,59 | 3,00 | 7,98 | 269,59 |
| 50 | 7,20% | 235,49 | 96,90 | 4,20 | 228,07 | 73,24 | 0,64 | 4,87 | 261,26 | 0,73 | 4,88 | 249,98 | 0,69 | 4,86 | 252,33 |
| 51 | 1,38% | 235,45 | 205,68 | 5,30 | 237,05 | 114,87 | 1,62 | 6,38 | 270,77 | 1,79 | 6,38 | 264,52 | 1,65 | 6,33 | 267,33 |
| 52 | 0,62% | 234,35 | 281,78 | 6,00 | 235,02 | 138,42 | 2,30 | 7,08 | 271,93 | 2,53 | 7,09 | 267,00 | 2,28 | 7,07 | 270,34 |
| 53 | 0,35% | 233,27 | 353,09 | 6,49 | 239,56 | 158,07 | 2,60 | 7,73 | 273,54 | 2,87 | 7,74 | 268,60 | 2,64 | 7,75 | 272,78 |
| 54 | 0,19% | 233,07 | 443,84 | 7,01 | 230,00 | 197,76 | 3,20 | 8,25 | 271,67 | 3,50 | 8,40 | 264,18 | 3,19 | 8,48 | 268,90 |
| 55 | 3,33% | 249,57 | 78,86 | 4,04 | 230,06 | 63,64 | 0,55 | 4,85 | 264,43 | 0,61 | 4,85 | 253,70 | 0,58 | 4,84 | 256,18 |
| 56 | 0,59% | 249,01 | 185,98 | 5,07 | 256,16 | 111,42 | 1,48 | 6,01 | 277,39 | 1,57 | 5,96 | 271,19 | 1,48 | 5,94 | 274,28 |
| 57 | 0,36% | 248,42 | 231,27 | 5,50 | 250,43 | 119,03 | 1,94 | 6,49 | 275,15 | 2,09 | 6,49 | 270,79 | 1,92 | 6,47 | 274,20 |
| 58 | 0,21% | 248,84 | 282,48 | 6,00 | 256,73 | 137,48 | 2,24 | 7,11 | 277,63 | 2,37 | 7,11 | 272,83 | 2,21 | 7,11 | 277,26 |
| 59 | 0,09% | 246,89 | 422,41 | 6,91 | 259,78 | 192,17 | 3,66 | 8,14 | 280,07 | 3,87 | 8,17 | 276,65 | 3,72 | 8,36 | 282,74 |
| 60 | 1,85% | 261,79 | 79,69 | 4,09 | 235,08 | 64,46 | 0,72 | 4,77 | 270,35 | 0,77 | 4,79 | 263,53 | 0,72 | 4,79 | 265,62 |
| 61 | 0,36% | 261,59 | 174,55 | 4,98 | 264,35 | 107,72 | 1,62 | 5,92 | 281,02 | 1,70 | 5,90 | 277,06 | 1,58 | 5,89 | 280,25 |
| 62 | 0,21% | 261,64 | 218,65 | 5,32 | 245,28 | 119,34 | 1,64 | 6,42 | 276,82 | 1,77 | 6,40 | 269,50 | 1,66 | 6,40 | 273,26 |
| 63 | 0,15% | 261,21 | 250,65 | 5,53 | 253,90 | 125,71 | 2,02 | 6,54 | 278,64 | 2,14 | 6,52 | 273,83 | 1,99 | 6,53 | 277,96 |
| 64 | 0,09% | 259,28 | 306,23 | 6,13 | 259,57 | 141,49 | 2,41 | 7,20 | 281,09 | 2,55 | 7,20 | 276,79 | 2,40 | 7,21 | 281,65 |
| 65 | 1,38% | 272,75 | 79,88 | 4,11 | 236,83 | 65,86 | 0,80 | 4,85 | 274,00 | 0,86 | 4,86 | 267,96 | 0,81 | 4,85 | 270,12 |
| 66 | 0,27% | 273,00 | 179,57 | 5,03 | 274,41 | 104,04 | 1,50 | 5,95 | 289,57 | 1,57 | 5,94 | 286,09 | 1,50 | 5,94 | 289,35 |
| 67 | 0,18% | 272,03 | 211,08 | 5,37 | 258,06 | 109,78 | 1,60 | 6,43 | 283,73 | 1,70 | 6,42 | 278,64 | 1,61 | 6,43 | 282,05 |
| 68 | 0,13% | 272,84 | 239,43 | 5,50 | 275,82 | 132,24 | 2,30 | 6,54 | 288,07 | 2,41 | 6,51 | 285,30 | 2,29 | 6,54 | 289,50 |
| 69 | 0,08% | 272,50 | 286,33 | 5,79 | 281,25 | 143,50 | 2,51 | 7,03 | 291,73 | 2,61 | 7,01 | 289,27 | 2,53 | 7,06 | 293,83 |
| 70 | 1,23% | 283,60 | 82,11 | 4,21 | 240,94 | 61,75 | 0,71 | 4,95 | 283,05 | 0,75 | 4,95 | 276,90 | 0,72 | 4,95 | 278,67 |
| 71 | 0,24% | 283,72 | 182,58 | 5,12 | 266,37 | 98,55 | 1,61 | 5,94 | 285,70 | 1,68 | 5,94 | 282,56 | 1,59 | 5,95 | 285,64 |
| 72 | 0,17% | 282,94 | 209,15 | 5,28 | 262,02 | 107,19 | 1,61 | 6,34 | 288,08 | 1,70 | 6,32 | 283,55 | 1,62 | 6,35 | 286,95 |
| 73 | 0,13% | 281,54 | 236,95 | 5,56 | 267,38 | 122,77 | 2,14 | 6,51 | 286,55 | 2,25 | 6,49 | 283,40 | 2,13 | 6,52 | 287,31 |
| 74 | 0,05% | 283,19 | 330,41 | 6,26 | 297,04 | 158,15 | 2,95 | 7,47 | 302,61 | 3,02 | 7,46 | 301,28 | 3,00 | 7,62 | 303,63 |
| 75 | 1,27% | 293,35 | 84,50 | 4,21 | 251,71 | 61,74 | 0,78 | 4,97 | 286,79 | 0,81 | 4,97 | 282,60 | 0,77 | 4,97 | 284,55 |
| 76 | 0,27% | 293,09 | 179,32 | 5,08 | 273,96 | 96,12 | 1,43 | 5,98 | 294,90 | 1,49 | 5,97 | 291,93 | 1,43 | 5,98 | 294,32 |
| 77 | 0,13% | 292,50 | 235,68 | 5,46 | 282,79 | 117,50 | 1,99 | 6,51 | 297,23 | 2,06 | 6,50 | 295,05 | 1,98 | 6,52 | 297,48 |
| 78 | 0,06% | 292,38 | 334,62 | 6,37 | 295,86 | 138,62 | 2,69 | 7,63 | 303,30 | 2,75 | 7,61 | 302,04 | 2,72 | 7,70 | 303,41 |
| 79 | 0,03% | 293,54 | 452,77 | 7,06 | 303,08 | 153,08 | 3,40 | 8,51 | 305,77 | 3,43 | 8,49 | 304,65 | 3,46 | 8,57 | 305,54 |
| 80 | 1,83% | 305,83 | 86,81 | 4,29 | 268,47 | 61,67 | 0,74 | 5,08 | 300,54 | 0,76 | 5,09 | 297,85 | 0,74 | 5,08 | 298,03 |
| 81 | 0,49% | 305,64 | 160,62 | 4,91 | 280,40 | 91,29 | 1,40 | 5,87 | 298,87 | 1,44 | 5,87 | 297,02 | 1,36 | 5,87 | 298,70 |
| 82 | 0,30% | 305,91 | 194,85 | 5,24 | 282,86 | 98,64 | 1,62 | 6,21 | 301,18 | 1,66 | 6,20 | 299,67 | 1,58 | 6,24 | 300,87 |
| 83 | 0,12% | 306,59 | 280,92 | 5,91 | 305,40 | 128,10 | 2,36 | 7,09 | 310,81 | 2,40 | 7,08 | 310,77 | 2,30 | 7,12 | 309,03 |
| 84 | 0,05% | 305,52 | 393,00 | 6,83 | 299,20 | 144,40 | 3,06 | 8,05 | 308,89 | 3,07 | 8,01 | 308,30 | 3,08 | 8,11 | 308,19 |
| 85 | 2,82% | 319,52 | 102,22 | 4,54 | 266,02 | 63,56 | 0,90 | 5,40 | 312,03 | 0,93 | 5,40 | 310,46 | 0,87 | 5,40 | 307,64 |
| 86 | 0,56% | 319,73 | 219,73 | 5,60 | 291,09 | 103,30 | 1,81 | 6,58 | 310,45 | 1,85 | 6,57 | 310,24 | 1,73 | 6,59 | 308,73 |
| 87 | 0,21% | 318,72 | 311,72 | 6,21 | 319,44 | 140,00 | 2,67 | 7,31 | 320,00 | 2,69 | 7,28 | 321,22 | 2,55 | 7,35 | 316,23 |
| 88 | 0,15% | 320,30 | 384,91 | 6,98 | 305,57 | 161,52 | 3,34 | 8,34 | 314,89 | 3,32 | 8,23 | 315,58 | 3,27 | 8,40 | 313,24 |
| 89 | 0,11% | 319,98 | 433,05 | 7,30 | 242,55 | 159,45 | 3,55 | 8,69 | 306,68 | 3,58 | 8,66 | 303,67 | 3,43 | 8,71 | 305,08 |
| 90 | 6,70% | 337,57 | 83,27 | 4,61 | 232,90 | 51,87 | 0,85 | 5,43 | 323,93 | 0,88 | 5,43 | 322,07 | 0,79 | 5,43 | 315,23 |
| 91 | 1,40% | 337,13 | 166,89 | 5,24 | 299,21 | 77,77 | 1,32 | 6,22 | 326,36 | 1,34 | 6,21 | 327,89 | 1,20 | 6,24 | 319,20 |
| 92 | 0,71% | 336,55 | 228,70 | 5,71 | 287,23 | 105,01 | 1,93 | 6,68 | 318,87 | 1,97 | 6,67 | 319,97 | 1,76 | 6,70 | 312,89 |
| 93 | 0,41% | 333,99 | 305,95 | 6,61 | 274,50 | 107,61 | 2,42 | 7,88 | 323,05 | 2,44 | 7,86 | 324,61 | 2,23 | 7,88 | 317,87 |
| 94 | 0,22% | 333,22 | 406,32 | 7,36 | 210,00 | 130,00 | 3,21 | 8,72 | 321,70 | 3,24 | 8,70 | 321,44 | 3,03 | 8,73 | 316,40 |
| 95 | 6,03% | 354,07 | 64,89 | 4,69 | 173,85 | 41,87 | 0,60 | 5,48 | 347,34 | 0,62 | 5,49 | 347,19 | 0,52 | 5,48 | 333,49 |
| 96 | 1,33% | 353,04 | 131,37 | 5,17 | 228,01 | 62,15 | 1,24 | 6,04 | 334,17 | 1,29 | 6,04 | 333,74 | 1,09 | 6,04 | 320,03 |
| 97 | 0,77% | 352,99 | 163,75 | 5,32 | 247,06 | 72,49 | 1,45 | 6,34 | 338,92 | 1,50 | 6,34 | 339,37 | 1,25 | 6,34 | 324,80 |
| 98 | 0,45% | 352,83 | 203,17 | 5,59 | 238,22 | 94,74 | 1,84 | 6,55 | 329,90 | 1,91 | 6,55 | 329,26 | 1,63 | 6,55 | 314,58 |
| 99 | 0,25% | 354,08 | 250,87 | 6,13 | 81,15 | 91,54 | 1,94 | 7,23 | 347,71 | 1,94 | 7,22 | 348,48 | 1,61 | 7,23 | 337,42 |

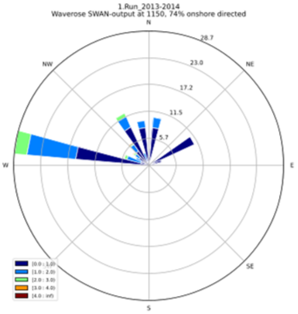
Table E.1: Results of the SWAN transformation of the 2013-2014 reduced wave climate (100 wave conditions) for Location 2000, Location 5000 and Location 7000.



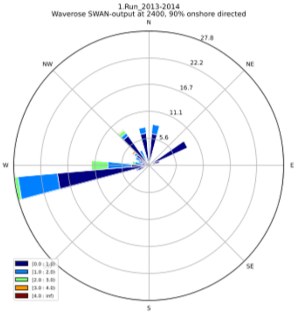

(Location -700. Period 2013-2014.)



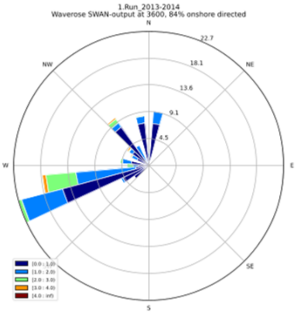

(Location 50. Period 2013-2014.)



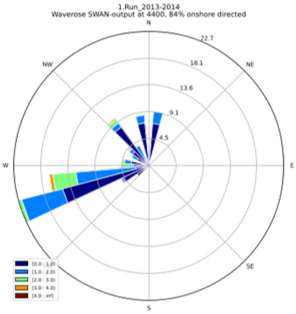

(Location 1150. Period 2013-2014.)



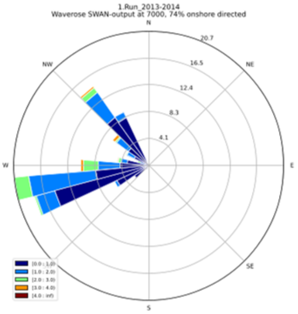

(Location 2400. Period 2013-2014.)



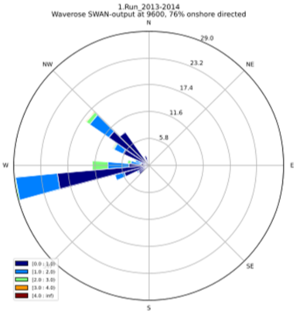

(Location 3600. Period 2013-2014.)




(Location 4400. Period 2013-2014.)




(Location 7000. Period 2013-2014.)




(Location 9600. Period 2013-2014.)

Figure E.1: SWAN nearshore wave roses for various locations. Period 2013-2014.

E

# F

# UNIBEST SETUP

In this appendix, a summary is given of the UNIBEST-LT and UNIBEST-CL input file requirements, physical settings and parameters.

**Input files, locations and wave climates**

The various input for the UNIBEST-LT and UNIBEST-CL models come from the data study and the previously performed SWAN model. In order to model the alongshore sediment transport and erosion, UNIBEST will require the following files, an example of which can be found in the Appendix. A description, origin and usage of each of these is briefly explained.

1. .LTR files: Input runs & coastal orientations for UNIBEST-LT;
   Coastal orientations and output locations remain constant throughout testing for both model 0 and model 1.
2. .PRO files: Cross-shore profiles;
   The actual- and design profiles are used for model 0, while the design profile of Maasvlakte 2 is used for the model 1 Delta21 modelling.
3. .CFS files: Transport parameters;
   Default parameters for wave induced transport in the North Sea are used for both model 0 and model 1, with a variation in grain size.
4. .CFE files: Wave parameters;
   Similarly to the .CFS files, the default parameters for both model 0 and model 1 are used.
5. .CSO files: Waves- & tides;
   Waves from the output files of SWAN are combined with tidal conditions from Delft3D and used as input for UNIBEST-LT.
6. .RAY files: UNIBEST-LT output files;
   Output file by UNIBEST-LT, which is fed into UNIBEST-CL for coastline modelling.

The .LTR files contain all the locations and coastal orientations which UNIBEST-LT needs to model. These files will be created by a Python script for each model that will be run, since a large range of various .PRO and .SCO files will be used and creating these by hand is tedious and prone to errors. For the Maasvlakte 2 and Delta21 modelling, 33 and

29 distinct locations will be looked at, respectively. The output locations for Maasvlakte 2 are similar to those used for the SWAN modelling, as seen in Figure A, except that only the coast-normals are used, since only coast-normals can be modelled in UNIBEST. The output locations and coastline orientations for the Delta21 modelling can be seen in Figure A and have been set up in the following matter:

1. For the research area, a buffer equal to the required distance for the design profile has been created.
2. Along this buffer, output locations are defined every 500 meter, to a total of 29 output locations for the Delta21 coastline, from the attachment-point to Maasvlakte 2 in the north to the location of the pumps in the south.
3. For each location, a line perpendicular towards the coast has been drawn which serves as the coast normal for each ray.

The cross shore profiles needed for the UNIBEST modelling are summarised in the .PRO files, input with the cross-shore profile data from PUMA for the design profile of Maasvlakte 2. This design profile has furthermore been used as the design profile for the profile of Delta21. This design profile can be seen in Figure F.1. The transport boundary is the boundary at which no more transport is calculated. For comparative reasoning to the sediment transport of Maasvlakte 2, this was set -8m NAP for all the profiles, such that transport below -8m NAP is not considered. The dynamic boundary is the boundary from which the coastline 'rotates' and acts dynamic and below at which point it does not change and behaves static, having a significant effect on the refraction of waves and the coastline modelling in UNIBEST-CL. This has been set to the same depth as the transport boundary.

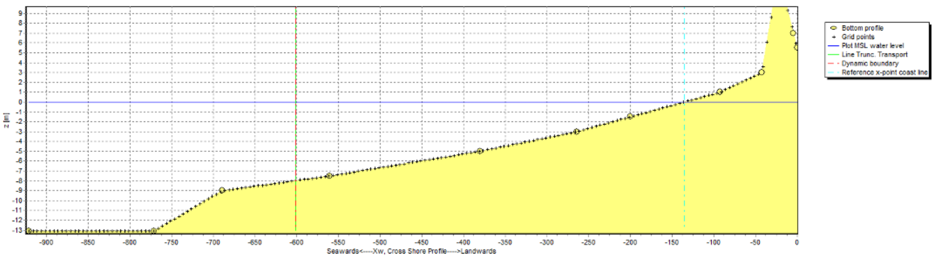



Figure F.1: General design profile for Maasvlakte 2, as represented in UNIBEST-LT.

The .CFS file contains the sediment transport parameters. The transport formula (Bijker), with the parameters similar or close to those present at Maasvlakte 2, the details of which can be found in Appendix D. Also see Chapter 5 for a further elaboration on these values. The waves input for the .SCO (wave & current) files is extracted from each individual exported .tab file from SWAN using a Python-script and combined into a single file for each location. The tidal currents are extracted from the Delft3D model and combined with the waves into a single file for each location for both the Maasvlakte 2 and Delta21 model.

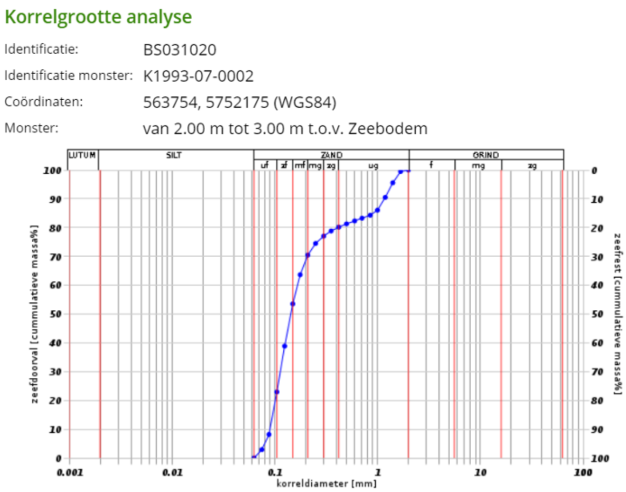



Figure F.2: Soil characteristics at 2-3 meters depth, compared to ground level. Example at an arbitrary location of the Energy Storage Lake. Source: Geographical Service Netherlands, TNO.

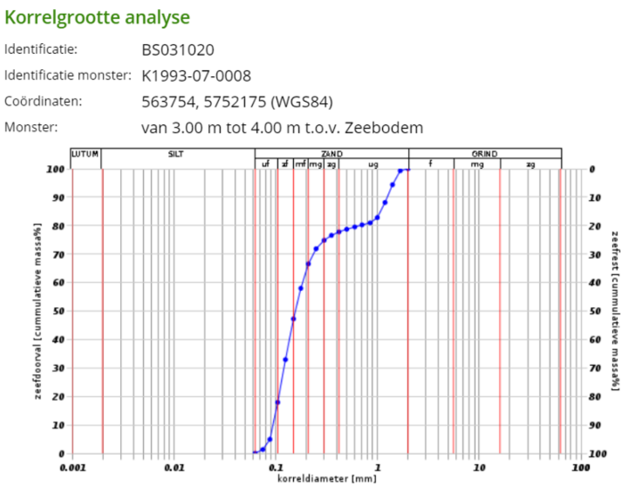



Figure F.3: Soil characteristics at 3-4 meter depth, compared to ground level. Example at an arbitrary location of the Energy Storage Lake. Source: Geographical Service Netherlands, TNO.

F

# G

# UNIBEST RESULTS

In this appendix, graphs show the alongshore sediment transport, erosion rates and erosion volume for Delta21 and Maasvlakte 2 after various years.

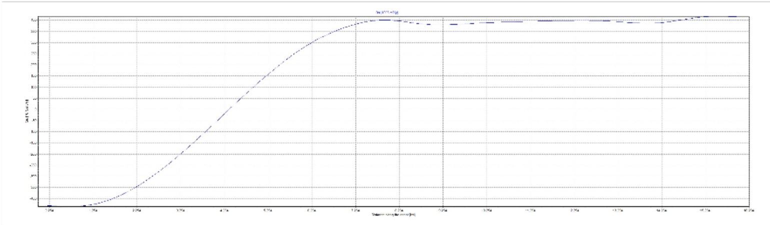


Figure G.1: Alongshore sediment transport after 5 years for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

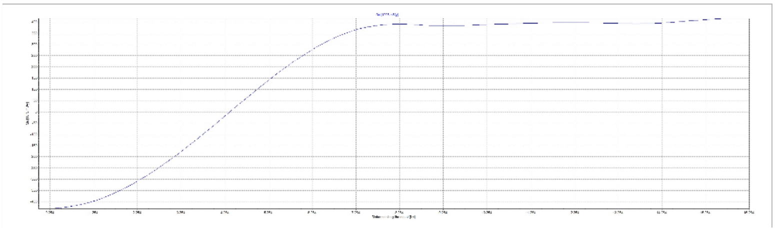


Figure G.2: Alongshore sediment transport after 10 years for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.



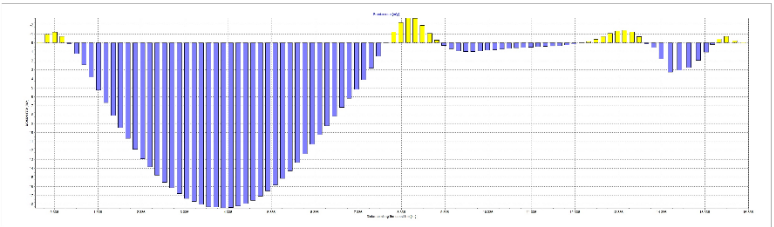


Figure G.3: Erosion rates after 5 years for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

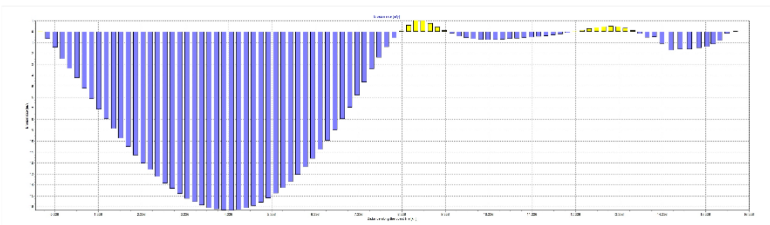


Figure G.4: Erosion rates after 10 years for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.