

# MASTER THESIS

## ALONGSHORE SEDIMENT TRANSPORT & RESULTING EROSION VOLUMES DUE TO THE DELTA21-PROJECT

### *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

by

Detmar Dieleman

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



*“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

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# 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. 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, in specific 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 -8m NAP.

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.

The Model 1 then models and compares these alongshore transports to those found at Maasvlakte 2. The extent and characteristics are summarised as being similar. In addition, the implementation of tidal data from an external Delft3D-model is modelled, however, no conclusive remarks could be given due to the inability of UNIBEST to model these accurately. This study furthermore shows that the grain size can have a significant impact, with alongshore sediment transports and erosion x2.5 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 hence shows that the current layout for the Delta21-project will behave similarly to Maasvlakte 2 in regards to alongshore sediment transport and erosion above -8m NAP.



# 1

## INTRODUCTION

The DELTA21-project is a proposed plan that can offer a future-proof solution to the water safety of the south-western delta in the Netherlands. Situated at the Haringvliet, south of Maasvlakte 2, it has three main ambitions;

1. **Flood protection.** The DELTA21-project is an alternative to continuous reinforcements of the dikes around the main rivers. During high water, 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 & 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.

Delta21  
Artist Impression  
Detmar Dieleman

Image: Sentinel2 - 10m resolution, 25-07-2019. Credits: European Space Agency (ESA)



## 1.1. FLOOD PROTECTION.

### 1.1.1. MAIN GOAL

The main goal of the DELTA21 is to protect the area around the main rivers from flooding during high water events. 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. 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. 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]

### 1.1.2. WORKINGS

With the DELTA21-project, during a high water event, pumps can be turned on with a capacity of up to 10,000  $m^3/s$  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. [3]

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, allowing for the flow of water inside this lake through turbines, generating electricity.

### 1.1.3. 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. 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. [2] 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.

## 1.2. ENERGY STORAGE.

### 1.2.1. SECONDARY GOAL

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. 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.

### 1.2.2. 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 [4]. 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 [2]. 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 [5]. 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.

### 1.2.3. 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. 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.

## 1.3. RECOVERY & PRESERVATION OF NATURE.

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.

### 1.3.1. 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. [6]

### 1.3.2. BUILDING WITH NATURE

The DELTA21-project allows for the usage of the Building with Nature principle, a fairly new principle which stands for working and building with nature, instead of building in nature. 'Hard' solutions and hydraulic structures are avoided and instead nature-based solutions are implemented to deal with floods, waves and sea level rise. These solutions provide a more sustainable and adaptable approach in which natural processes and materials are used. A good example of this is the Sand Motor, a large sand nourishment at the Dutch coast, which is designed such that waves and currents will transport the sand along the coast over the course of time.



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

### 1.3.3. 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. An increase in flora and fauna due to the presence of the tidal lake and the created dune area is expected, which can lead to an increase in ecotourism in the area. Although it is 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-project.

### 1.3.4. 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 [7]. This area stretches from the Maasvlakte south-ward 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 [8]. 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. [9].

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.



# 2

## PROBLEM DESCRIPTION

The DELTA21-project faces many challenges, such as providing flood protection and avoiding severe ecological damage. Issues such as the combined flood protection that the project can deliver, the impact on the ecology or the salt intrusion have already been researched or are currently still being researched. Studies regarding the morphological impact on 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 DELTA21-project.

The research area can be seen in Figure 2.1. 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.

### 2.1. GENERAL PROBLEM DELTA21

#### 2.1.1. 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 the 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



Figure 2.1: 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.

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, however this is outside the scope of this report and more over this can be read in the these other reports made.

### 2.1.2. 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 from the otherwise straight coast of the Netherlands 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.

## 2.2. 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 severely 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.

### 2.2.1. BEACHES & 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. [10]

Another section of beaches are those just above the dune-row making up the energy storage lake. There are situated between the hard coastal defence in the north and the ESL to the south. These will maintain their interaction with the North-Sea and are not directly linked to the ESL. They are 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 these dunes are 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 defensive and recreation functions of the beach and dunes there and will need therefore need investigating.

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 effects in the modelling performed, such as armouring and clay sub-layers [11]. The effects of large scale scour are important, since they have environmental impacts, such as habitat loss and reduce of feeding areas, but also 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. The formation of the large scour hole at Maasvlakte 2 was the combination of tidal contraction and the bottom

### 2.2.2. HARD SEA DEFENCE

The last stretch of coastal defence present at Maasvlakte 2 is a hard sea defence in the northern part. Here, large concrete cubes weighing up to 40 tonnes have been placed in front of a cobble beach for 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 several dozen meters 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. 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 [12].

It is important that the presence of the DELTA21-project does not interfere with this hard sea defence, whether it is the cube reef, the cobble stone beach or 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.



# 3

## RESEARCH QUESTIONS, OBJECTIVES & APPROACH

### 3.1. PRIMARY OBJECTIVE

The primary objective of this thesis is to study the expected behaviour of the alongshore sediment transport and the maintenance requirements 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, such as the hydrodynamics and morphology of Maasvlakte 2 and subsequently on the maintenance requirements. Stakeholders of the project, such as PUMA and the Port of Rotterdam, would therefore be interested in the results regarding flood safety, reduced port access and increased yearly maintenance costs. The initial assumption, or default position, is that the Delta21 project will show similar alongshore transport behaviour and maintenance requirements to Maasvlakte 2 and that there will be a positive correlation between the construction of the DELTA21-project and the effect this will have on the maintenance requirements for 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.”*

### 3.2. 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:

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

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

1. What have been 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- & tidal characteristics in the research area and what is the expected variability?
4. What is the modelled 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?

### 3.3. RESEARCH APPROACH

To answer to these sub-questions, a different approach for each should be used. While some can be answered by doing a data or literature study, others can only be answered using the results from the respectively models. In Figure 3.1, the research approach for each research question is presented.

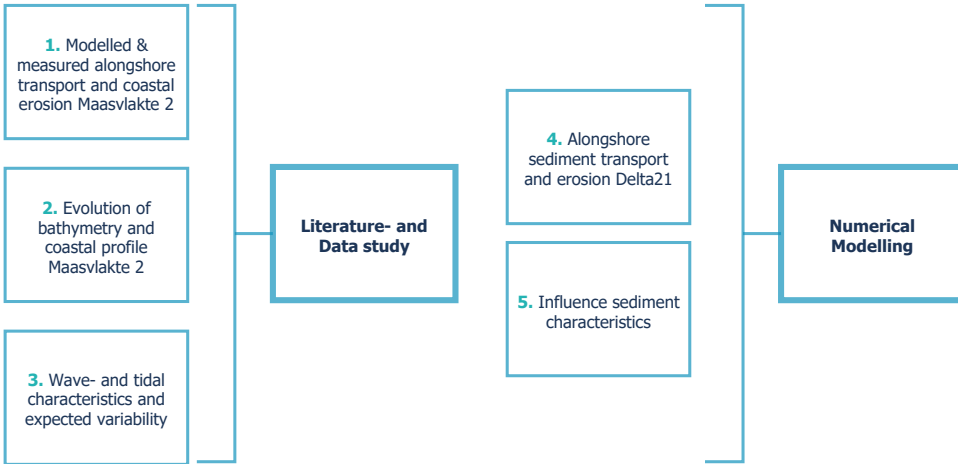


Figure 3.1: Differentiation of the research approach for the research questions.

The first three research questions will mostly be answered by performing either a literature or data study, while the remainder will be assessed with the help of the models SWAN and UNIBEST. In Chapter 4, the detailed research methodology is explained.



# 4

## METHODOLOGY

### 4.1. 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 study and a part done by numerical modelling. The literature 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.

### 4.2. LITERATURE STUDY & DATA HANDLING

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

The literature and data study will consist of using public-domain sources such as research papers, technical reports, articles and guidelines specific for the research area. An

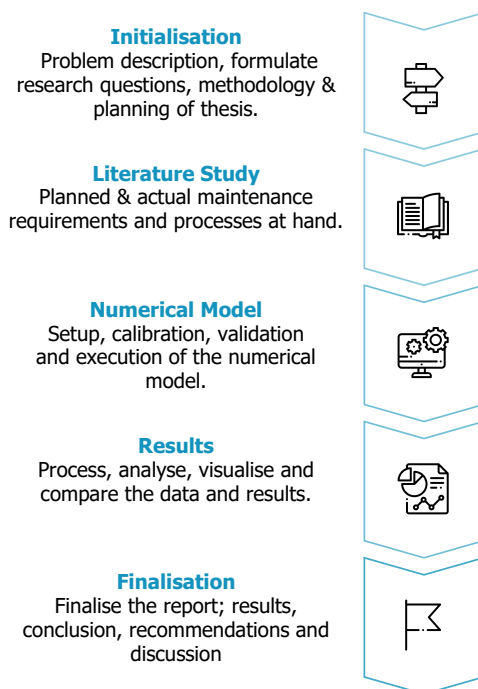


Figure 4.1: Step-wise methodology of this thesis.

understanding is made what the maintenance requirements for Maasvlakte 2 have been and how they varied, both temporally and spatially. That these can then be compared to the results of the modelling stage. 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 data 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 of 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 data study. This data will also be outputted by the model, and as such the acquired information from the processes study is therefore 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 mainte-

nance requirements can then be monitored during the modelling.

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.

#### 4.2.1. SWAN, UNIBEST & DELFT3D

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. Therefore, there are three numerical models that will be needed: SWAN, UNIBEST and Delft3D. For an accurate depiction and modelling of the waves within Delft3D 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 UNIBEST model. 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.

### 4.3. NUMERICAL MODELLING

In this section the process of setting up the numerical models is explained. The general outline can be seen in Figure 4.2. In Section 3.3 it is clear 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.

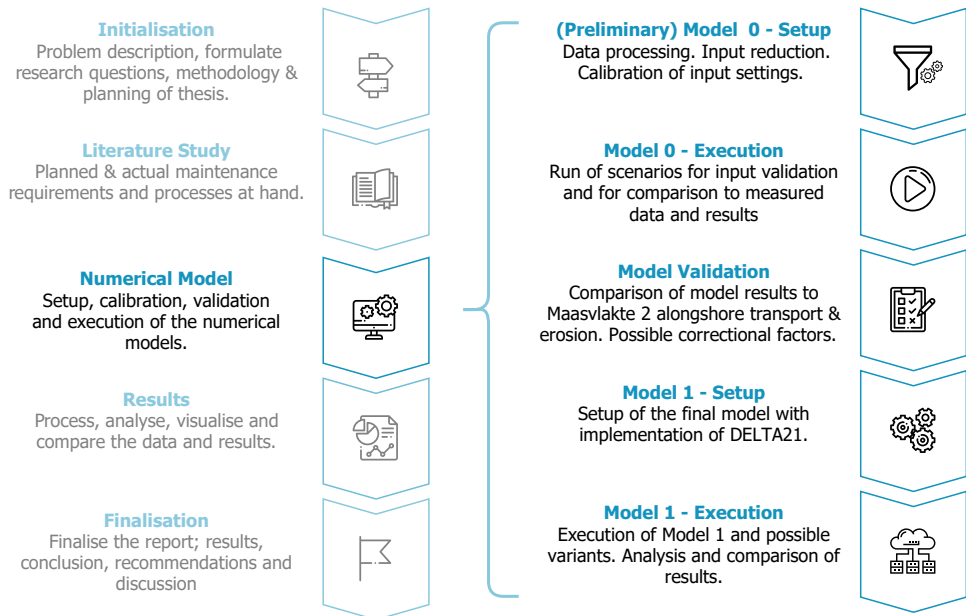


Figure 4.2: Outline of the modelling-approach. This process is iterative.

Two distinctive models will be executed; 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.

#### 4.3.1. DATA PROCESSING & PREPARING

The first step before setting up the numerical model is to analyse, process and make appropriate the data that has been collected. The data will not be ready to use instantly in the model and will require some manipulating and modification in order to be usefully implemented in the model. 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.

### 4.3.2. 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. For the PUMA Maasvlakte 2 modelling, the input reduction was based on equidistant wave bins. 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 [13].
- 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.

### 4.3.3. MODEL VALIDATION & CALIBRATION

The numerical models used will need validation that it is an accurate representation of reality. 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.

1. Validation of the SWAN Model 0 by means of comparison to the available near-shore 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

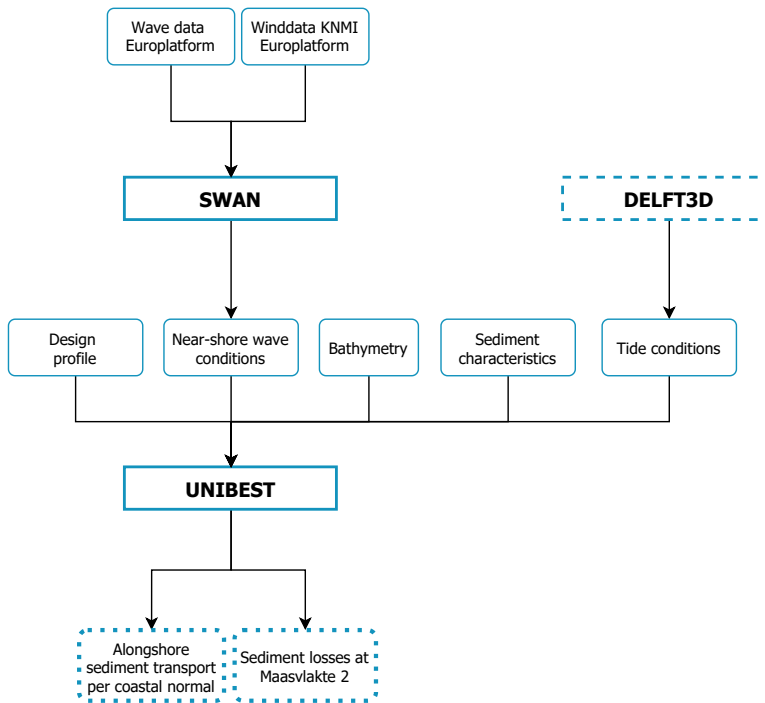


Figure 4.3: Model setup of SWAN, UNIBEST & external D3D model.

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 look of how the models will be executed and how they interact can be found in Figure 4.3.

# 5

## LITERATURE STUDY

### 5.1. INTRODUCTION

In this chapter, a literature study is performed on Maasvlakte 2, the parameters most important for the coastal maintenance and the current maintenance requirements.

### 5.2. DESIGN PROFILE

The design profile for the land reclamation of Maasvlakte 2 was based on the natural profile, found along the nearby coast [14].

- 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. 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  $285 \mu m$  [15]. 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.

## 5

### 5.3. SEDIMENT CHARACTERISTICS & INFLUENCE

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. Additionally, increasingly smaller grain sizes could lead to seaward directed sediment transports. 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 [16]. This increased transport can also be deduced when looking at the influence of the grain sizes in the different sediment formulae [17]. 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 [14].

(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 [15]. 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 [14]. 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 as-

sumed 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 [11]. 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.

## 5.4. SCOUR-HOLE

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 [11]. 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 [14].

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 [18].

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 m<sup>3</sup>/year for the total coastal section [14]. 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 [19].

### 5.5. UNCERTAINTIES & 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 6.2.4. 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 [15]. 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 m<sup>3</sup>/year were assumed, based on a grain size  $D_{50}$  of 160  $\mu m$  [14]. In the PUMA study, a sea level rise of 0.006 m/year was maintained, resulting in an additional nourishment need of 30.000 m<sup>3</sup>/year. 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 effect of sea level rise will not be taken into account.

## 5.6. MAINTENANCE REQUIREMENTS

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  $100 \text{ m}^3/\text{m}$  at the breakerzone has much more impact on the profile stability than an erosion of  $100 \text{ m}^3/\text{m}$  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  $270.000 \text{ m}^3/\text{y}$  for  $D_{50} = 250 \mu\text{m}$  up to  $750.000 \text{ m}^3/\text{y}$  for  $130 \mu\text{m}$  [19]. (Boer, 2003) shows that during the 90's, multiple sand nourishments were carried out at the Slufterdam, with an average of  $900.000 \text{ m}^3/\text{year}$  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 [16]. 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  $570.000 \text{ m}^3/\text{year}$  for a  $D_{50}$  of  $285 \mu\text{m}$ , with a probability spread of 70% for any given year and 55% for an average year [14]. At the western-bend,  $200.000 \text{ m}^3/\text{y}$  was directed northward,  $240.000 \text{ m}^3/\text{y}$  was directed southward. At the northern coastal-section,  $130.000 \text{ m}^3/\text{y}$  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 [14].

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 5.1 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  $140.000 \text{ m}^3/\text{year}$  was modelled. At the north side a net northbound sediment loss of  $120.000 - 300.000 \text{ m}^3/\text{year}$  was modelled, for a combined modelled mean yearly maintenance of approximately  $260.000 - 440.000 \text{ m}^3/\text{year}$ , with a bandwidth of 50%.

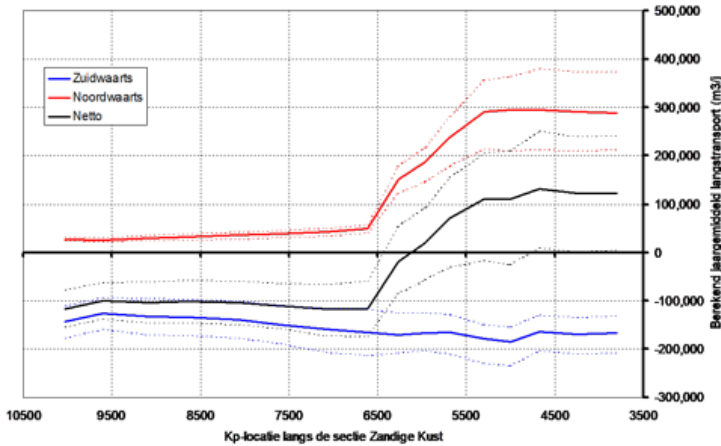


Figure 5.1: Alongshore gross- and net sediment transport above -8m NAP, as modelled by PUMA with UNIBEST-LT. Source: PUMA.

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 present. The original plan for determination the requirements 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. [20]

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

(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 change between

<b>Nourishment Year</b>	<b>Nourishment Strandoever (Kp.5300 - Kp.6600) [Million m3]</b>	<b>Nourishment Vooreover (Kp.3495 - Kp.7000) [Million m3]</b>	<b>Nourishment Total [Million m3]</b>
<i>0 (initial)</i>	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
<b>Total</b>	<b>2.22</b>	<b>4.09</b>	<b>6.31</b>

Table 5.1: Initially planned coastal nourishment volumes soft sea defence Maasvlakte 2. Source: PUMA.

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 raai 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 6.

In Figure C.5 the 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 coastline changes for the entire coastline, as calculated in Section 6.4.8 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.

The initial planned nourishment volumes that were estimated and modelled can be seen in Table 5.1 per year and per section, while the actual performed coastal nourishment volumes can be seen in Table 5.2. 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  $1.09 \text{ m}^3/\text{year}$  and  $0.91 \text{ million m}^3/\text{year}$  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. For the Model 0 validation and calibration, a correctional factor can therefore be applied, more of which can be read in Section 8.2.2.

<b>Year</b>	<b>Location</b>	<b>Quantity in million m3</b>	<b>Total Mm3</b>
2014	7500-10200	0.76	
2014	Cone-5000	0.31	
2014	3495-4800	0.35	
2014	5600-6600	0.30	<b>1.7</b>
2016	Cone-6200	0.46	
2016	8200-10000	0.35	
2016	Cone-8800	0.58	<b>1.4</b>
2018	3800-6200	0.42	
2018	8800-9400	0.64	
<b>Total</b>			<b>3.1</b>

Table 5.2: Actual performed coastal nourishment volumes soft sea defence 2014-2018 for Maasvlakte 2. Source: PUMA.



# 6

## DATA RESULTS

### 6.1. INTRODUCTION

In this chapter the origin, extent, method, usage and results of the data study is further explained and studied. Additionally, for a transparent and candid study, the used assumptions and shortcomings of the data are also listed. The data study forms the basis for the data used in the SWAN and UNIBEST models and the results which they produce.

### 6.2. WAVES

#### 6.2.1. MEASUREMENTS

The wave data used in this study is data from Rijkswaterstaat from the period 1997 to 2021, available at <https://waterinfo-extra.rws.nl/>. 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 6.1 and Figure 6.2. 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 ac-

quisition was performed correctly.

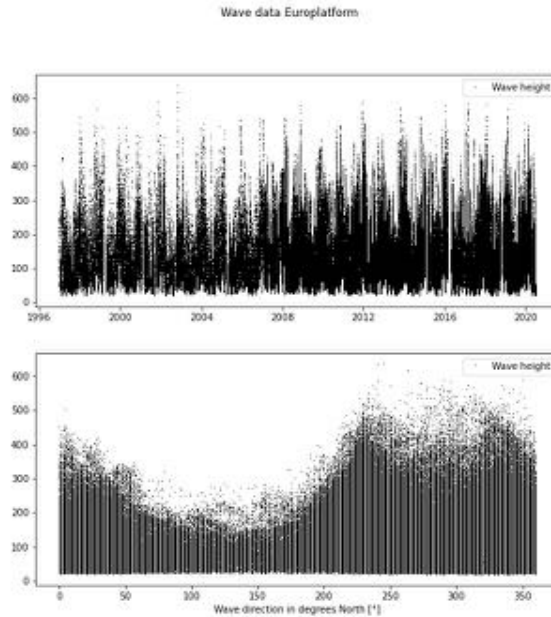


Figure 6.1: Wave data 1997 - 2020 for Europlatform. Some gaps in the available wave data can be seen. The directional resolution is also visible in the bottom graph, as shown by the vertical white bars.

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. These wave climates for the various periods (ranging between the second quarter of each respective year) can be found in Figure B.3 and Figure B.4 in the Appendix. From these graphs it can be seen that there can be quite a variation in the wave height and direction between different years. Furthermore, the wave-roses for the entire dataset and the different modelled years can be seen in Figure B.5 in the Appendix. From these graphs, it can be seen that the 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.

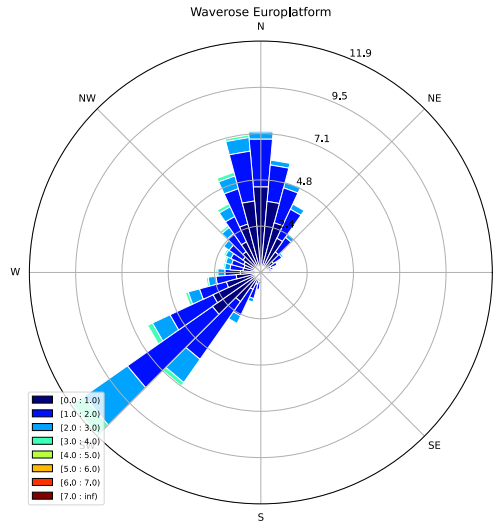


Figure 6.2: Wave rose for 1997 - 2020 for Europlatform.

### 6.2.2. 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 6.1 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 6.1 the Appendix. However, for  $F_p$ , 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  $m_0$  &  $m_2$  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.

### 6.2.3. 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 re-

quirements for Maasvlakte 2, for an accurate modelling of the sediment transport and the coastline changes, especially in UNIBEST, the wave data will have to be 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 at the south and northern side of Delta21 and the wave height. 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  $\phi_b$  and proportional such that  $S_y \propto f(H_{s,b}^{2.5} \sin(2\phi_b))$ . [13]

The two leading wave angles can be determined from the orientation of Maasvlakte 2 and are verified in a study [21]. The optimal coast-normal for alongshore transport (for a  $D_{50}$  of 285  $\mu\text{m}$ ) 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. 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 wave input reduction is schematised in Figure B.1. The input reduction is performed according to the following steps:

- First, for each wave, calculate its 'weight' according to the sediment transport proxy
- 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

Firstly, the determination of the 'weight' is visualised by the plots as shown in Figure B.1. Here we can see the directional factors for the south- and north coast normal angles respectively, based on  $\sin(2\phi_b)$  and the separate  $H_{s,b}^{2.5}$  weight. The resulting sediment transport proxy is then shown in the end, in which clearly 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.

The second and third step are then performed, which bin these weighted values, firstly in directional bins and then in wave height bins. This is based on the weighted value of each wave condition, firstly within the directional bin, then within the wave height bin.

The result for this reduced wave-climate is the graph as seen in Figure 6.3. 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  $\approx 25 - 180^\circ$  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, their weighted value is similar to those at the bottom bins.

A table with the full representative wave conditions for both can also be found in the Appendix.

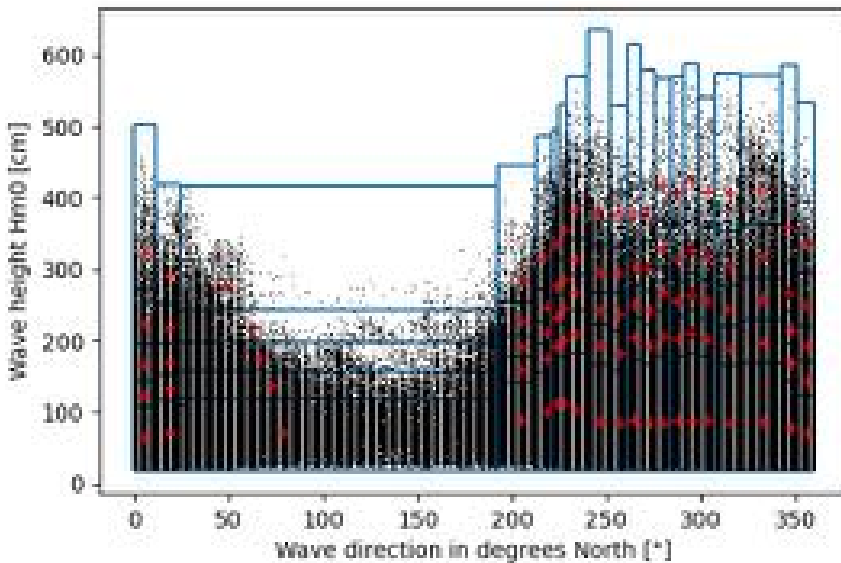


Figure 6.3: Variable bin-size, 2D-binned wave climate for the period 1997-2020 by means of Sediment Transport proxy. Location Europlatform.

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. These reduced wave climates can be found in Figure B.2. 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 in Figure B.2. 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. These differences can cause a shift and difference in alongshore transport, which can be visible in the bathymetric survey data and alongshore sediment transport rates in the Model 0 modelling.

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 8.2.

#### 6.2.4. WAVE VARIABILITY

To analyse the variability in alongshore sediment transport that occurs at Maasvlakte 2, the variability in wave climate 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 sediment transport per year, wave direction per year and wave flux per direction. In Figure 6.4, the sediment transport proxy for the years 1997 to 2019 is shown. Since the measuring period and the total number of measured waves varies from year to year, conclusive remarks regarding the total sediment transport per year are hard to formulate. However, we can see that the mean sediment transport per year can deviate substantially over the years, with up to a factor of 2-3 between specific years.

In Figure B.9 and Figure B.10 in the Appendix, 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

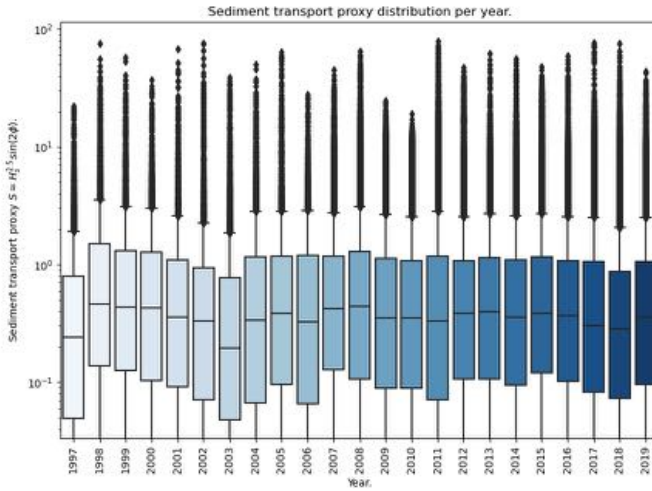


Figure 6.4: Box plot of the sediment transport proxy per year for 1997-2019.

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, see Section 8.2.

## 6.3. WIND

### 6.3.1. 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  $0.1 \text{ m/s}$  are used. The wind data has been visualised as 'period - wind speed' and 'direction - wind speed' graphs in Figure 6.5. In these graphs, the accuracy of the model is also shown, as the coarseness of the individual measurements is clearly visible. A wind rose representing the wind direction and wind speeds can be found in Figure 6.6, visualising the wind speeds and chance of occurrence from each wind direction, grouped by 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 wave data for these various periods can be found in Figure B.6 and Figure B.7 in the Appendix, while the visualised wind roses can be found in Figure B.8 in the Appendix. These wind roses 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.

### 6.3.2. 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 m/s, both of which are clearly visible in the graphs in Figure 6.5. 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.

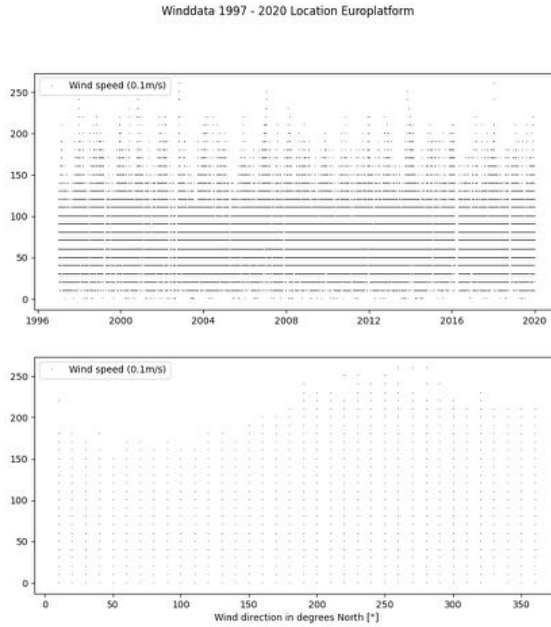


Figure 6.5: Winddata 1997 - 2020 Location Europlatform

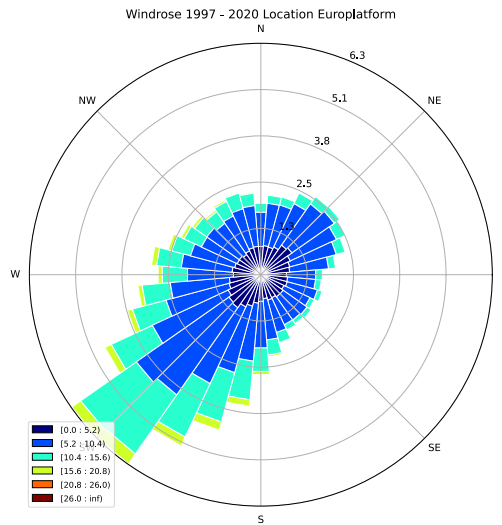


Figure 6.6: Windrose 1997 - 2020 Location Europlatform

## 6.4. BATHYMETRY

### 6.4.1. BATHYMETRY EXTENT & 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. This data-set was mostly used for the UNIBEST model-0, as the coastal profile for each ray at Maasvlakte 2 could be determined using this data as well as the difference between certain years in bottom level elevation.

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 used are displayed in Table A.1. Extensive maps of the bathymetry used can be found in Appendix A.

### 6.4.2. 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 6.7. This Figure, along with the bathymetric difference between all other years, can also be seen in higher detail in Appendix A. From this Figure, 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 6.4.3. With these coastal profiles, a better prediction of the profile-changes for Delta21 can be made.

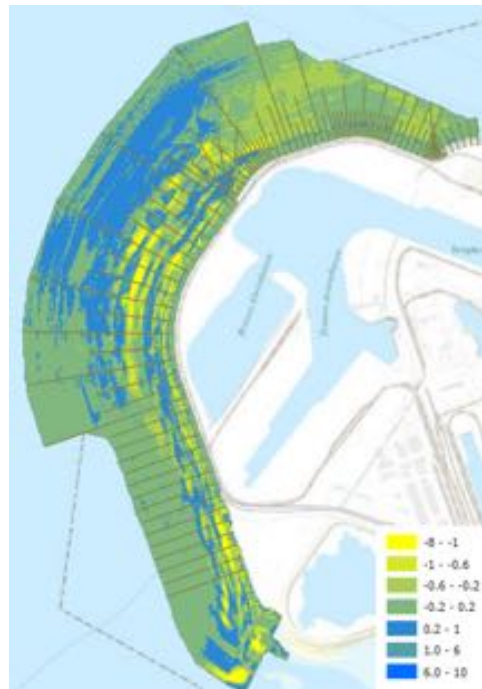


Figure 6.7: Difference in bathymetry between measurements 2016Q2 and 2017Q2. Location Maasvlakte 2. Processed and visualised in ArcGIS, data-source; PUMA.

### 6.4.3. 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 6.7. 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. Data from 2008, the year when construction started, up until the start of the available data, was not available for this study. 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 6.10, 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 detailed as following:

### 6.4.4. NORTHERN SIDE OF MAASVLAKTE 2.

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 6.8. 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.

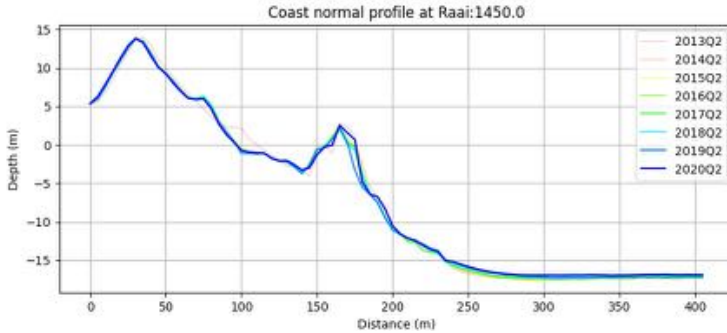


Figure 6.8: Profile changes over the years 2013-2020 for ray 1450, the northern hard sea defence at Maasvlakte 2.

#### 6.4.5. TRANSITION SOFT & HARD SEA DEFENCE MAASVLAKTE 2.

The transition between the soft & hard sea defence is visualised by Figure 6.9 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 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 result in an 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.

#### 6.4.6. WESTERN BEND OF MAASVLAKTE 2.

For the analysis of the western bend, the rays 5200, 5600, 6000 and 6400 are visualised, as seen in Figure 6.10, and in higher detail in Figure C.3 in Appendix C. These rays are spaced out further apart (400 meters) and have a longer length (1250 compared to 400)

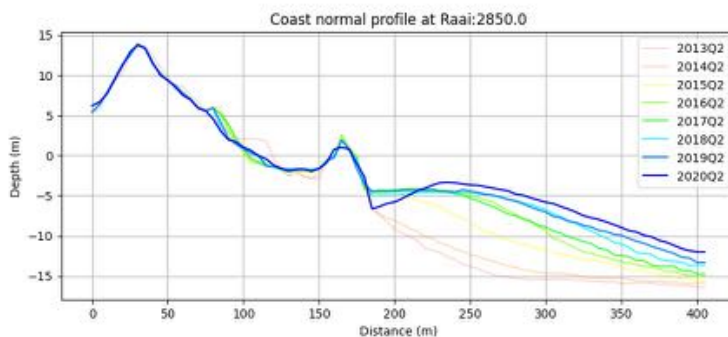


Figure 6.9: Profile changes over the years 2013-2020 for ray 2850, the transition of the soft- and hard sea defence at Maasvlakte 2.

than the other other rays looked at, such that the entire western bend can be analysed. 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 8 a quantification of these sediment transports that will occur is attempted.

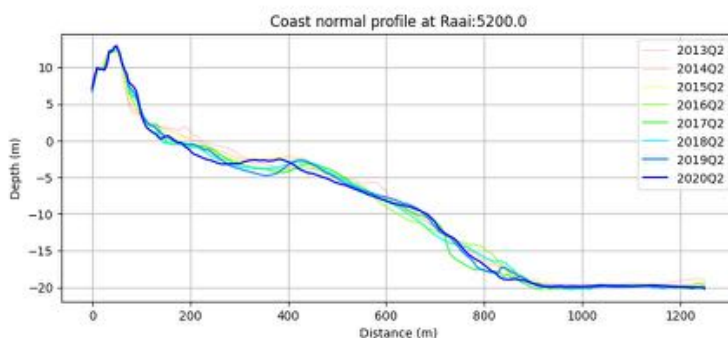


Figure 6.10: Profile changes over the years 2013-2020 for ray 5200, at the western bend of Maasvlakte 2.

### 6.4.7. SOUTH-WESTERN SIDE OF MAASVLAKTE 2.

Lastly, for the analysis of the south-western side of Maasvlakte 2, the representative rays 9000 - 9600 were used, as visualised in Figure 6.11 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 sub-tidal 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 8.1. The south-western side of Delta21 will be similarly sheltered and show the same process, although the numerical model will have to quantify this.

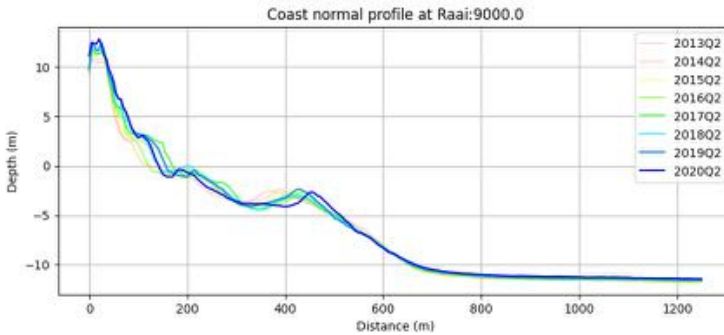


Figure 6.11: Profile changes over the years 2013-2020 for ray 9000, at the south-western side of Maasvlakte 2.

### 6.4.8. 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 6.13 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,

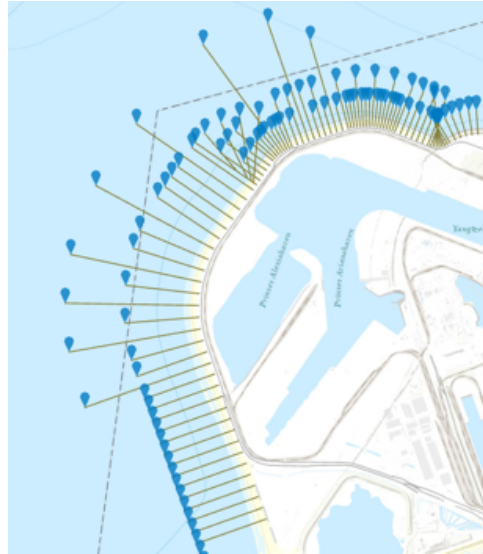


Figure 6.12: Map showing the rays (coastal normals) for a section of Maasvlakte 2. The blue pins indicate the end of the rays for which the Output locations were defined in SWAN. See Appendix A for a large scale map. Visualisation in ArcGIS. Data-source: PUMA.



Figure 6.13: 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

and that no comparison to the base coastline is made, only a calculation whether the bathymetry in the area has increased or decreased [22] [23]

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.

#### 6.4.9. BATHYMETRY DELTA21

For the bathymetry of the Delta21 area for the model 1 modelling, it is assumed that the future design parameters 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 that of 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 is schematised in the figure on page 97 in the Appendix. The exact location and method that Delta21 will connect to Maasvlakte 2 is explained in Section 7.3.2.

#### 6.4.10. 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. 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. Both methods have been investigated and seemed to have little impact on the definitive results. Lastly, it should be noted that data before 2013 was not available for this study and as such, no remarks about this period and the formation of certain characteristics, such as the sandbanks that are seen, can and will be made. For this is referred to the respective authors and reports.

## 6.5. 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  $\mu\text{m}$  and a  $D_{90}$  of 555  $\mu\text{m}$ . For a full overview of all the 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  $\mu\text{m}$  and a  $D_{90}$  of 200  $\mu\text{m}$  was taken across several samples. These were used to model the effects for the alongshore

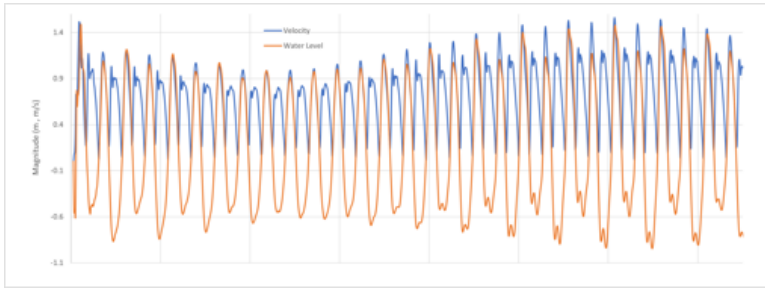


Figure 6.14: Tidal time series, showing the velocity and water level elevation at Ray 3600, at the western bend of Maasvlakte 2.

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.

## 6.6. 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 6.14 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 6.15, 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 are 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.

This schematisation of the model has been validated by means of comparison to the

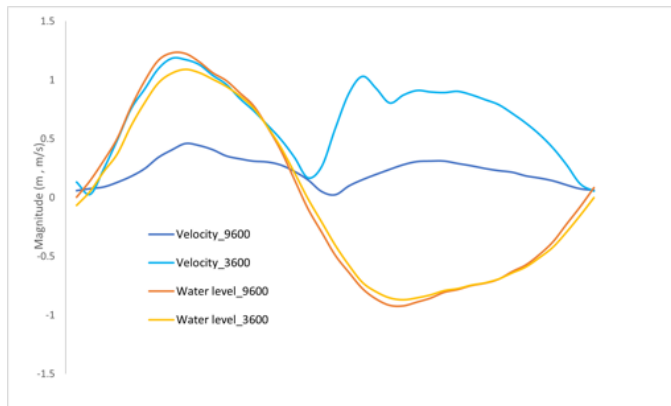


Figure 6.15: Tidal elevation and velocity of ray 3600 (western bend) compared to ray 9600 (south-western side) at Maasvlakte 2

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.

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.1 in Appendix B.

## 6.7. 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 [14]. 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.



# 7

## MODEL SETUP

### 7.1. 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 all other parameters are maintained the same.

### 7.2. SWAN

#### 7.2.1. INTRODUCTION

SWAN (Simulation of Waves in Nearshore Areas, Ris et al., 1999, Booij et al. (2004) is used to model the transformation of our reduced representative off-shore wave conditions (Europlatform) at deep water to the surf zone at Maasvlakte 2 and the Delta21-dunes. 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 nonlin-

ear wave-wave interactions [24] [25]. 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. The version of SWAN used in this study is 41.20, released in May 2019.

### 7.2.2. 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 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 6.2.3. 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 can be seen visually in the Figure on page 98 in Appendix A and are summarised in Table 7.1. All grids are rectangular grids with their coordinates in the Cartesian notation. The grids' origin, extent and resolution can be seen in Table 7.1. 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.

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

<b>Grid</b>	<b>Origin X</b>	<b>Origin Y</b>	<b>Rotation</b>	<b>M-cells</b>	<b>N-cells</b>	<b>Resolution</b>
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 7.1: Computational grids of SWAN

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  $\Delta\Theta = 360^\circ/72 = 5^\circ$  is obtained. The lowest (flow) and highest (fhigh) discrete frequency is defined as 0.03 and 1.50 respectively.

### 7.2.3. SWAN SETTINGS

#### 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. The run-time of a single wave-condition for all 3 grids is around 15-20 min and for a full wave-climate (100 wave conditions) around 30 hours. The 8 modelled wave-climates for the various periods took a total of 250 hours calculative time on a personal desktop. 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 H. 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

#### 7.2.4. 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- and wave-induced currents have not been included in the model. There 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.

Secondly, during the SWAN modelling, several problems and bugs were encountered which hindered and delayed the modelling progress. Since the modelling process was long and a large number of conditions was tested, this error-solving and bug-fixing was very time consuming. 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.

Lastly, errors due to the immediate calculation of subsequent grids occurred. These errors are caused due to SWAN not having properly processed and synced the output of previous grid before executing the next one. This caused very large files of upwards to 10GB per wave condition to be made and made computation long and storage-heavy.

## 7.3. UNIBEST

### 7.3.1. INPUT FILES, LOCATIONS & 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 7.1. 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.

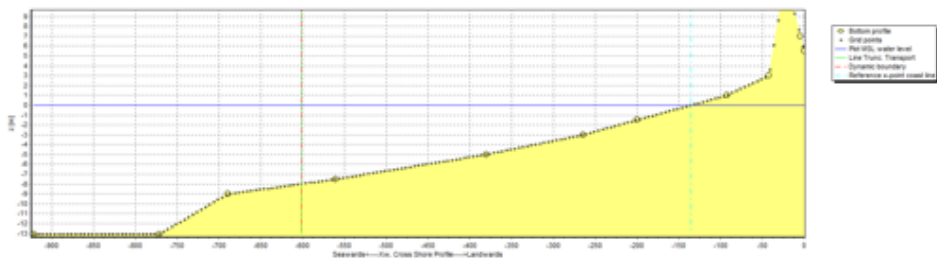


Figure 7.1: General design profile for Maasvlakte 2, as represented in UNIBEST-LT.

The .CFS file contains the sediment transport parameters. The transport formula chosen is Bijker (1968), with the parameters similar or close to those present at Maasvlakte 2, the details of which can be found in Appendix D. Also see the data study 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.

### 7.3.2. CONNECTION TO MAASVLAKTE 2

For the effect of the Delta21-project on Maasvlakte 2, the method, location and characteristics of the 'attachment' need to be modelled. A connection to, or close at, the transition between the soft- and hard sea defence at Maasvlakte 2 can negatively impact the gravel 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 bend of Maasvlakte 2 will likely have a positive effect on current development of the scour hole at Maasvlakte 2, since the tidal contraction point 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. Since exact design specifications are not yet determined for this connection and it is beyond the scope of this study to investigate this optimal location, this connection was modelled in UNIBEST-LT and UNIBEST-CL as a simple connection from ray 58 of Delta21 to ray 3800 of Maasvlakte. In Figure 7.2, this connection is visualised. Here, the design profile and bathymetry of Delta21 meets up with the bathymetry of Maasvlakte 2. No further study or statements will be made regarding the optimum attachment location for the connection between Delta21 and Maasvlakte 2.

### 7.3.3. OUTPUT

The output of the UNIBEST-LT models are summed in .RAY and .GLO files. These 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 7.2. 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.

### 7.3.4. 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 over-estimation of the waves in this shadow-zone at the connection.

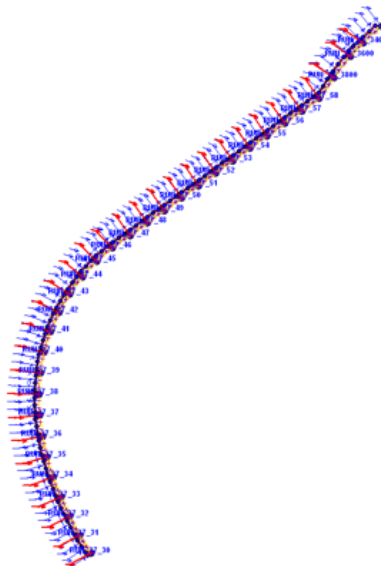


Figure 7.2: Visualisation of the Delta21 coastline, as represented in UNIBEST-CL. The connection of Delta21 to Maasvlakte 2 is modelled at ray 3800. For each run, the distinct wave conditions present at every ray are modelled, summarised in the UNIBEST-LT .RAY-files.

# 8

## 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.

### 8.1. SWAN RESULTS

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 H) was used to then extract the wave conditions for each individual location from each .tab file and is then combined with the tidal-current data from the external Delft-3D model to create an .SCO-file (wave and current file). 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 8.1.

	Occur. (%)	Dir. (°)	Hm0 (cm)	Tper (s)	Wind (°)	Wind (.1m/s)	Location 2000			Location 5000			Location 7000		
							Hsig (m)	Tper (s)	Dir (°)	Hsig (m)	Tper (s)	Dir (°)	Hsig (m)	Tper (s)	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 8.1: SWAN Model 0 - Largest 10 occurrences (total  $\approx$  50%) of reduced wave conditions for the period 2013-2014, transformed by SWAN to nearshore for the locations 2000, 5000 and 7000.

In Table 8.1, the 10 largest occurrences of transformed waves (not excluding any off-shore 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 ( $330^\circ - 15^\circ$ ), dependent on the location. This can be seen in more depth in the table on page 132 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 dampened 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 8.1, 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 8.2. 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 or the map in Appendix E 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 'directional sediment transport potential' than behaving as a conventional wave-rose.

### 8.1.1. 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 transformation to the nearshore at Delta21. However, this appeared to be challenging. As previously shown in Chapter 6 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.

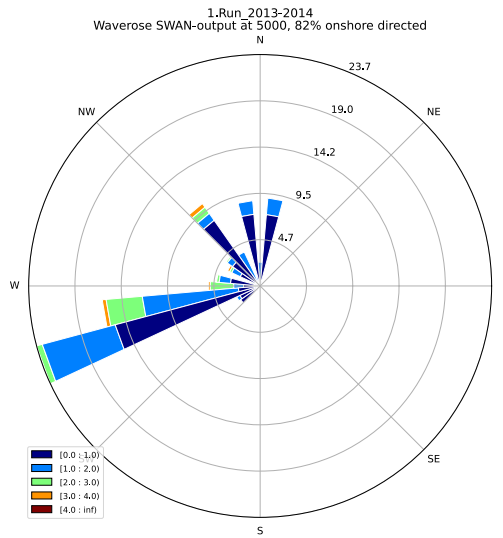


Figure 8.1: SWAN wave rose for Location 5000 at the western bend of Maasvlakte 2. Period 2013-2014.

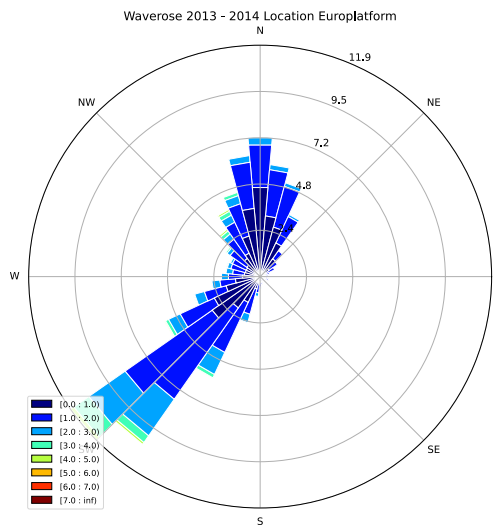


Figure 8.2: Wave rose for 2013 - 2014 for Europlatform.

## 8.2. UNIBEST MODEL 0 RESULTS

For the Model 0 modelling and the validation of the model, for each of the available years (2013-2020), a UNIBEST 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 8.3. 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 8.4 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  $m^3$ /year, while the north-ward transport has a much wider range of 80.000-500.000  $m^3$ /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 an 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 [14]. This is also visible in the decreased erosion pattern for 2016-2017 on page 102 in the Appendix.

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 5.6 and seen in Figure C.5, 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.

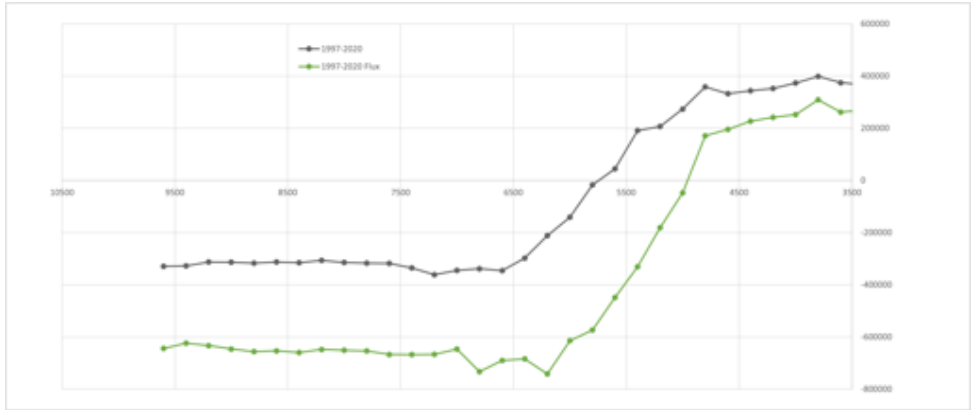


Figure 8.3: UNIBEST modelled net sediment transports per year, per ray in  $m^3$ /year above -8m NAP for the Sediment Proxy-reduced wave climate (black) and the Wave Energy Flux-reduced wave climate (green), excluding tides.

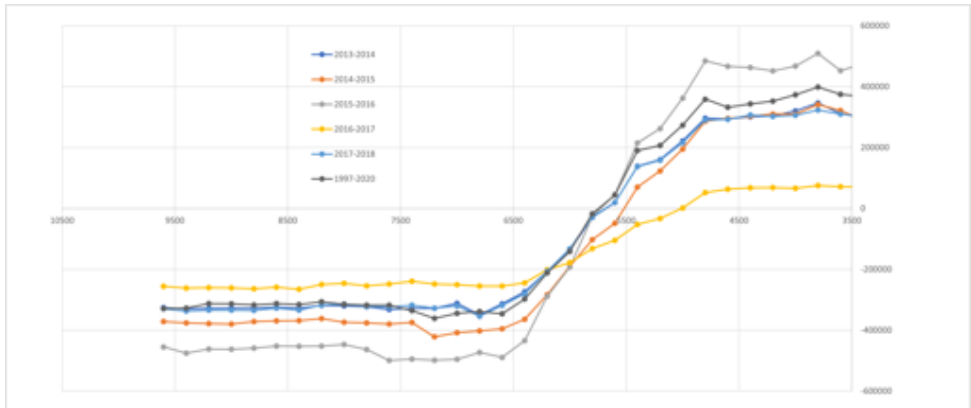


Figure 8.4: UNIBEST modelled net sediment transports above -8m NAP for Maasvlakte 2 per year, per ray in  $m^3$ /year. Wave climate per year, excluding tides.

### 8.2.1. INFLUENCE OF TIDAL CURRENTS

Following Section 6.6 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 8.5, 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. Although the gross contribution of the tide can be rather large, the net contribution is much smaller. The modelled absolute net differences in alongshore sediment transport range between 1.000 and 22.000  $m^3$ /year. The differences are lowest at the south side, between ray 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 are not 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 [20]. 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 validated. The decision was therefore made that no conclusions can be drawn from this data and the tidal currents will not be modelled in the model 1 results for Delta21.

### 8.2.2. 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 6, 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

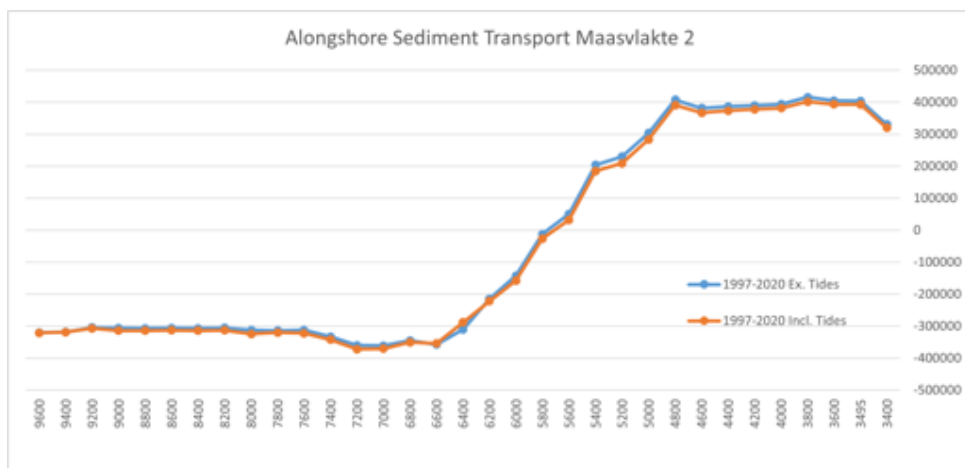


Figure 8.5: Maasvlakte 2: difference in mean alongshore sediment transport per year between a wave climate excluding tides (blue) and including tides (orange) for the period 1997-2020. Per ray, for the section above -8m NAP. Quantities in  $m^3$ /year.

behaviour and erosion volumes [20].

For the results shown in Section 8.2, the decision is therefore made to match the results to those of the actual coastal nourishments and erosion, as mentioned in Section 5.6. This calibration will then also be applied to the Model 1 results for the Delta21 modelling. 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 8.6 and Figure 8.7, 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 furthermore calculated, seen in Figure G.1 in the Appendix. In Figure 8.7, showing the erosion along the coastline of Maasvlakte 2, the distinct erosion along the western bend is clearly 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 5.6. 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.

For these transports, no interaction with the surroundings & transports are assumed at the most southern- and northern transects, such that a net zero boundary condi-

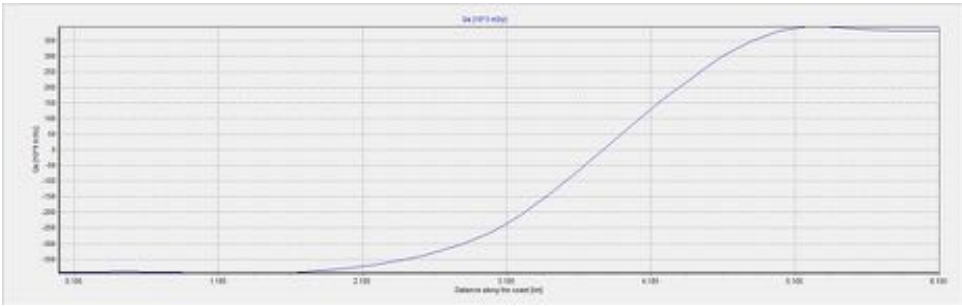


Figure 8.6: Modelled alongshore sediment transport rate of Maasvlakte 2 in UNIBEST-CL after one year. From ray 9600 (left) to ray 3400 (right), for the reduced wave climate of 1997-2020, excluding tides.

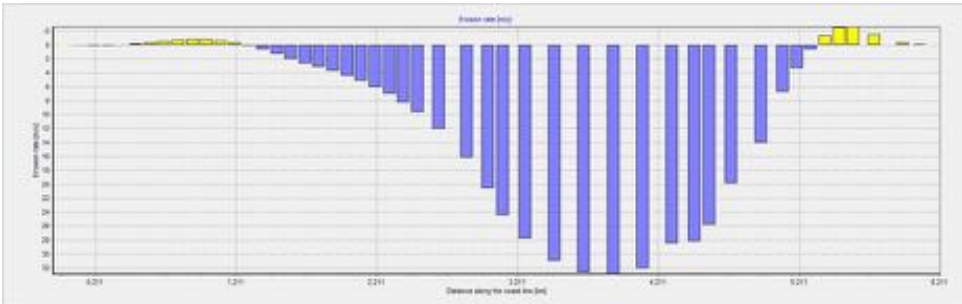


Figure 8.7: Modelled erosion rate in UNIBEST-CL per year of Maasvlakte 2 coast from ray 9600 (left) to ray 3400 (right) after one year, for the reduced wave climate of 1997-2020, excluding tides.

tion 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 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 contribution of the tidal currents above -8m NAP. Cross-currents and sediment redistribution across the profile also create a more diverse behaviour than assumed. Additionally, 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.

## 8.3. UNIBEST MODEL 1 RESULTS

### 8.3.1. ALONGSHORE SEDIMENT TRANSPORT

Following the setup for the model 1, as seen in Chapter 7, the results of the UNIBEST-LT model for Delta21 for each ray can be seen in Figure 8.8.

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.

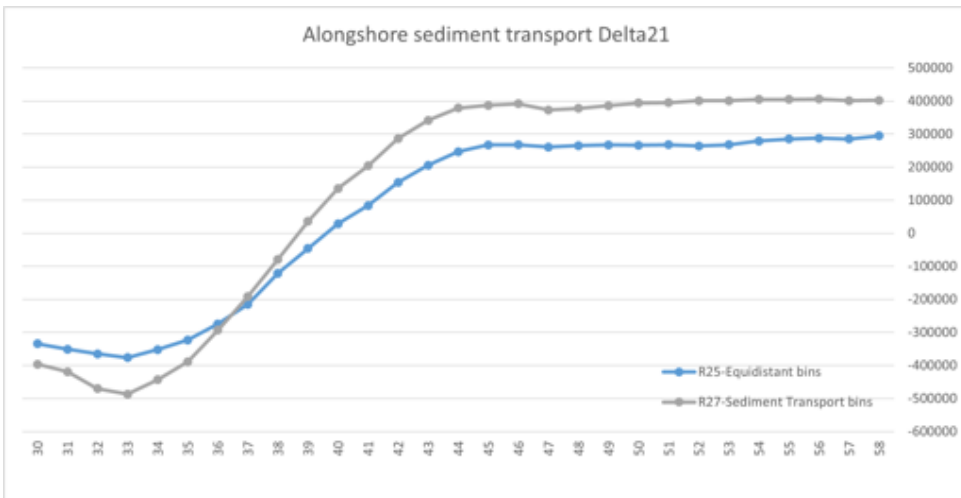


Figure 8.8: Modelled mean alongshore sediment transport per ray for Delta21 using the Equidistant bins (blue) and Sediment Transport bins (grey) wave input reduction methods for the period 1997-2020. Quantities in  $m^3$ /year.

The modelled alongshore sediment transport numbers seem to correlate well with those from Maasvlakte 2. Northward directed transport is a very continuous  $400.000 \text{ m}^3/\text{year}$ , while southward directed is around  $400.000 \text{ m}^3/\text{year}$ , with a small dip at Ray 33 to  $500.000 \text{ m}^3/\text{year}$ . 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  $0.8 \text{ Mm}^3/\text{year}$  is obtained.

### 8.3.2. 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 7.2. The results of this UNIBEST-CL model after one year are visualised as the alongshore sediment transport rate in Figure 8.9 and the erosion rate in Figure 8.10.

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  $850.000 \text{ m}^3/\text{year}$ . This number remains consistent throughout

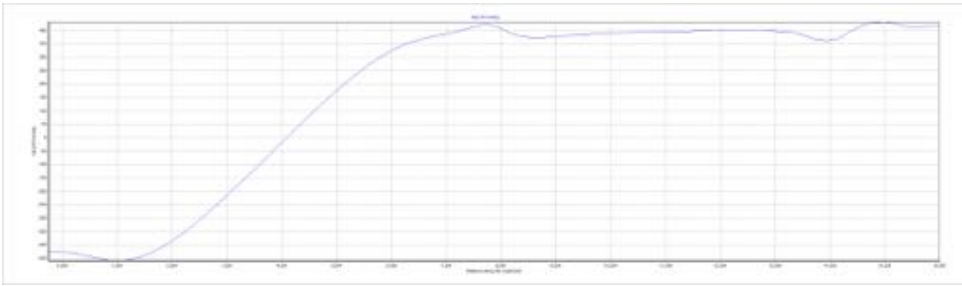


Figure 8.9: Alongshore sediment transport after 1 year for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

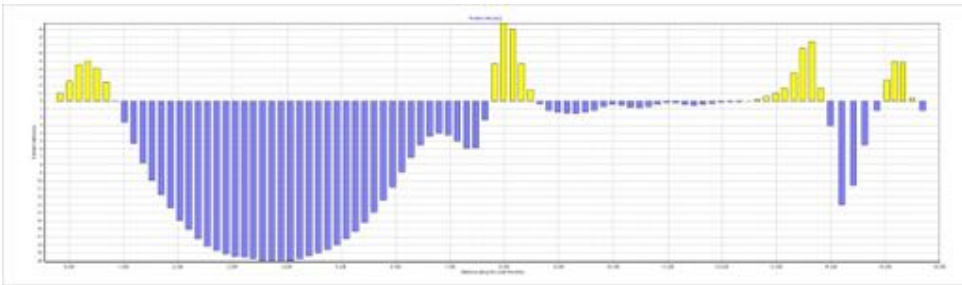


Figure 8.10: Erosion rates after 1 year for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

the first 10 years. Compared to the Model 0 erosion volumes from Maasvlakte 2, this number is thus very similar.

### 8.3.3. INFLUENCE OF SEDIMENT CHARACTERISTICS

As seen in Section 6.5, 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 8.11 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  $D_{50}$  of  $140 \mu\text{m}$  significantly amplifies the sediment transport to both the south and the north. Both the northbound and southbound sediment transports went up from  $0.4 \text{ Mm}^3/\text{year}$  to around  $1.0 \text{ Mm}^3/\text{year}$ . This will therefore also result in a much greater maintenance requirement for the Delta21 dune area, especially since the gradients in the alongshore sediment transport in the bend at Delta21 are significantly larger compared to the  $370 \mu\text{m}$ -model..

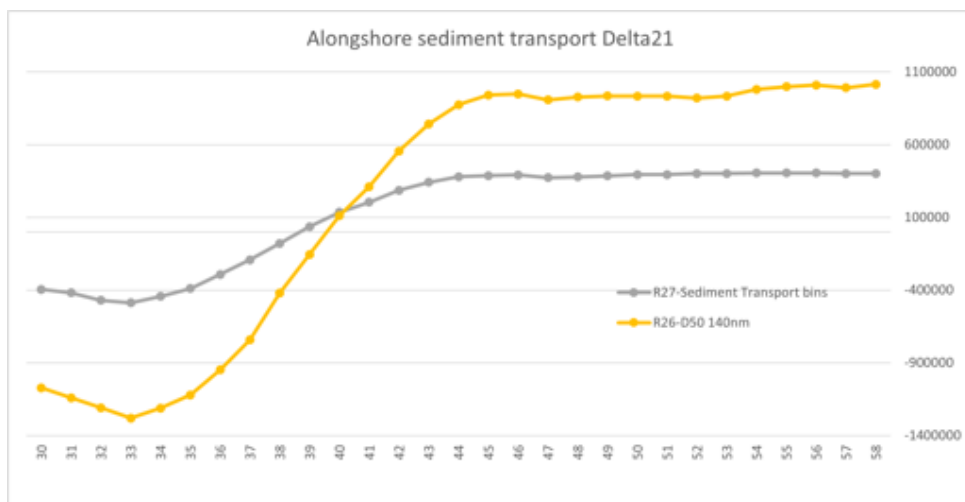


Figure 8.11: Modelled mean alongshore sediment transport per ray for Delta21 for using the default  $D_{50}$  of  $370 \mu\text{m}$  (grey) and for the usage of decreased grain size,  $D_{50}$  of  $140 \mu\text{m}$  (yellow), present at the location of the ESL. Reduced wave climate 1997-2020, excluding tides. Quantities in  $\text{m}^3/\text{year}$ .

### 8.3.4. 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 5.5, it was already clear that substantial differences in the wave-climate could occur between years. Section 5.6 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. 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.

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, is then:

- North-bound alongshore sediment transport:  $128.000 - 628.000 \text{ m}^3/\text{year}$ .

- South-bound alongshore sediment transport: 296.000 - 528.000  $m^3$ /year.
- Total erosion due to alongshore sediment transport: 424.000 - 1.156.000  $m^3$ /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.



# 9

## DISCUSSION & RECOMMENDATIONS

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 same cannot be said for the Delta21 project. 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 limited 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. However, the applicability of these models outside of their respective scopes is limited.

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.

In the case of the continuation of the used models and data by future students, it is recommended to put further strive towards a more extended validation and calibration of the models. 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, 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, it is too early to decide what will be the best maintenance strategy for Delta21. The exact location, layout, size and characteristics are yet to be fully determined and as such, an in-depth study regarding coastal maintenance in its current form 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.

# 10

## CONCLUSION

In this study, the alongshore sediment transport and erosion volumes due to the construction of the proposed Delta21-project were studied.

In the literature and data review, it became apparent that the bathymetry and coastal profile at Maasvlakte 2 varied significantly. 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 could only yield a mere qualitative comparison to Delta21. Many of the visible interactions were due to processes and factors specifically for Maasvlakte 2, such as the interaction between the soft and hard coastal defence. It was decided that no decisive conclusions for the design profile or bathymetry of the Delta21-project could be made based on these results and that modelling was needed to get better representative results.

Due to the method of wave input reduction, which was based on a sediment transport proxy, combined with the lack of usable nearshore wave data, the validation of the SWAN Model 0 proved difficult. 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  $770.000 \text{ m}^3/\text{year}$  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  $m^3$ /year in both directions. Erosion was visible along the entirety of the western bend, at an erosion rate up to 20 meters per year which creates a total erosion volume of 0.85 million  $m^3$ /year.

During the implementation of the Delft3D tidal data in the UNIBEST model, the effect of the tidal velocities and elevations were shown to be limited for the area above -8m NAP. The literature study concluded a mostly current-driven transport below -8m NAP and a wave-driven transport above -8m NAP. However, it became apparent that in UNIBEST, the effects of the tidal currents could not be modelled accurately due to the imposed depth of the tides in Delft3D and the way UNIBEST translates these to the nearshore. As a consequence, no validation and definitive conclusions could be made for the effect of tidal currents on the alongshore sediment transport and erosion above -8m NAP.

The 140  $\mu m$ -model 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, therefore, confirms the null hypothesis that the Delta21-project will show comparative morphological behaviour, alongshore sediment transport and erosion characteristics to Maasvlakte 2.

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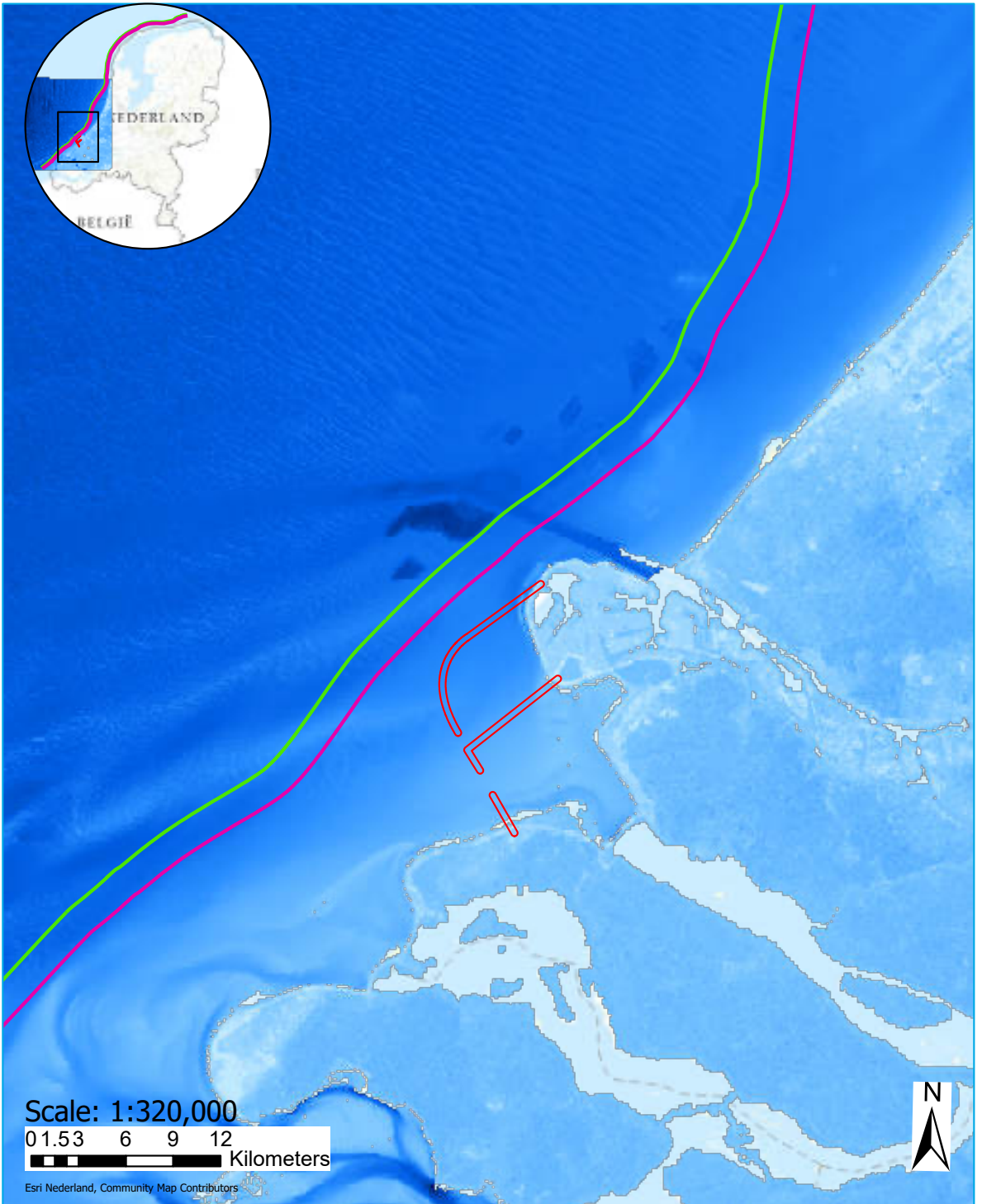
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**A**

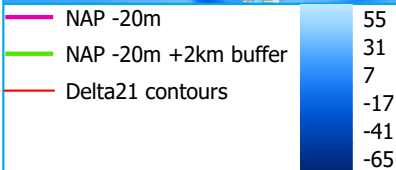
**MAPS & OVERVIEWS**



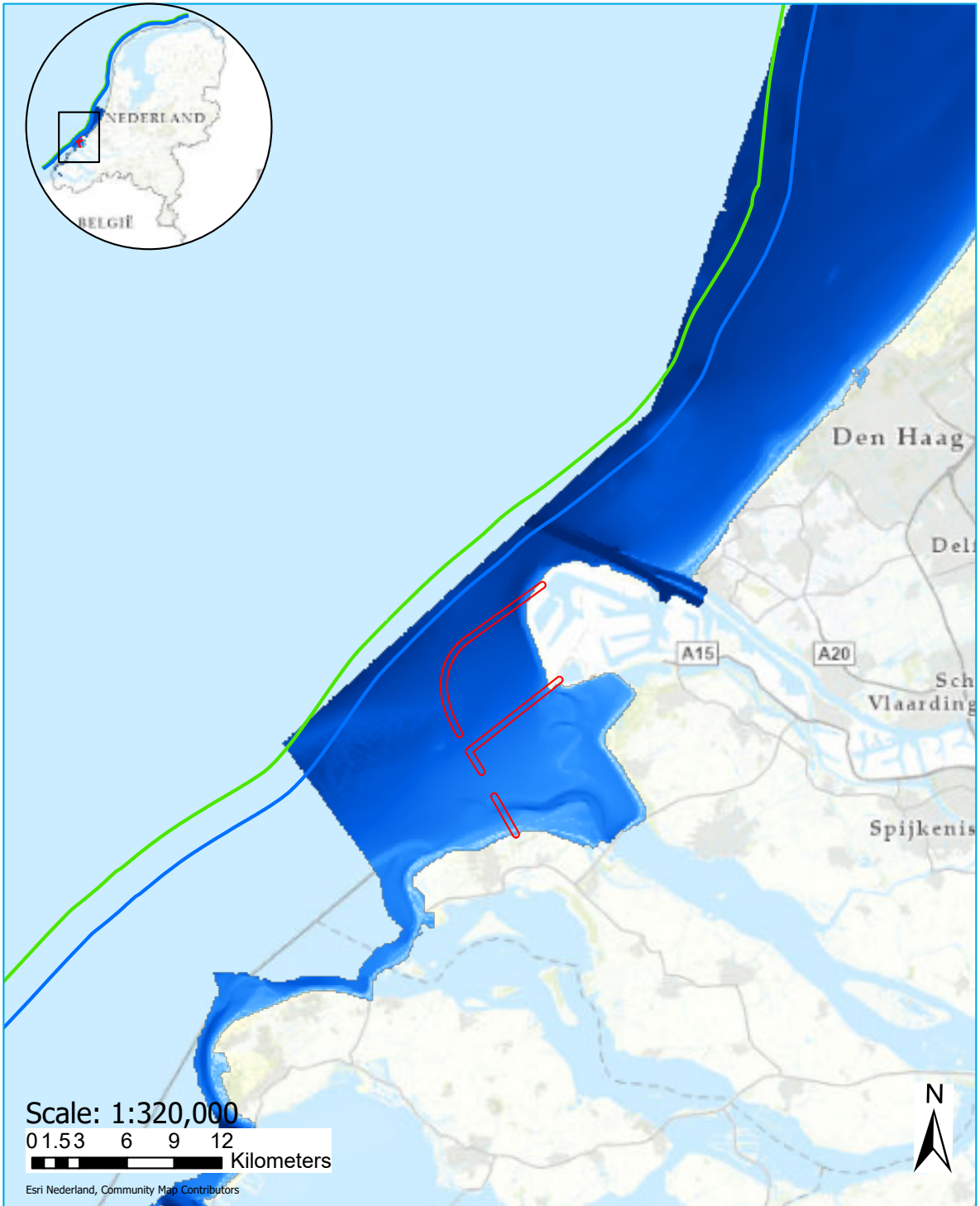
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0 1.53 6 9 12  
Kilometers

Esri Nederland, Community Map Contributors

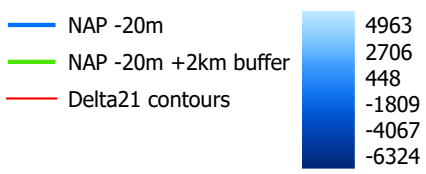


## EMODnet Bathymetry 2020



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Kilometers

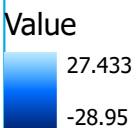
Esri Nederland, Community Map Contributors



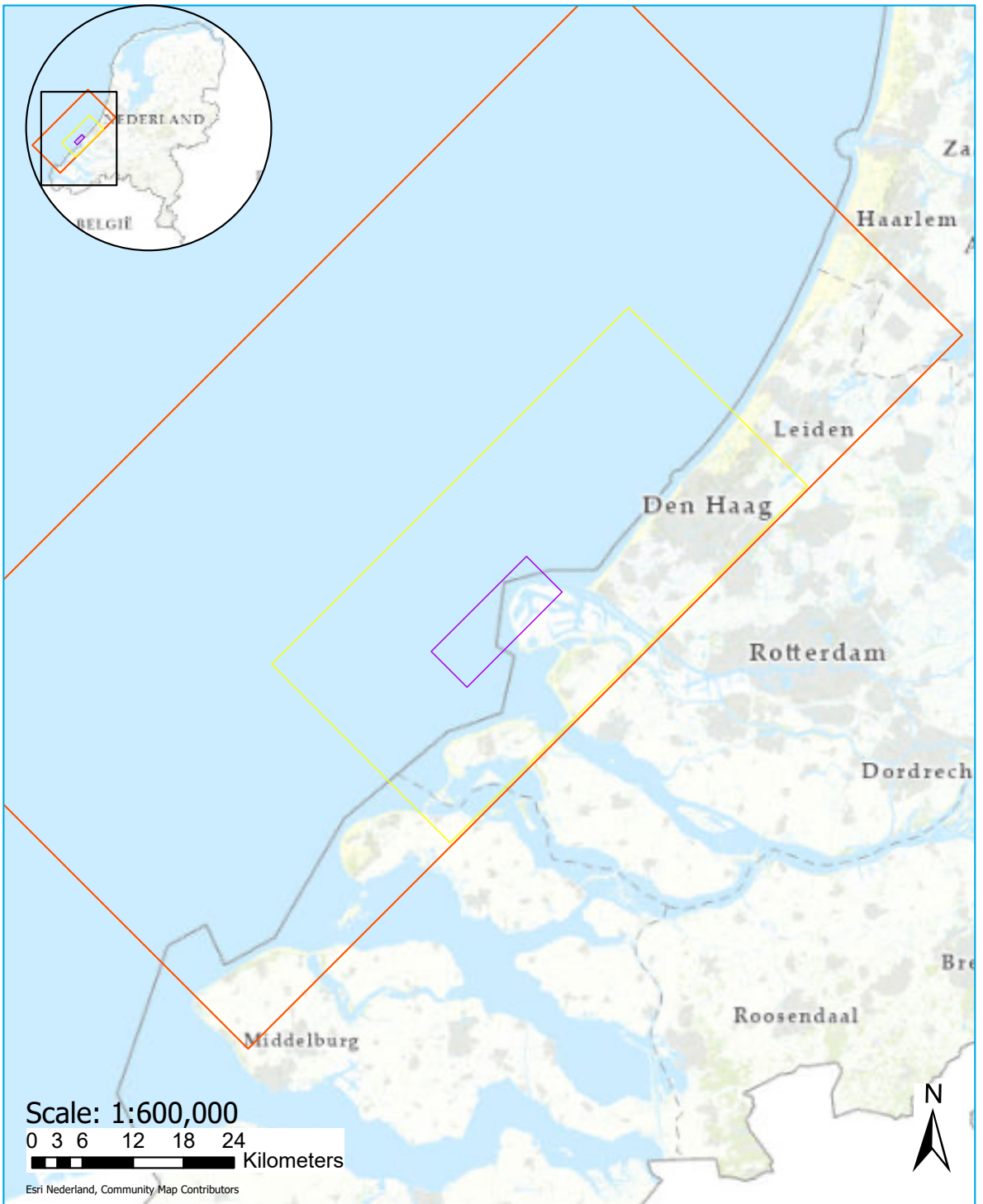
# RWS Bathymetry 2020



- NAP -20m
- Delta21 contours



## Extent bathymetry PUMA (Showing: 2013Q2)



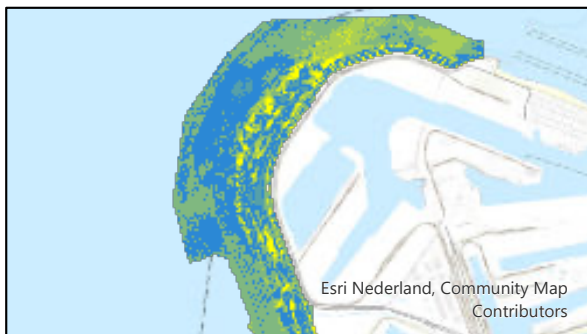
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0 3 6 12 18 24  
Kilometers

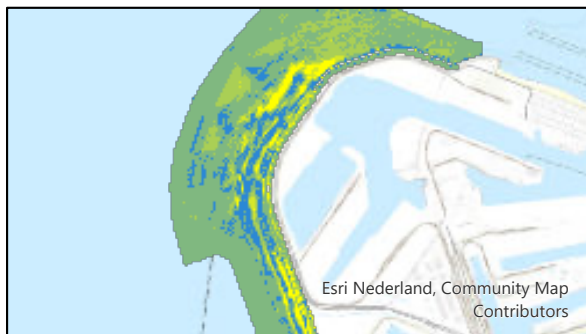
Esri Nederland, Community Map Contributors

- Grid 250x250m
- Grid 150x150m
- Grid 50x50m

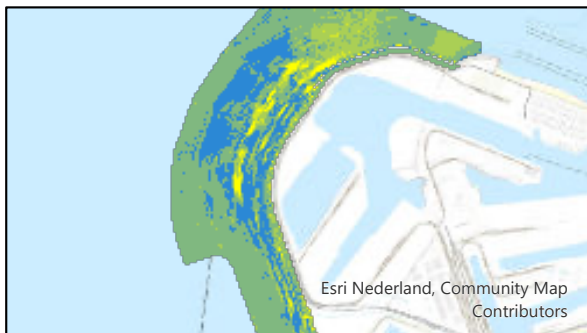
## Computative grids SWAN



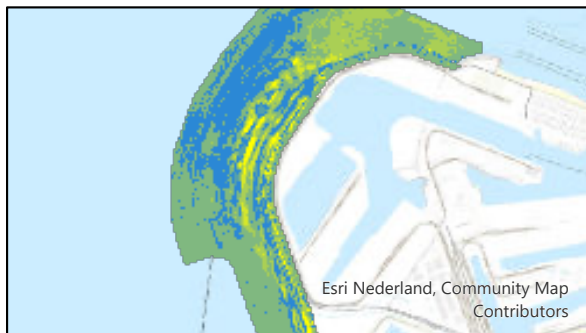
Bathymetric difference 2013-2014



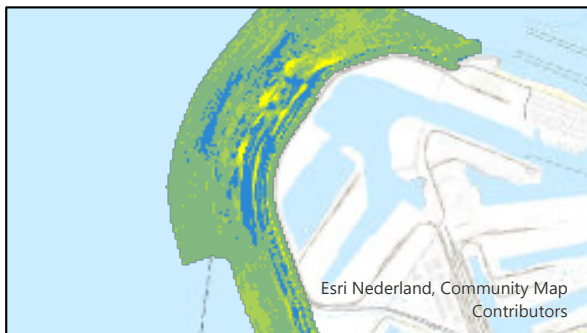
Bathymetric difference 2014-2015



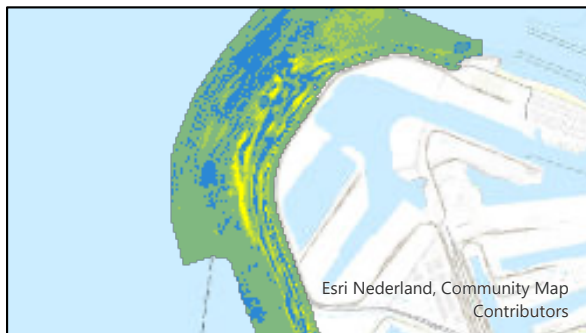
Bathymetric difference 2015-2016



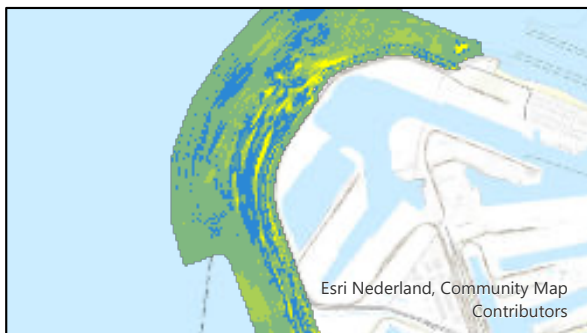
Bathymetric difference 2016-2017



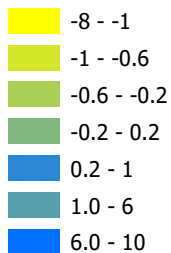
Bathymetric difference 2017-2018

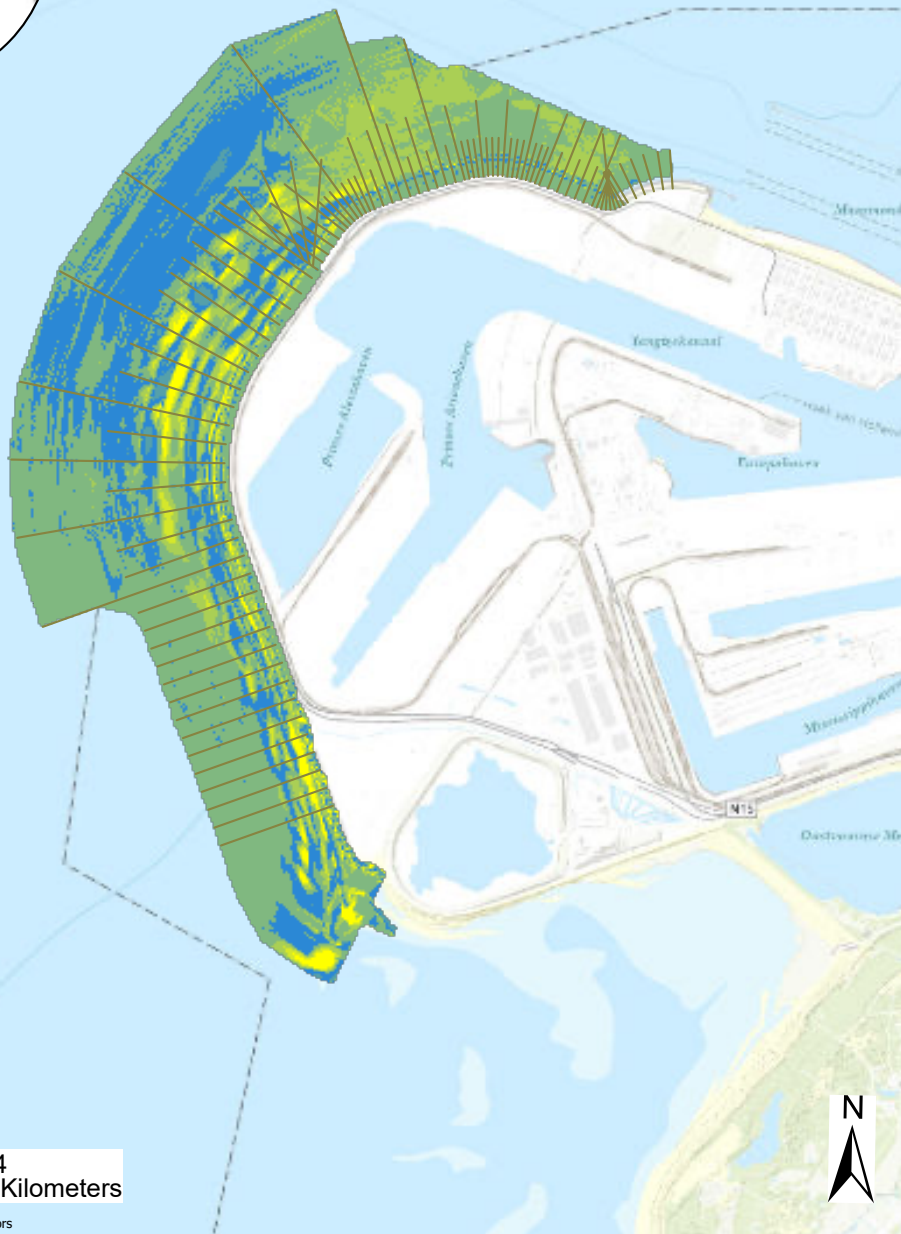


Bathymetric difference 2018-2019

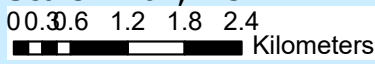


Bathymetric difference 2019-2020





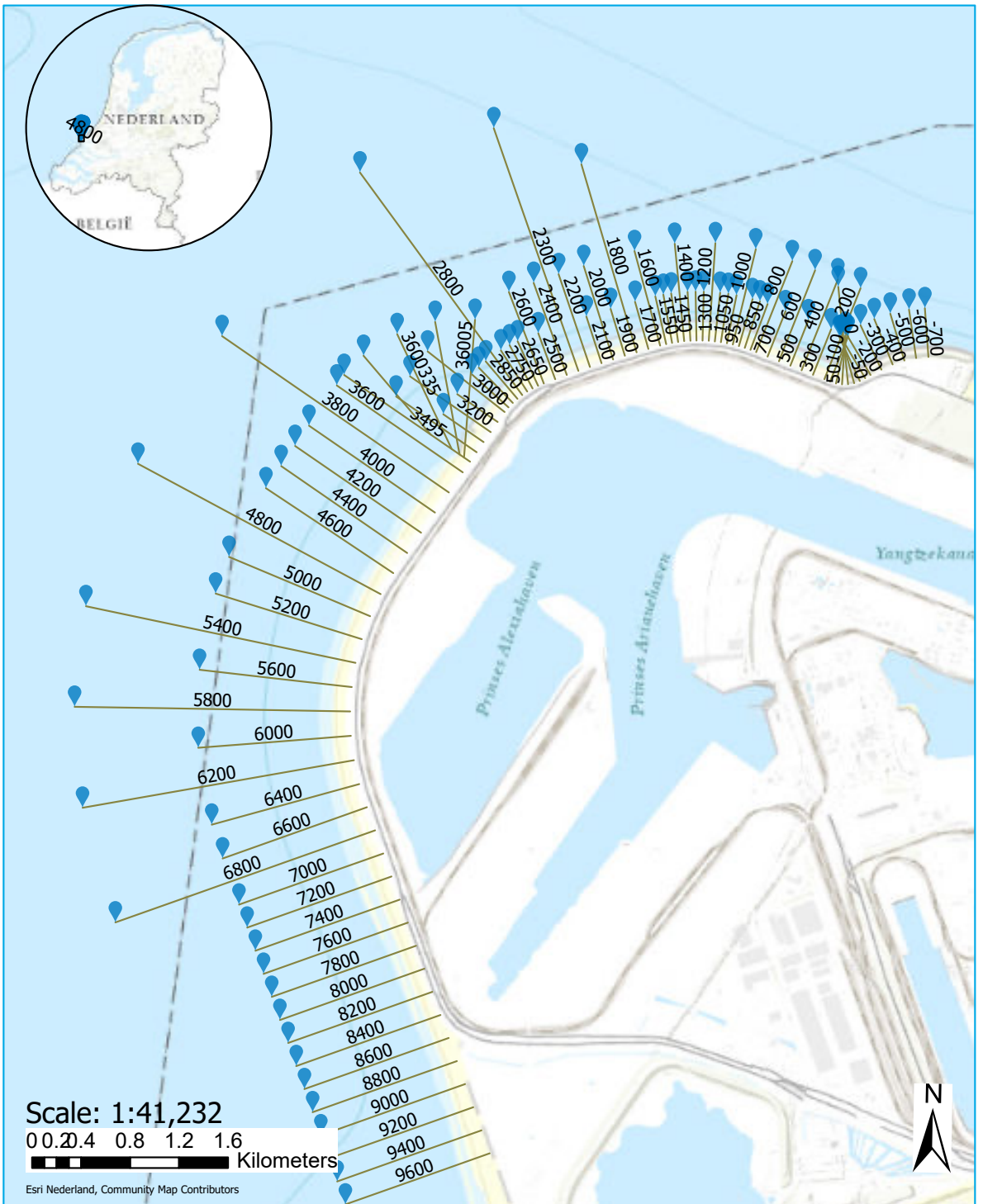
Scale: 1:64,425



Esri Nederland, Community Map Contributors

Raaien	Color	Range
	Yellow	-8 - -1
	Light Green	-1 - -0.6
	Medium Green	-0.6 - -0.2
	Dark Green	-0.2 - 0.2
	Blue	0.2 - 1
	Teal	1.0 - 6
	Dark Blue	6.0 - 10

## Difference in bathymetry BIP2016Q - BIP2017Q2



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



Difference 2013-2014



Difference 2014-2015



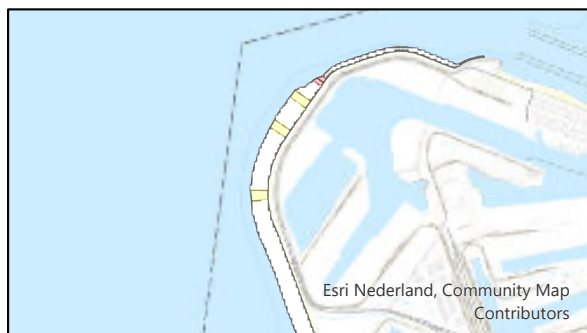
Difference 2015-2016



Difference 2016-2017



Difference 2017-2018

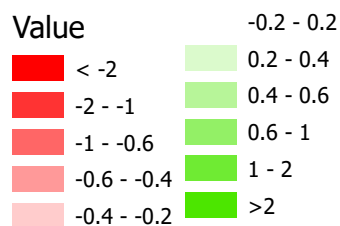


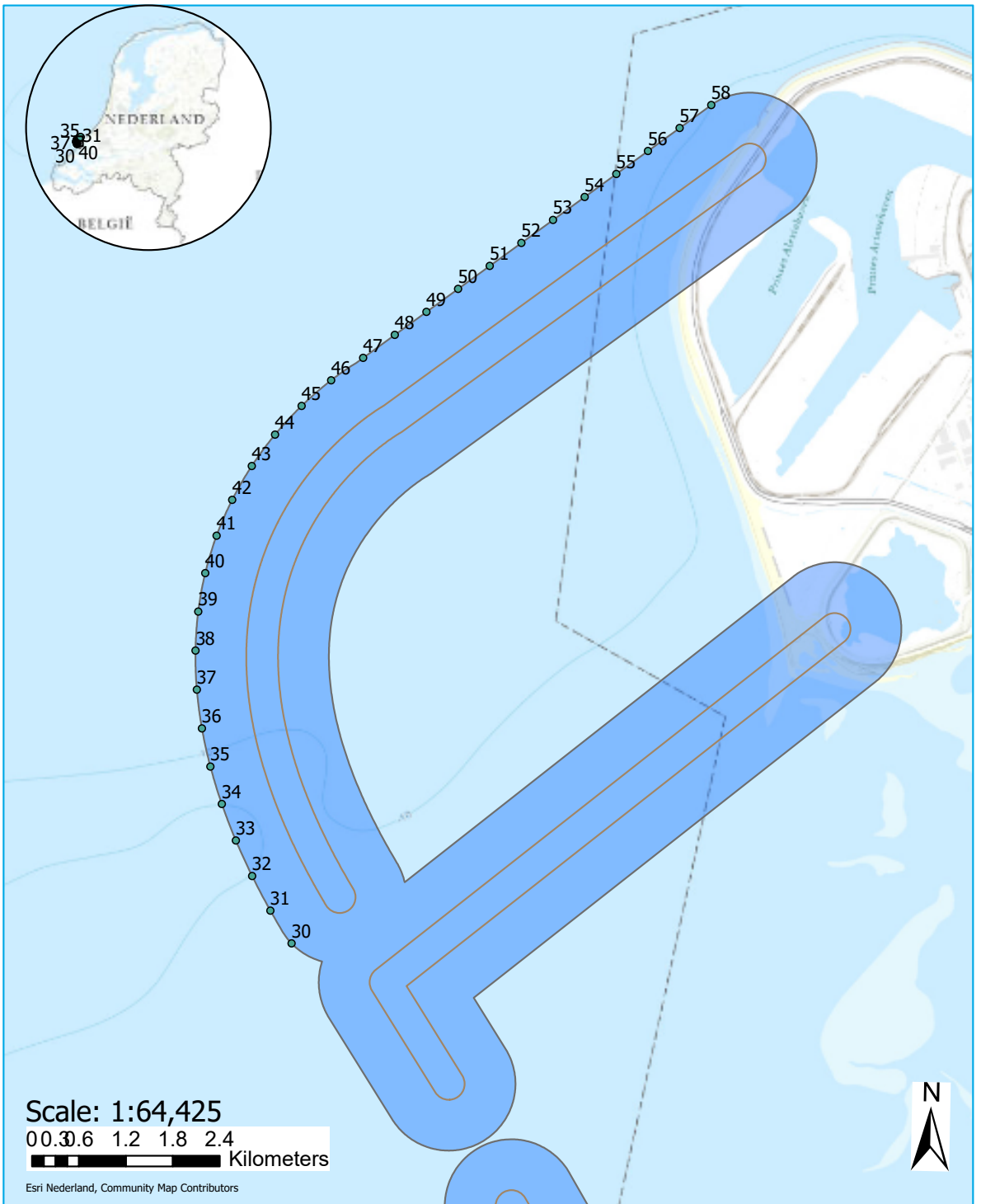
Difference 2018-2019



Difference 2019-2020

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





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

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 DATA

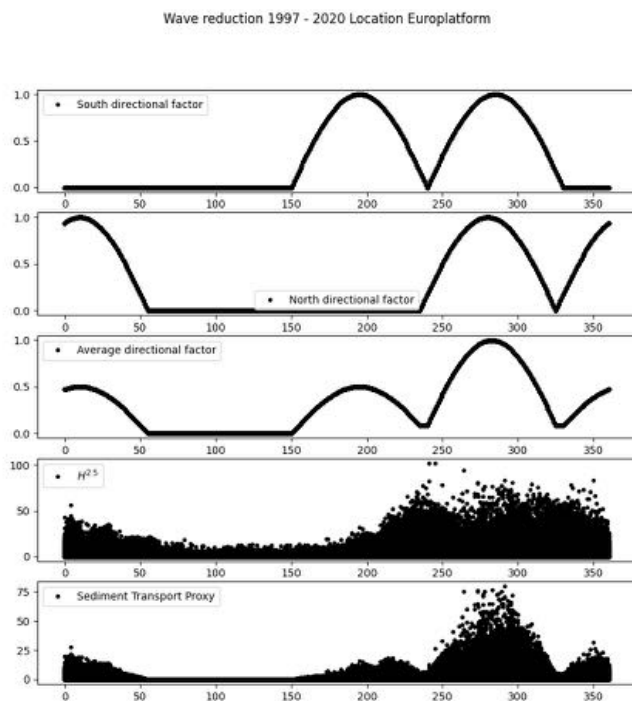
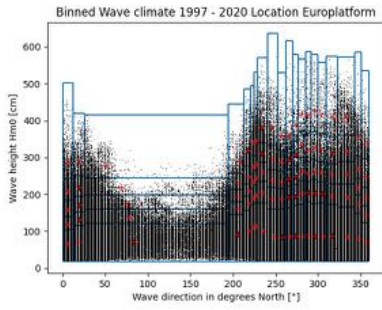
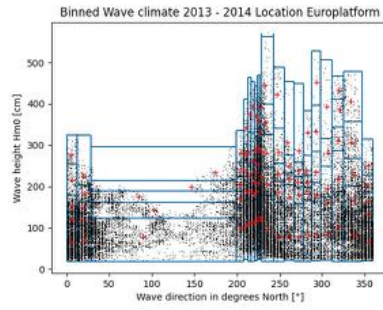


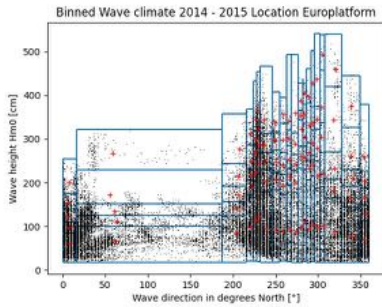
Figure B.1: Wave reduction for period 1997 - 2020 Location Europlatform



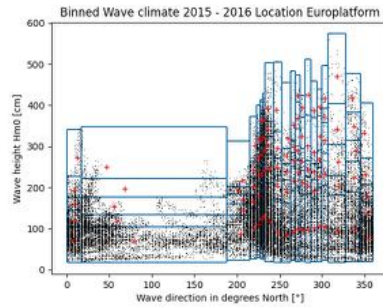
(1997-2020)



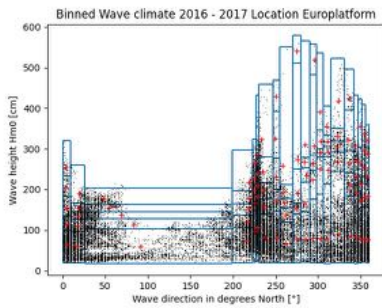
(2013Q2 - 2014Q2)



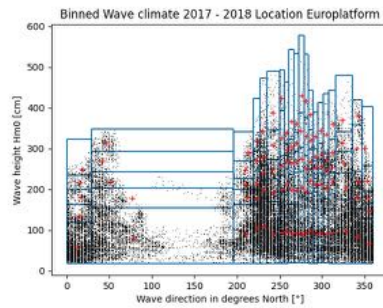
(2014Q2 - 2015Q2)



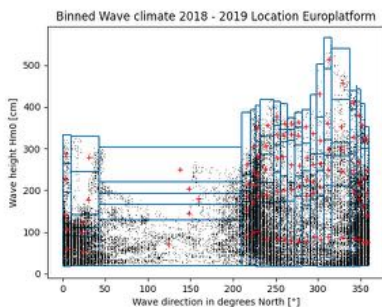
(2015Q2 - 2016Q2)



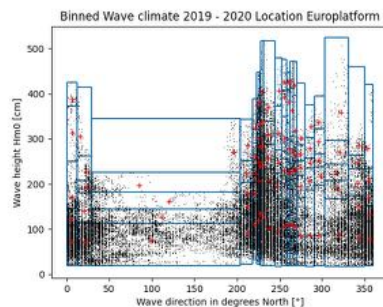
(2016Q2 - 2017Q2)



(2017Q2 - 2018Q2)



(2018Q2 - 2019Q2)



(2019Q2 - 2020Q2)

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

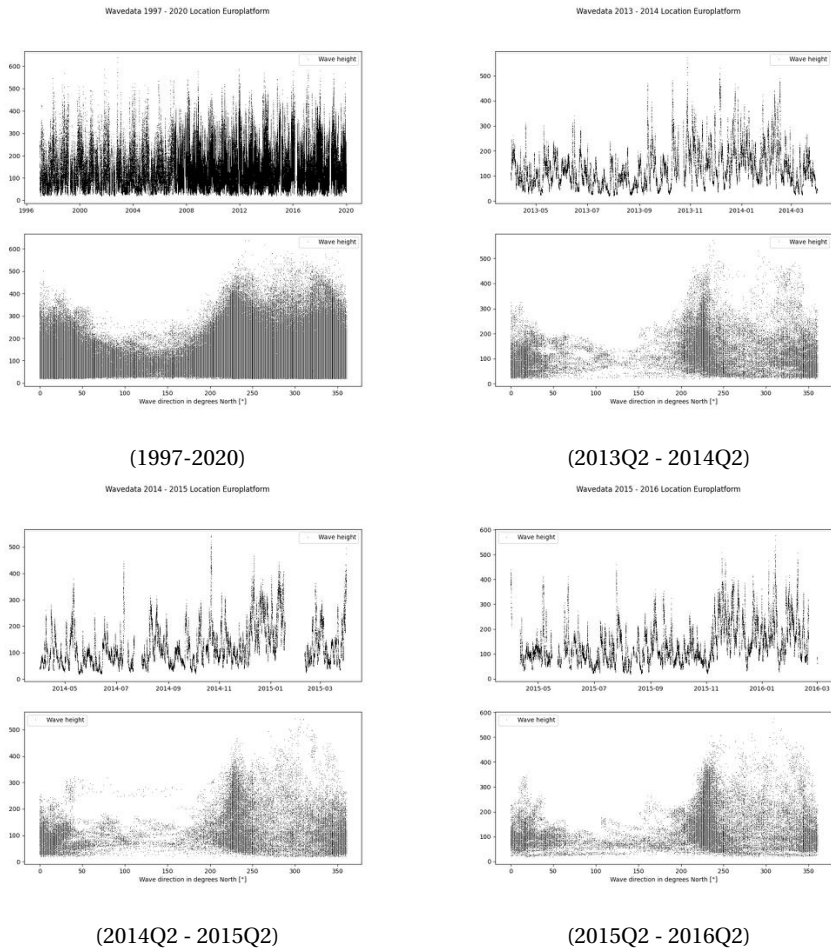


Figure B.3: Wave climates for various years.

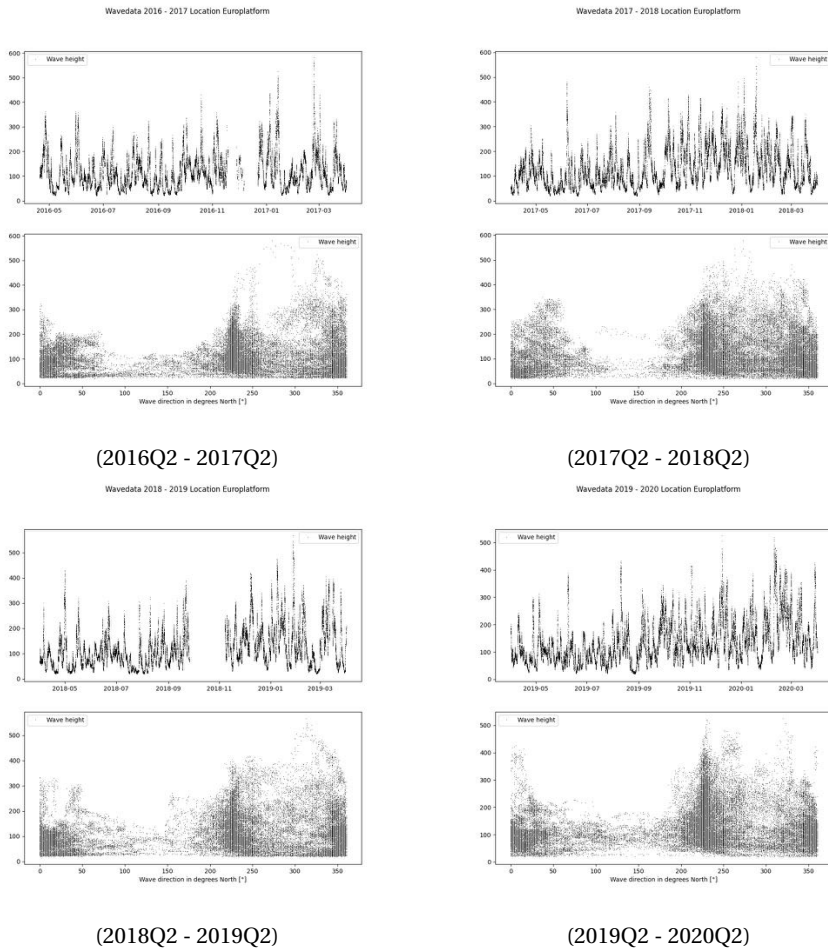


Figure B.4: Wave climates for various years.

B

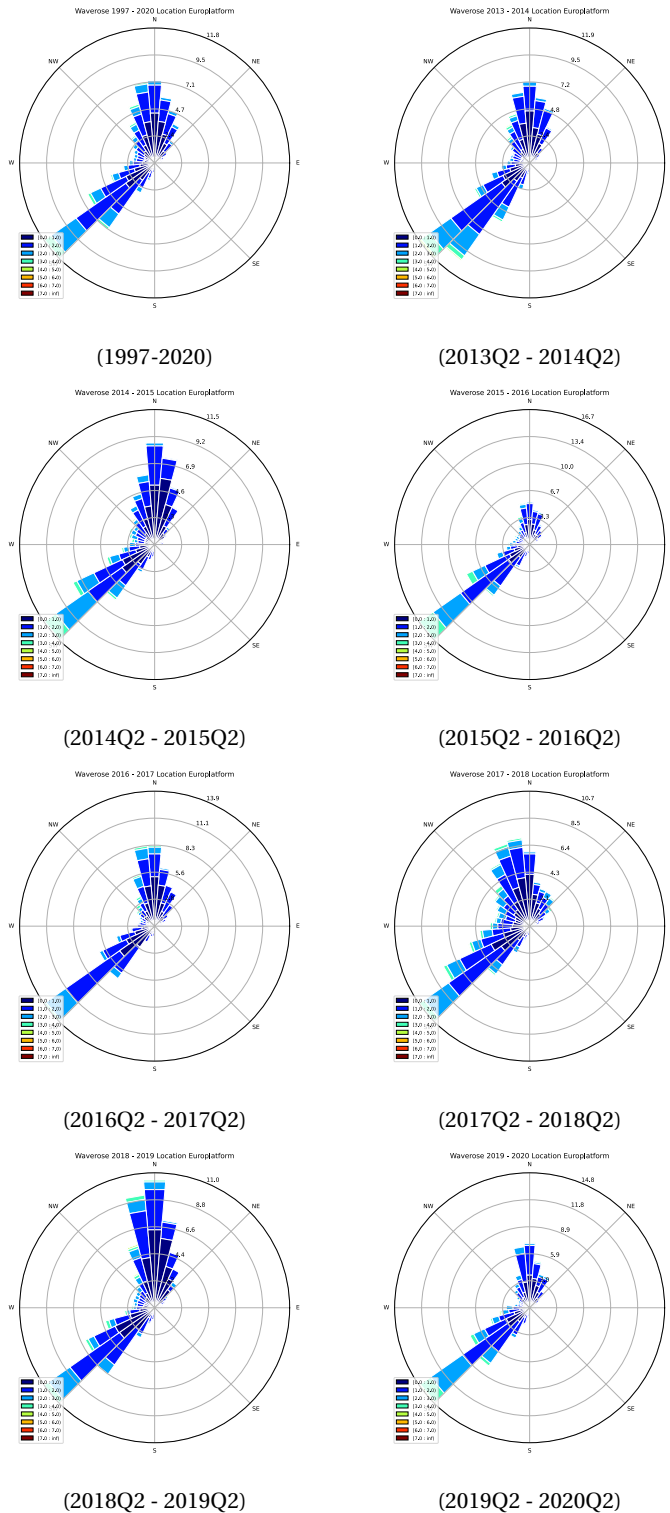
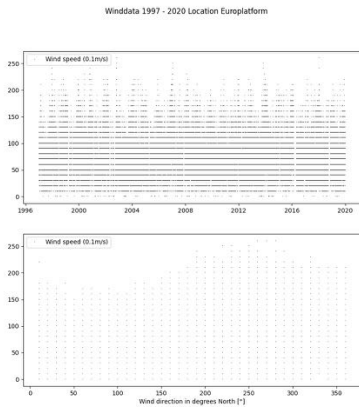
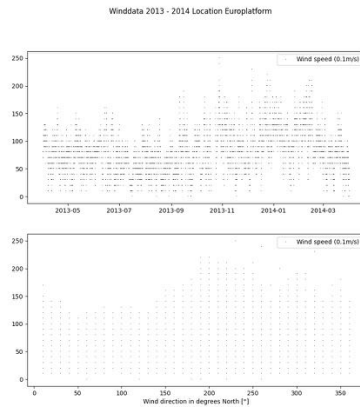


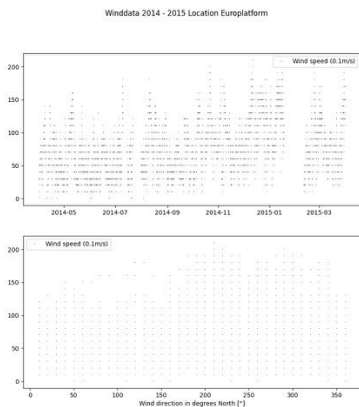
Figure B.5: Wave roses for various periods. Location Europlatform



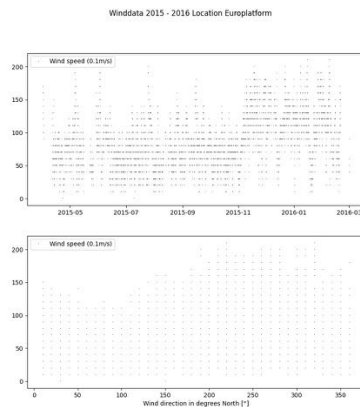
(1997-2020)



(2013Q2 - 2014Q2)



(2014Q2 - 2015Q2)



(2015Q2 - 2016Q2)

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

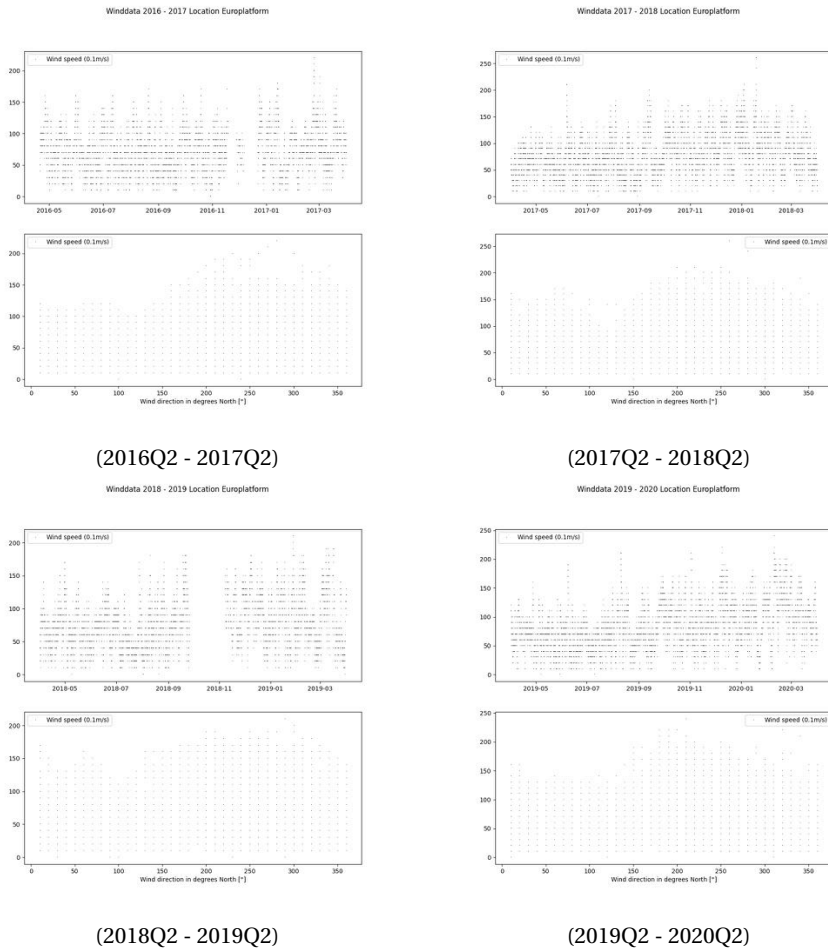


Figure B.7: Wind data for various periods. Location Europlatform.

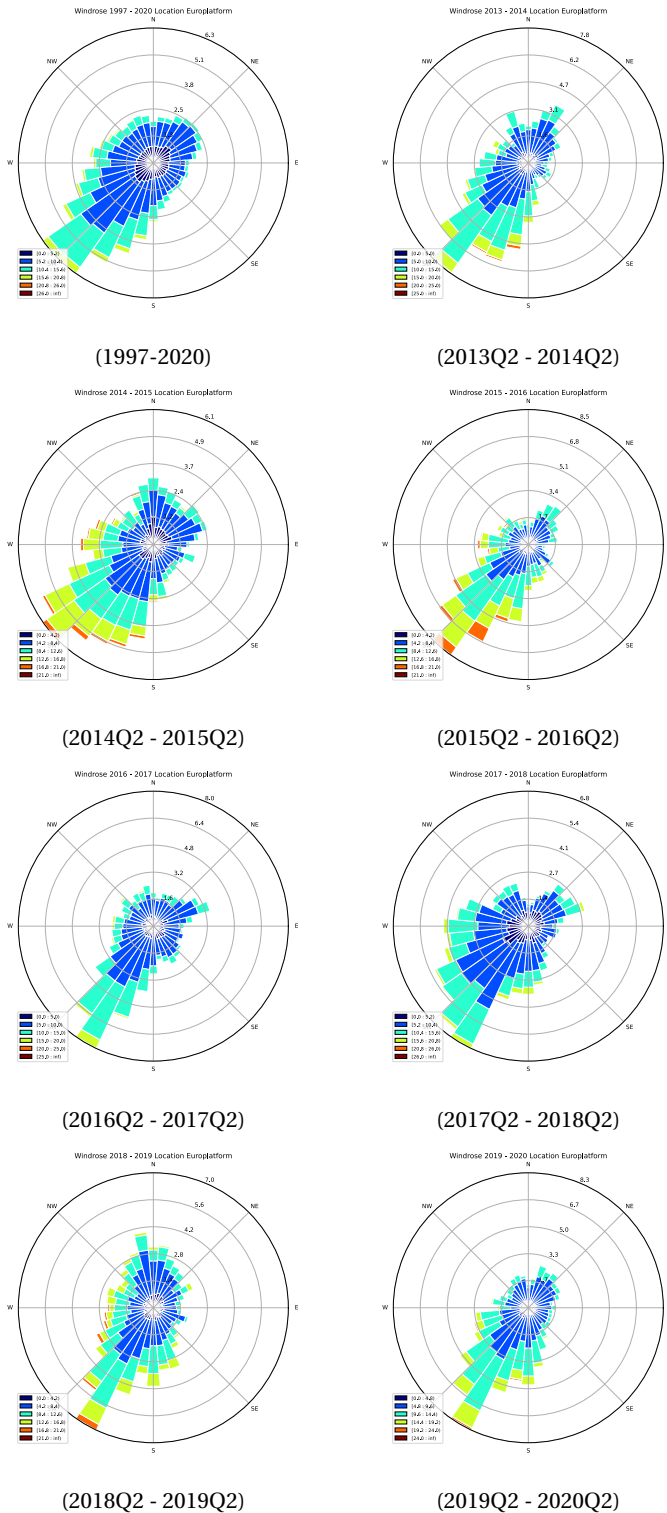


Figure B.8: Wind roses for various periods. Location Europlatform.

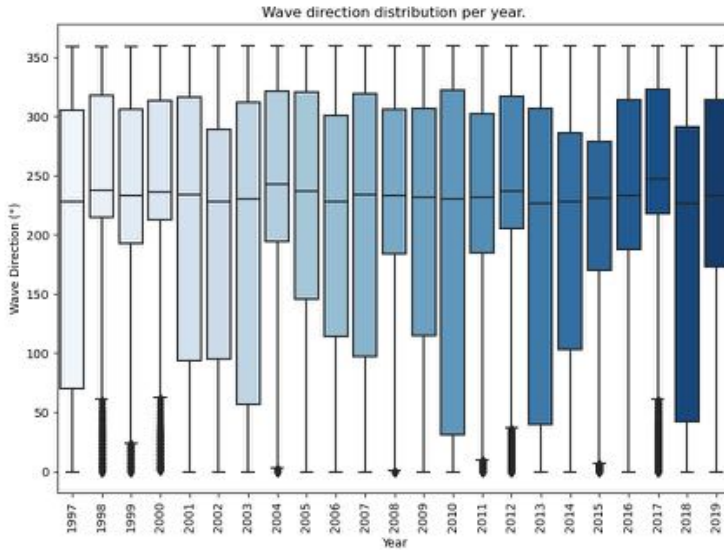


Figure B.9: Variability of the wave climate by means of a box plot of the wave direction per year.

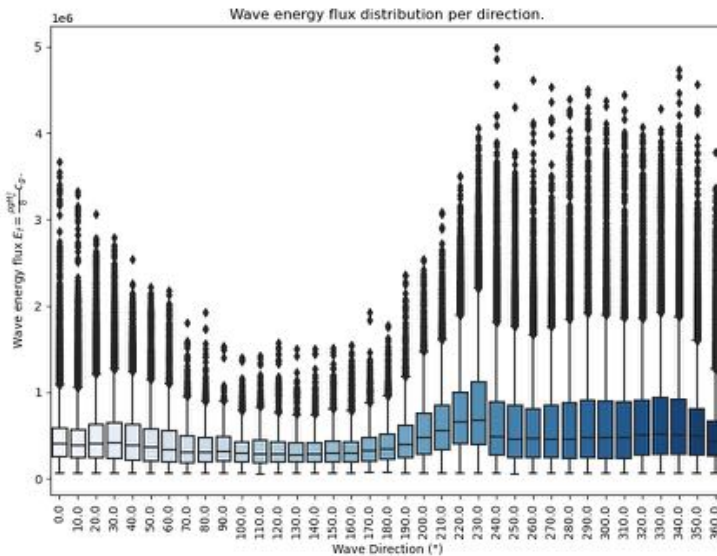


Figure B.10: Variability of the wave climate by means of a box plot of the wave energy flux per wave direction. The many outliers are due to the way wave energy flux is calculated and the amplification of large waves.

<b>Velocity</b>	<b>Occurence</b>	<b>Ref. Depth</b>	<b>Elevation</b>
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	10	0

Table B.1: Schematised tidal conditions for Ray 3600, at the western bend of Maasvlakte 2. 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%.

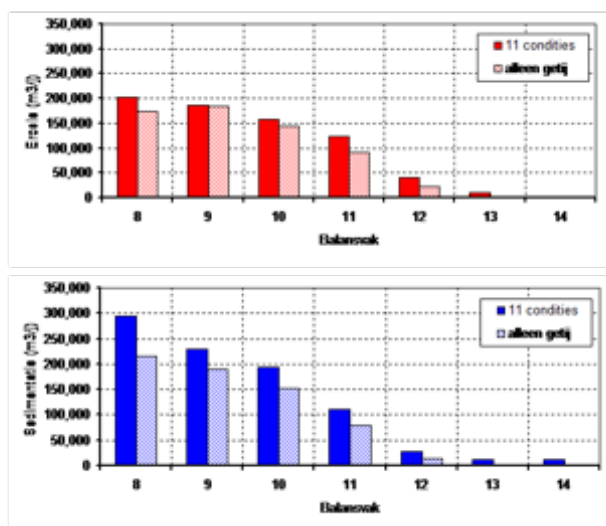


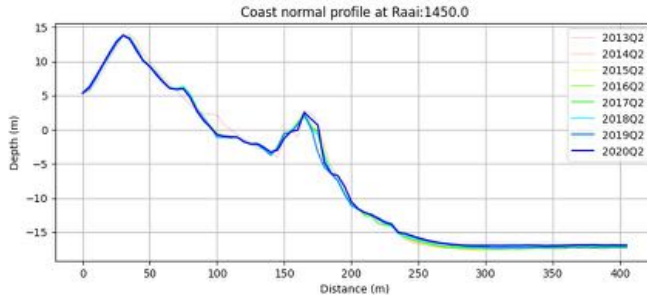
Figure B.11: PUMA modelled sedimentation- and erosion rates due to waves and tides per modelled section. From: PUMA Kenmerk puma-p-mo-onb07

	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

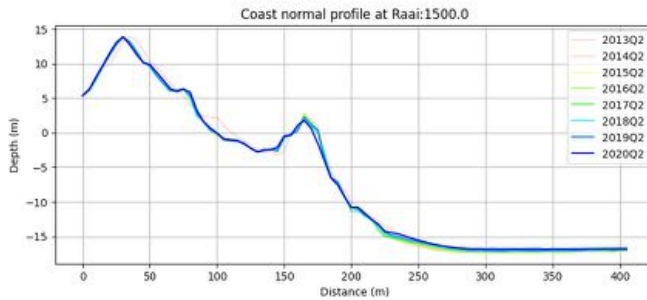
	Wave Dir.	Hm0	Tm01	Wind Dir.	Wind Speed	Chance of occurrence (p)
53	264.498	302.891	6.094	264.134	146.979	0.00085990
52	264.724	252.579	5.694	261.587	129.593	0.00134386
51	264.750	204.937	5.297	260.091	113.965	0.00225161
50	264.946	88.972	4.221	231.559	65.637	0.01291223
58	271.762	301.374	6.088	268.603	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

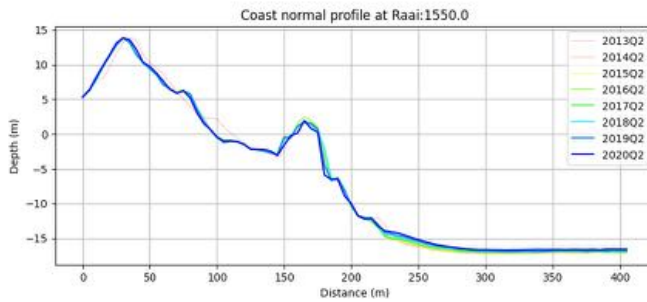
## PROFILES



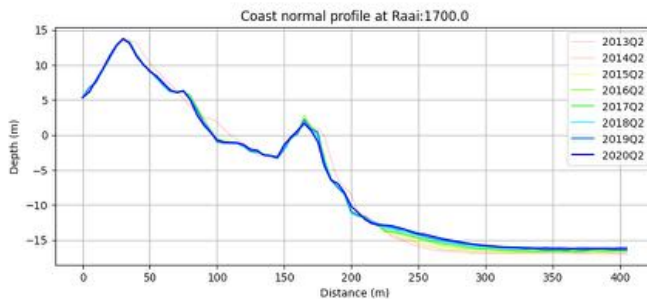
(Profile over the years 2013-2020. Raai 1450.)



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

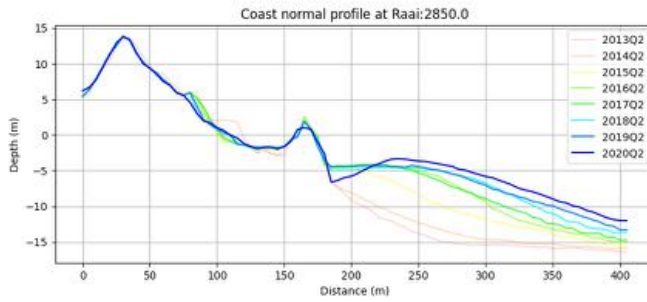


(Profile over the years 2013-2020. Raai 1550.)

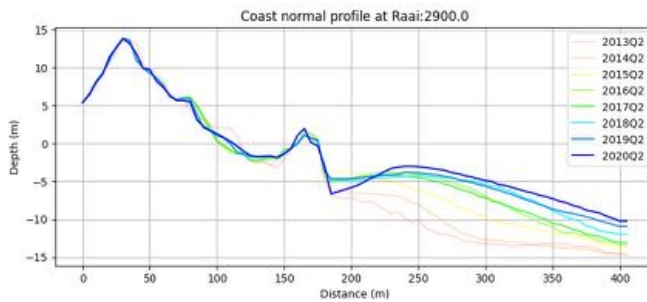


(Profile over the years 2013-2020. Raai 1700)

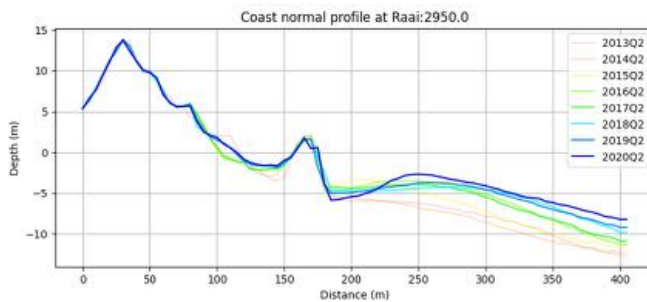
Figure C.1: Depth profiles for various coastal normals at northern side Maasvlakte 2



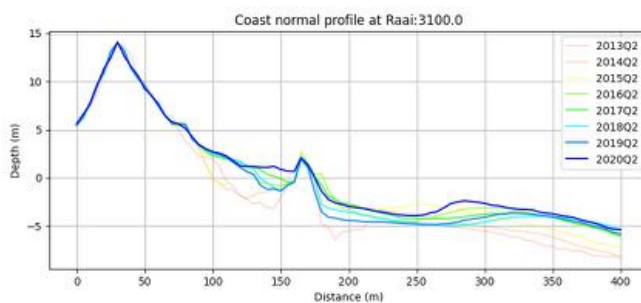
(Profile over the years 2013-2020. Raai 2850.)



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

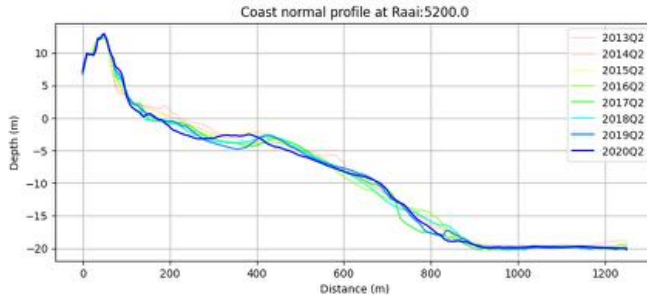


(Profile over the years 2013-2020. Raai 2950.)

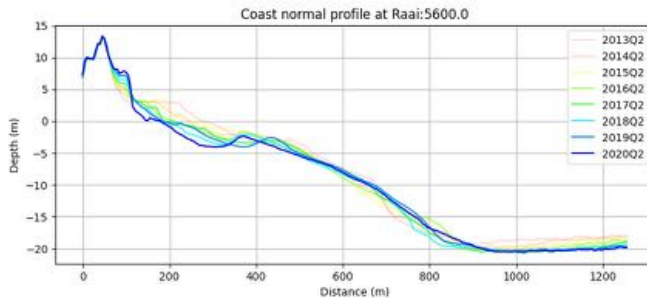


(Profile over the years 2013-2020. Raai 3100.)

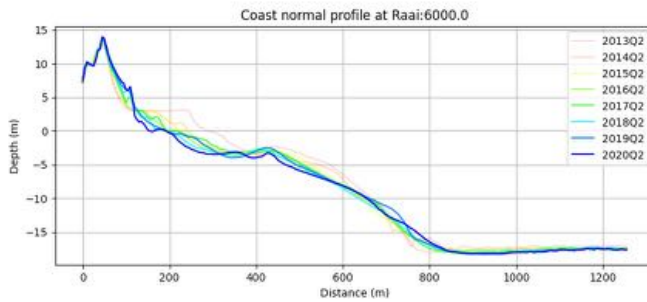
Figure C.2: Depth profiles various coastal normals at the transition between soft- and hard coastal defence, north-western side of Maasvlakte 2.



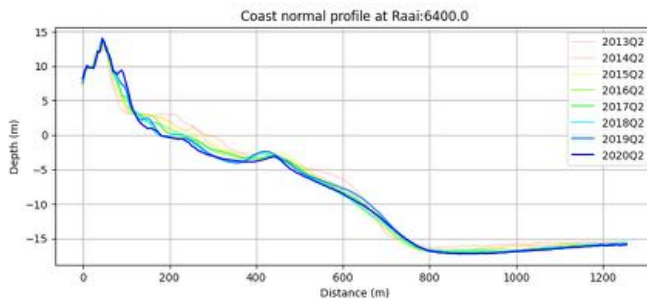
(Profile over the years 2013-2020. Raai 5200.)



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

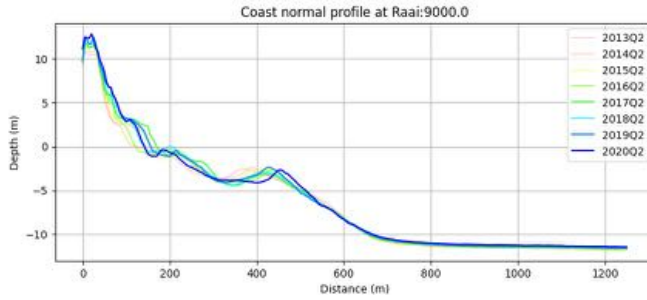


(Profile over the years 2013-2020. Raai 6000.)

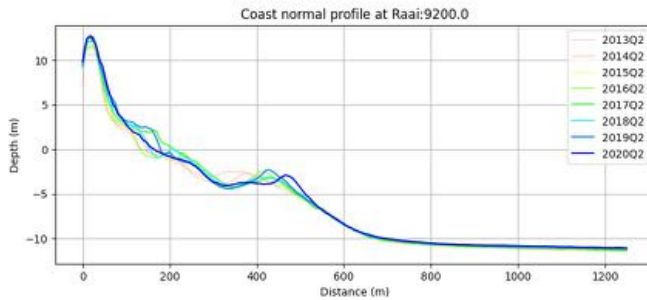


(Profile over the years 2013-2020. Raai 6400.)

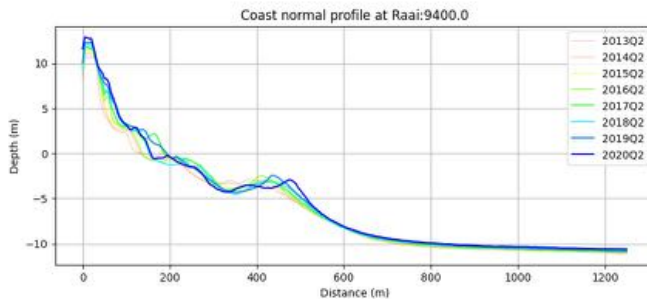
Figure C.3: Depth profiles for various coastal normals at the western bend along Maasvlakte 2.



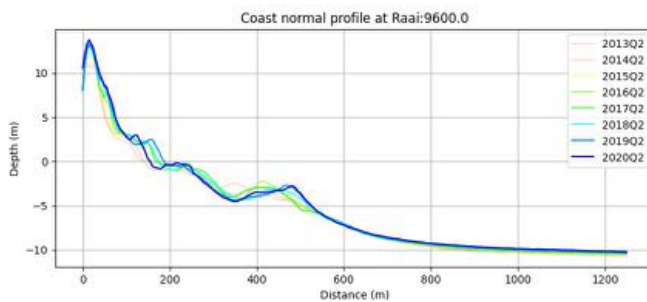
(Profile over the years 2013-2020. Raai 9000.)



(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.

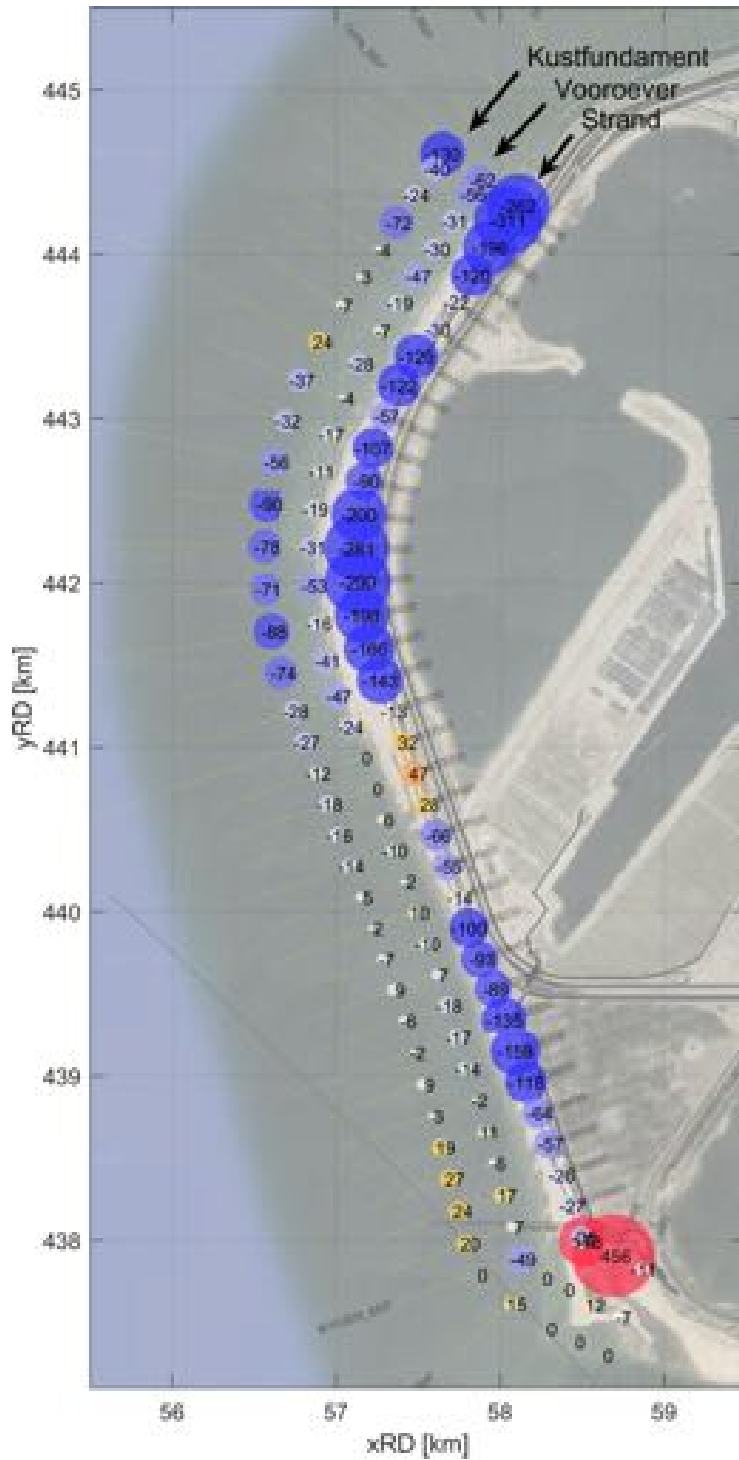


Figure C.5: Average erosion/accretion per year for the three different sections, foreshore, breakerzone and coastal foundation. Average over 2013-2017. Source: PUMA.

# D

## SWAN SETUP

### 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 whitecapping. The Komen et al. (1984) formulation (KOMEN) for exponential 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,  $S_{wc}(\sigma, \theta)$  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,  $S_{bot}(\sigma, \theta)$ , 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  $0.038 \text{ m}^2 \text{ s}^{-3}$  (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 SETTINGS *****
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

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$***** 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 SETTINGS *****
WIND [windspeed] [windir]
$***** INITIAL AND BOUNDARY CONDITIONS *****
$ Incident wave conditions from parent grid
BOUdary 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

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NEST 'nst02' '[runmap]\nests\NC[runnumber].rvw'
$***** LOCK UP *****
TEST ITEST= 1 ITRACE= 0
COMPUTE
STOP

```

## BASE FILE GRID C

```

$***** HEADING *****
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'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 SETTINGS *****
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 DRIM01 XP YP

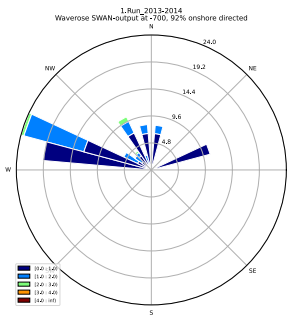
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COMPUTE
STOP

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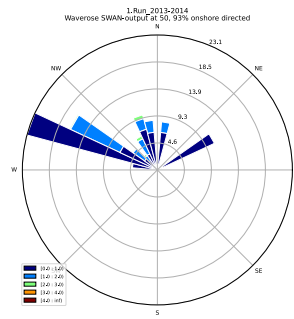
# E

## SWAN RESULTS

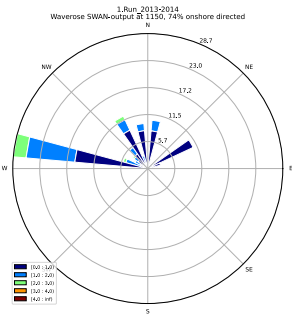
	Occur. (%)	Dir. (°)	Hm0 (m)	Tper (s)	Wind (°)	Wind (.1m/s)	Location 2000			Location 5000			Location 7000		
							Hsig (m)	Tper (s)	Dir (°)	Hsig (m)	Tper (s)	Dir (°)	Hsig (m)	Tper (s)	Dir (°)
0	5.18%	5.57	65.24	4.56	158.76	45.17	0.60	5.39	352.26	0.63	5.39	352.22	0.49	5.39	332.09
1	1.37%	6.94	120.95	4.98	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	9.30	4.00	4.87	333.02
6	1.43%	18.47	120.91	4.06	70.41	76.91	1.09	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	3.24	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	250.20	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	268.19	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	267.92
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	262.86
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	5.51	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										



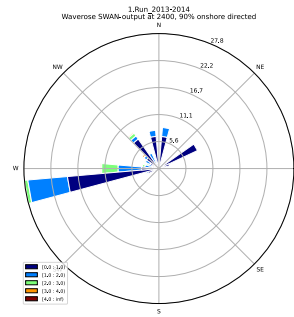
(Location -700. Period 2013-2014.)



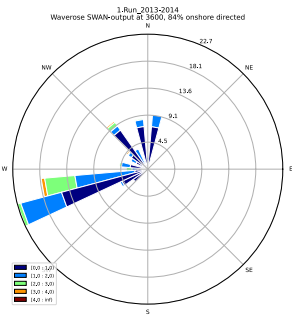
(Location 50. Period 2013-2014.)



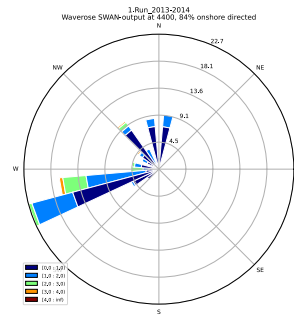
(Location 1150. Period 2013-2014.)



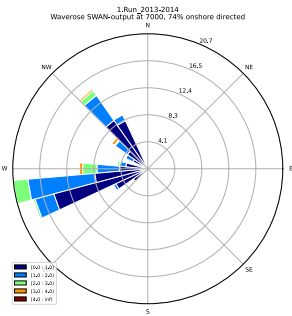
(Location 2400. Period 2013-2014.)



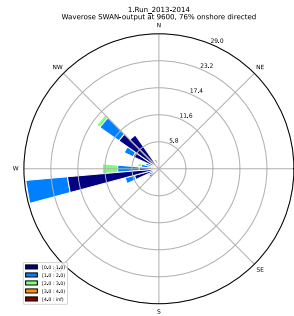
(Location 3600. Period 2013-2014.)



(Location 4400. Period 2013-2014.)



(Location 7000. Period 2013-2014.)

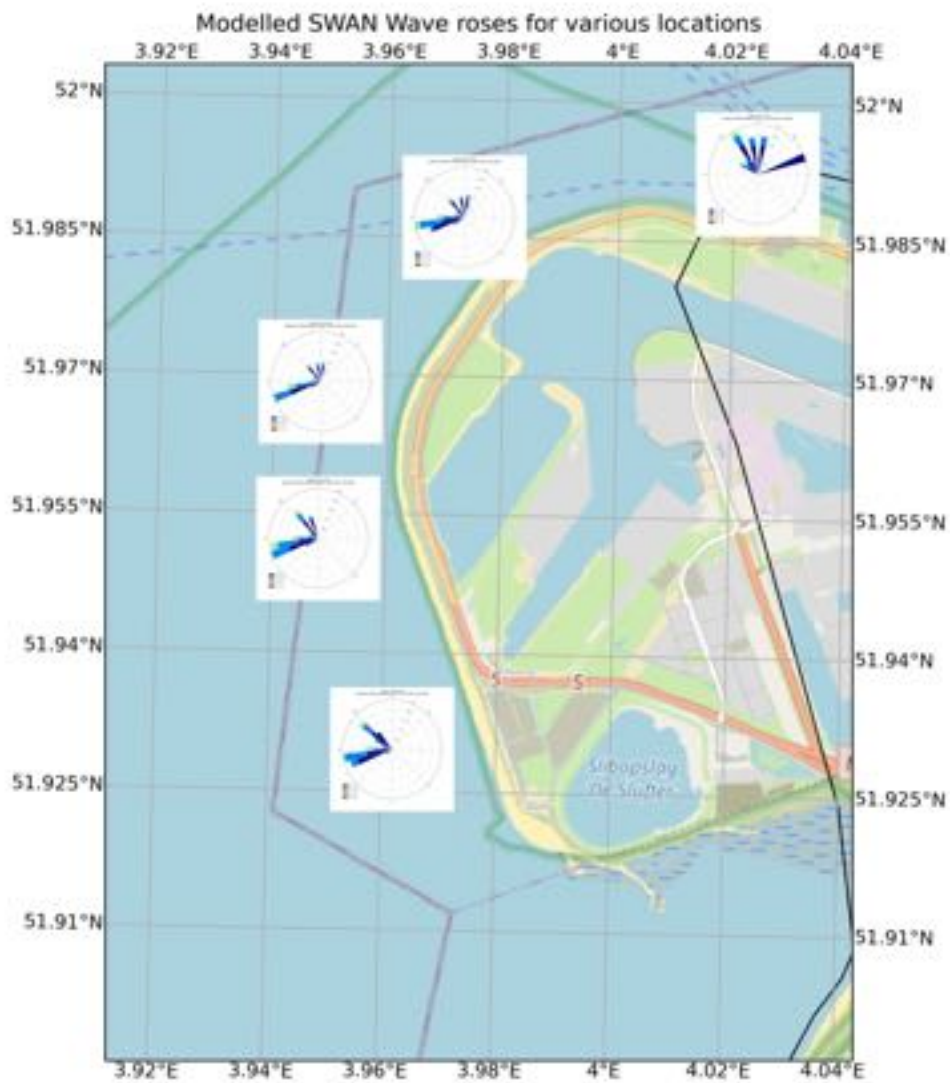


(Location 9600. Period 2013-2014.)

E

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

## 1.Run\_2013-2014



E

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

**F**

**UNIBEST SETUP**

### Korrelgrootte analyse

Identificatie: BS031020  
 Identificatie monster: K1993-07-0002  
 Coördinaten: 563754, 5752175 (WGS84)  
 Monster: van 2.00 m tot 3.00 m t.o.v. Zeebodem

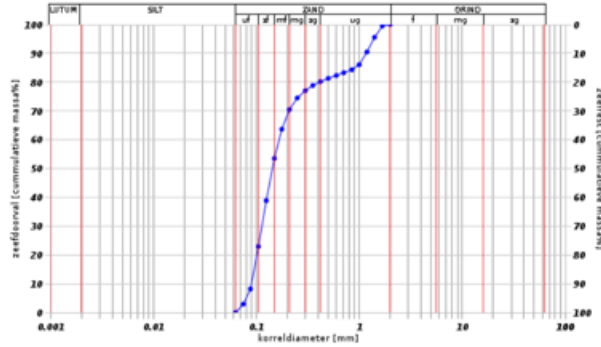


Figure F.1: Soil characteristics at 2-3 meters depth, compared to ground level. Example at an arbitrary location of the Energy Storage Lake. Source: Geographical Service Netherlands, TNO.

### Korrelgrootte analyse

Identificatie: BS031020  
 Identificatie monster: K1993-07-0008  
 Coördinaten: 563754, 5752175 (WGS84)  
 Monster: van 3.00 m tot 4.00 m t.o.v. Zeebodem

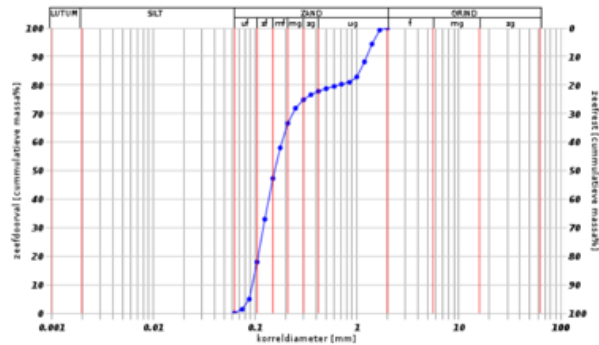


Figure F.2: Soil characteristics at 3-4 meter depth, compared to ground level. Example at an arbitrary location of the Energy Storage Lake. Source: Geographical Service Netherlands, TNO.

# G

## UNIBEST RESULTS

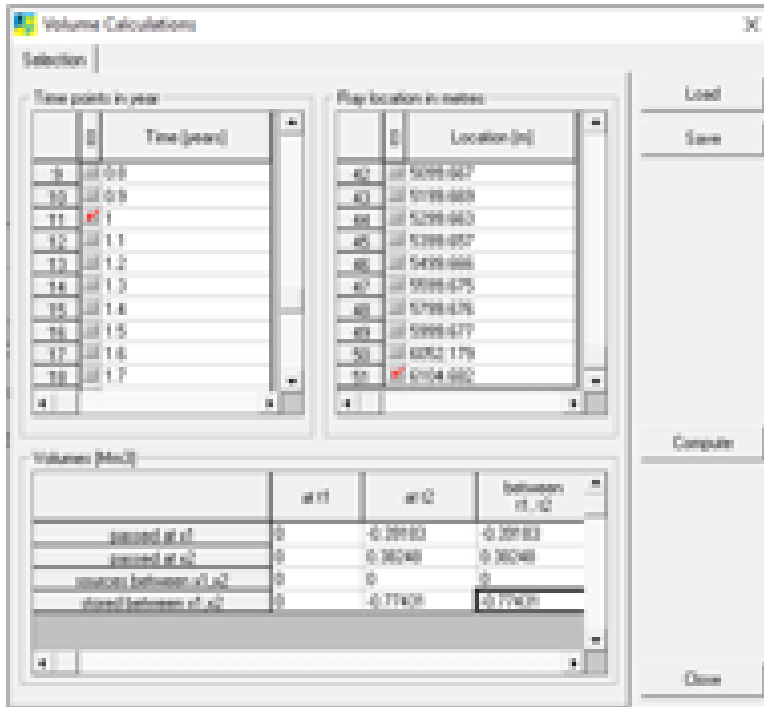


Figure G.1: Erosion/Sedimentation volume calculation for 1 year across the entire coast of Maasvlakte 2, as shown in UNIBEST-CL. Reduced wave climate of 1997-2020, excluding tides.

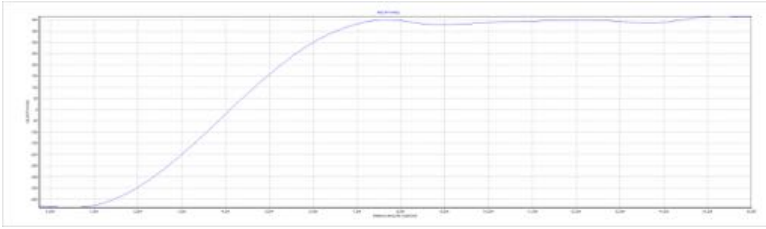


Figure G.2: Alongshore sediment transport after 5 years for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

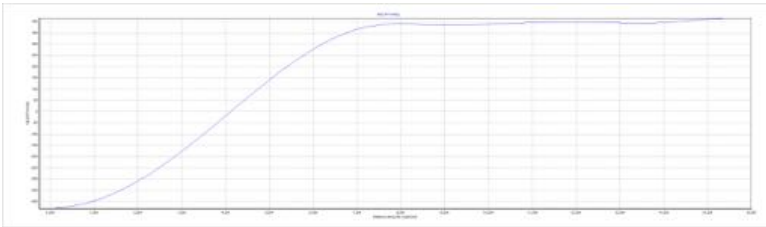


Figure G.3: Alongshore sediment transport after 10 years for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

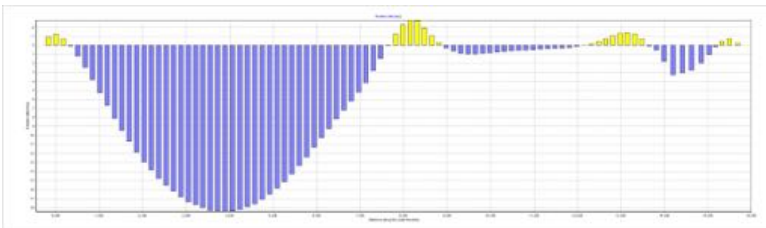


Figure G.4: Erosion rates after 5 years for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.

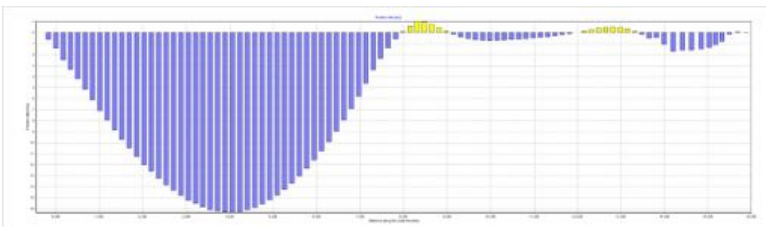


Figure G.5: Erosion rates after 10 years for Delta21 connection to Maasvlakte 2. Left side is Ray 30 of Delta21, right side is Ray 3400 of Maasvlakte 2.



# H

## PYTHON SCRIPTS

```

1 |
2 | # %%
3 | #####
4 | # #
5 | # WAVE/WIND INPUT REDUCTION #
6 | # & #
7 | # 2D BINNING #
8 | # #
9 | # Author: Detmar Dieleman #
10 | # Last update: 12-04-2021 #
11 | # #
12 | #####
13 |
14 | import pandas as pd
15 | import math
16 | import chardet
17 | import numpy as np
18 | import matplotlib.pyplot as plt
19 | import scipy.stats
20 | import matplotlib.cm as cm
21 | from matplotlib.pyplot import figure
22 | from windrose import WindroseAxes
23 | from scipy.stats import binned_statistic
24 | from datetime import datetime
25 |
26 | ## INPUT FILES & FOLDERS
27 | start = '4-1-2013'
28 | end = '4-1-2014'
29 |
30 | # Load wind data KNMI .txt file, source: https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens_Noor
31 | file1 = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Data\Wind\uurgeg_321_1991-2000.txt"
32 | file2 = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Data\Wind\uurgeg_321_2001-2010.txt"
33 | file3 = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Data\Wind\uurgeg_321_2011-2020.txt"
34 |
35 | # Load wave data
36 | file_init = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Data\Waves\20210205_023\20210205_023.c
37 | file_tm02 = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Data\Waves\20210210_014.csv"
38 |
39 | ## OUTPUT FILES & FOLDERS
40 | save_location_figures = r"C:\\Users\\detma\\Google Drive\\TU Delft\\Master Thesis\\Images, Graphs,
41 | Tables\\Results\\Data analysis\\"
42 |
43 | binned_wave_climate_name = 'Binned Wave climate ' + start[-4:] + ' - ' + end[-4:] + ' Location Europlatf
44 | wave_reduction_name = 'Wave reduction ' + start[-4:] + ' - ' + end[-4:] + ' Location Europlatform'
45 | waverose_name = 'Waverose ' + start[-4:] + ' - ' + end[-4:] + ' Location Europlatform'
46 | windrose_name = 'Windrose ' + start[-4:] + ' - ' + end[-4:] + ' Location Europlatform'
47 | subplots_wavedata_name = 'Wavedata ' + start[-4:] + ' - ' + end[-4:] + ' Location Europlatform'
48 | subplots_winddata_name = 'Winddata ' + start[-4:] + ' - ' + end[-4:] + ' Location Europlatform'
49 | wave_conditions_name_csv = 'Reduced wave climate Period ' + start[-4:] + ' - ' + end[-4:] + ' Location
50 | Europlatform'
51 |
52 | # %%
53 | period = pd.date_range(start =start, end =end, freq = '10T')
54 |
55 | # %%
56 | # -----
57 | # Wind data
58 | # -----
59 | # Read data, assign it to dataframe and merge to one dataframe.
60 | df1 = pd.read_csv(file1, sep=',', usecols=[1,2,3,4], header=0)
61 | df2 = pd.read_csv(file2, sep=',', usecols=[1,2,3,4], header=0)
62 | df3 = pd.read_csv(file3, sep=',', usecols=[1,2,3,4], header=0)

```

```

62
63 data = pd.concat([df1, df2, df3])
64
65 # Set the columns header as they are not recognized properly
66 data.columns = ['YYYYMMDD', 'HH', 'DD', 'FH']
67
68 # Create a new column datetime based on the 2 columns and assign it as index
69 data['datetime'] = pd.to_datetime(data['YYYYMMDD'], format='%Y%m%d')
70 data['datetime'] += pd.to_timedelta(data['HH'], unit='h')
71 data.set_index('datetime', inplace=True)
72
73 # Create new 10 min. index of waves and re-index the dataframe using backfill method
74 df_wind = data.reindex(period, method='bfill')
75
76 # Value adjustments. DD: 0=windstil 990=veranderlijk, replace with NaN
77 df_wind['DD'] = pd.to_numeric(df_wind['DD'], errors='coerce')
78 df_wind['FH'] = pd.to_numeric(df_wind['FH'], errors='coerce')
79
80 df_wind.loc[df_wind['DD'] == 0] = np.nan
81 df_wind.loc[df_wind['DD'] == 990] = np.nan
82
83 # Drop unnecessary columns after using them
84 df_wind = df_wind.drop(columns=['YYYYMMDD', 'HH'])
85
86 # %%
87 # -----
88 # Wave data
89 # -----
90
91
92
93 # Import Rijkswaterstaat wave file, create dataframe
94 df_init = pd.read_csv(file_init, sep=';', encoding='ISO-8859-1', header=0)
95 df_tm02 = pd.read_csv(file_tm02, sep=';', encoding='ISO-8859-1', header=0)
96
97 # Check names of parameters in the file
98 #df_tm02['GROOTHEID_CODE'].unique().tolist()
99
100 # Delete all unnecessary columns
101 df_init.drop(df_init.columns.difference(['WAARNEMINGDATUM', 'WAARNEMINGTIJD', 'NUMERIEKEWAARDE', 'GROOTHEID_CODE']), 1, inplace=True)
102 df_tm02.drop(df_tm02.columns.difference(['WAARNEMINGDATUM', 'WAARNEMINGTIJD', 'NUMERIEKEWAARDE', 'GROOTHEID_CODE']), 1, inplace=True)
103
104 # Replace , with . in TM02 dataframe, as otherwise it will not save as float
105 df_tm02['NUMERIEKEWAARDE'] = df_tm02['NUMERIEKEWAARDE'].str.replace(",", ".").astype(float)
106
107 # %%
108 # Combine the initial and separate Tm02 wave-data dataframes
109 df = pd.concat([df_init, df_tm02])
110
111 # Create a new column datetime based on the 2 columns and assign it as index
112 df['datetime'] = pd.to_datetime(df['WAARNEMINGDATUM'], format='%d-%m-%Y')
113 df['datetime'] += pd.to_timedelta(df['WAARNEMINGTIJD'])
114 df.set_index('datetime', inplace=True)
115
116 # Pivot table based on index 'datetime' and columns 'GROOTHEID_CODE'
117 df_pivot = df.pivot_table(index='datetime', columns='GROOTHEID_CODE', values='NUMERIEKEWAARDE')
118
119 # Handling of multiple entries at same datetime index, since there are multiple entries per 10 min.
120 ## 1. Group by index and take mean,
121 df_pivot.groupby(df_pivot.index).mean()
122
123 ## 2. Delete the duplicates

```

```

124 # df_pivot.drop_duplicates(keep='first')
125
126 # Temporary, only use 2020
127 #df_pivot = df_pivot.loc['2020']
128
129 # %%
130 # Replace large values with NaN as these are incorrect
131 df_pivot.loc[df_pivot['Tm02'] > 20] = np.nan
132 df_pivot.loc[df_pivot['Hm0'] > 999] = np.nan
133 df_pivot.loc[df_pivot['Th0'] > 360] = np.nan
134
135 # %%
136 # -----
137 # Intermediate sub-plots Euro-platform
138 # -----
139
140 # %%
141 # Drop column Fp as this is 'replaced' by Tm02
142 del df_pivot['Fp']
143
144 # Hasselmann 1978 empirical relation for JONSWAP y=3.3
145 df_pivot['Tm01'] = 1.073*df_pivot['Tm02']
146
147 del df_pivot['Tm02']
148 # %%
149 # Merge dataframes
150 df_merged = pd.concat([df_wind, df_pivot], axis=1)
151
152 # Replace empty strings with NaNs
153 df_merged['FH'].replace("", np.nan, inplace=True)
154 #df_merged['FH']= df_merged['FH'].astype(np.float32)
155
156 # Drop the entire index if ANY of the five columns Hm0, Th0, Tm01, DD, DS contain a NaN-value.
157 df_merged = df_merged.dropna()
158
159 df_merged= df_merged.astype(np.float32)
160 # %%
161 # -----
162 # BINNING WITH EQUIDISTANT BINS BASED ON WAVE DIRECTION (FOR COMPARISON)
163 # -----
164
165 # Amount, width and centres of bins
166 eq_bins = 9
167 eq_dist = 360/eq_bins
168 centres= np.linspace(eq_dist/2, 360-(eq_dist/2), num=eq_bins)
169
170 # Average the other parameters within the bins
171 eq_binned_Th0 = scipy.stats.binned_statistic(df_merged['Th0'], df_merged['Th0'], statistic='mean',
bins=eq_bins, range=None)
172 eq_binned_hm0 = scipy.stats.binned_statistic(df_merged['Th0'], df_merged['Hm0'], statistic='mean',
bins=eq_bins, range=None)
173 eq_binned_Tm01 = scipy.stats.binned_statistic(df_merged['Th0'], df_merged['Tm01'], statistic='mean',
bins=eq_bins, range=None)
174 eq_binned_DD = scipy.stats.binned_statistic(df_merged['Th0'], df_merged['DD'], statistic='mean',
bins=eq_bins, range=None)
175 eq_binned_FH = scipy.stats.binned_statistic(df_merged['Th0'], df_merged['FH'], statistic='mean',
bins=eq_bins, range=None)
176
177 # Create a new dataframe
178 rows = ["Th0", "Hm0", "Tm01", "Wind_dir", "Wind_speed"]
179 data = np.array([eq_binned_Th0[0], eq_binned_hm0[0], eq_binned_Tm01[0], eq_binned_DD[0], eq_binned_FH[0]])
180 df_eq_binned = pd.DataFrame(data=data, index=rows, columns=centres)
181
182 # Transpose the dataframe for eassier comparison & reading

```

```

183 df_eq_binned_transposed = df_eq_binned.transpose()
184
185 # Show preview
186 df_eq_binned_transposed
187 # %%
188 # -----
189 # PLOTTING (SAME WIDTH) BINS BASED ON WAVE DIRECTION
190 # -----
191
192 # Plot Th0 on x-axis, wave height on y-axis
193 # plt.plot(df_merged['Th0'], df_merged['Hm0'], ',', color='black')
194
195 # Plot the bin edges
196 # for x_coor in eq_binned_Th0[1]:
197 #     plt.vlines(x=x_coor , ymin=0, ymax=df_merged['Hm0'].max())
198 #     plt.hlines(y=0, xmin=0, xmax=df_merged['Th0'].max())
199 #     plt.hlines(y=df_merged['Hm0'].max(), xmin=0, xmax=df_merged['Th0'].max())
200 # # Plot the bin averages (centres): x=average Th0, y=average Hm0
201 # plt.plot(df_eq_binned_transposed['Th0'], df_eq_binned_transposed['Hm0'], '+', color='red')
202
203 # Preview plots
204 # plt.show()
205 # %%
206 # -----
207 # 2D BINNING WITH INPUT REDUCTION BASED ON WAVE DIRECTION & WAVE HEIGHT
208 # -----
209
210 # -----
211 # STEP 1: CALCULATING THE FACTOR/WEIGHT ON WHICH TO BIN (SEDIMENT TRANSPORT PROXY, WAVE FLUX ETC.)
212 # -----
213
214 # Number of weighted directional and wave height bins
215 wt_dir_bins = 20
216 wt_hm0_bins = 5
217
218 # Get the total numbers of valid wave measurements in the dataframe for determination of chance of occur
219 n_total = len(df_merged)
220
221 # Create new column for H_s^2.5
222 df_merged['Hss'] = ((df_merged['Hm0']/100)**2.5)
223
224 # Major coast normal orientations (outwards of coast) for Delta21 design are 240 & 325, so:
225 o_north = 325
226 o_south = 240
227
228 # Calculate the normalised and absolute difference in degrees between wave incidence and shore normal
229 df_merged['norm_diff_north'] = ((df_merged['Th0']-o_north) %360)
230 df_merged['abso_diff_north'] = np.minimum(360-df_merged['norm_diff_north'], df_merged['norm_diff_north'])
231
232 df_merged['norm_diff_south'] = ((df_merged['Th0']-o_south) %360)
233 df_merged['abso_diff_south'] = np.minimum(360-df_merged['norm_diff_south'], df_merged['norm_diff_south'])
234
235 # For absolute angles <90, calculate the 'F-factor' ([0-1]), based on sin(2*alpha). For absolute angles
set to 0.
236 df_merged.loc[df_merged['abso_diff_north'] >= 90, 'F_North'] = 0
237 df_merged.loc[df_merged['abso_diff_north'] < 90, 'F_North'] = abs(np.sin(np.radians(
(df_merged['abso_diff_north']*2) )))
238
239 df_merged.loc[df_merged['abso_diff_south'] >= 90, 'F_South'] = 0
240 df_merged.loc[df_merged['abso_diff_south'] < 90, 'F_South'] = abs(np.sin(np.radians(
(df_merged['abso_diff_south']*2) )))
241
242 # Take the average of the F-factors for the north and the south.
243 df_merged['F_average'] = (df_merged['F_North']+df_merged['F_South'])/2

```

```

244 |
245 # Multiple the average F-factor with the Hss, to get an function of the amount of longshore sediment
transport.  $Sy = Hm0^{2.5} * \sin(2*\alpha)$ 
246 df_merged['Sy'] = df_merged['F_average']*df_merged['Hss']
247 |
248 |
249 |
250 |
251 # %%
252 # -----
253 # STEP 2: CREATING THE DIRECTIONAL BINS
254 # -----
255 |
256 # Sort dataframe by wave-direction 'Th0'
257 # Flaw: how to determine at what index values with the same Th0 go and are thus binned? Bin borders at
degrees, not index with groupby.
258 df_sorted_dir = df_merged.sort_values(by=['Th0', 'Hm0'])
259 |
260 # Add new indices to the sorted dataframe
261 df_reset_dir = df_sorted_dir.reset_index(drop=True)
262 |
263 # Total amount of Sy (to be divided into bins)
264 Sy_total = df_reset_dir['Sy'].sum()
265 |
266 # Determine the cumulative sum of the entire 'Sy' column for each increasing (wave-direction)-index
267 df_reset_dir['sy_cumsum'] = df_reset_dir['Sy'].cumsum()
268 |
269 # Check where the cumulative sum-column reaches '1/bins'-th of the total Sy and store these locations.
270 #####wt_dir_bin_borders = [ np.argmax(df_reset_dir['sy_cumsum'] > (Sy_total*i / wt_dir_bins)) for i in
range(wt_dir_bins+1) ]
271 wt_dir_bin_borders = [ np.argmax(df_reset_dir['sy_cumsum'] > (Sy_total*i / wt_dir_bins)) for i in
range(wt_dir_bins+1) ]
272 wt_dir_bin_borders[-1] = len(df_reset_dir)-1
273 |
274 # %%
275 # -----
276 # STEP 3: CREATING THE WAVE HEIGHT BINS PER DIRECTIONAL BIN
277 # -----
278 # APPROACH 1 : MAKING A NEW DATAFRAME FOR EACH BIN ###
279 |
280 # The amount of Sy in 1 directional bin = Sy_total/#dir bins
281 sy_dir_bin = Sy_total/wt_dir_bins
282 |
283 # The amount of Sy in 1 wave height bin
284 sy_hm0_bin = sy_dir_bin / wt_hm0_bins
285 |
286 # Create the empty arrays for storing the data per bin
287 array_dir = []
288 array_wh = []
289 array_dd = []
290 array_fh = []
291 array_tm01 = []
292 array_p = []
293 |
294 #Loop through every directional bin.
295 for j in range(len(wt_dir_bin_borders)-1):
296 |
297     # Take the part of the original dataframe where the directional bin borders are defined. Keep original
indexes for easier lookup later.
298     df_dir_bin = df_reset_dir.loc[wt_dir_bin_borders[j]:wt_dir_bin_borders[j+1]]
299 |
300     # Sort by waveheight Hm0
301     df_dir_bin_sorted = df_dir_bin.sort_values(by=['Hm0', 'Th0'])
302 |

```

```

303 # Determine the cumulative sum of the entire 'Sy' column for each increasing (wave-direction)-index
304 df_dir_bin_sorted['sy_cumsum'] = df_dir_bin_sorted['Sy'].cumsum()
305
306 # Check at what row-number (not index!) the cumulative sum-column reaches '1/bins'-th of the total
store these locations.
307
308 wt_wh_bin_borders = [ np.argmax(df_dir_bin_sorted['sy_cumsum'] > (sy_dir_bin*k / wt_hm0_bins))
in range(wt_hm0_bins+1) ]
309
310 # Find the corresponding index of these row numbers in the reduced (and sorted) dataframe
311 # The index in the reduced (and sorted) dataframe is the same index as in the original dataframe!
312 wt_wh_bin_indexes = df_dir_bin_sorted.index[wt_wh_bin_borders]
313
314 # -----
315 # STEP 4: PLOTTING AND EXPORTING 2D WAVE INPUT REDUCTION
316 # -----
317
318 # Loop through the wave height bins (between the bin borders)
319 for i in range((len(wt_wh_bin_borders)-1)):
320     # Getting the average of the wave height bins for all the parameters
321     array_dir.append(df_dir_bin_sorted['Th0'].iloc[wt_wh_bin_borders[i]:wt_wh_bin_borders[i+1]].mean())
322     array_wh.append(df_dir_bin_sorted['Hm0'].iloc[wt_wh_bin_borders[i]:wt_wh_bin_borders[i+1]].mean())
323     array_dd.append(df_dir_bin_sorted['DD'].iloc[wt_wh_bin_borders[i]:wt_wh_bin_borders[i+1]].mean())
324     array_fh.append(df_dir_bin_sorted['FH'].iloc[wt_wh_bin_borders[i]:wt_wh_bin_borders[i+1]].mean())
325     array_tm01.append(df_dir_bin_sorted['Tm01'].iloc[wt_wh_bin_borders[i]:wt_wh_bin_borders[i+1]].mean())
326
array_p.append((df_dir_bin_sorted['Tm01'].iloc[wt_wh_bin_borders[i]:wt_wh_bin_borders[i+1]].count())/n_t)
327
328
329 # Loop through the bin borders for plotting
330
331 # Plotting wave direction vs wave height
332 plt.plot(df_reset_dir['Th0'], df_reset_dir['Hm0'], ',', color='black')
333
334 # Plotting vertical weighted directional bin borders.
335 ## V-LINES: Start & End X: Th0-value of each directional-bin-borders.
336 ## V-LINES: Start Y: lowest value of waveheights in current directional bin.
337 ## V-LINES: End Y: highest value of waveheights in current directional bin.
338
339 plt.vlines(x=df_reset_dir['Th0'][wt_dir_bin_borders[j]] , ymin=df_dir_bin['Hm0'].min(),
ymax=df_dir_bin['Hm0'].max())
340 plt.vlines(x=df_reset_dir['Th0'][wt_dir_bin_borders[j+1]] , ymin=df_dir_bin['Hm0'].min(),
ymax=df_dir_bin['Hm0'].max())
341
342 # Plotting horizontal weighted directional bin borders.
343 ## H-LINES: Start X: Th0 of the left directional-bin-border.
344 ## H-LINES: End X: Th0 of the right directional-bin-border.
345 ## H-LIENS: Start & End Y: Hm0-value of each waveheight-bin-borders.
346
347 for y_coor in wt_wh_bin_indexes:
348     plt.hlines(y=df_reset_dir['Hm0'][y_coor], xmin=df_reset_dir['Th0'][wt_dir_bin_borders[j]],
xmax=df_reset_dir['Th0'][wt_dir_bin_borders[j+1]])
349
350 # Creating a dataframe from the averages_arrays to export it and for easier plotting.
351 columns = ["Wave Dir.", "Hm0", "Tm01", "Wind Dir.", "Wind Speed", "Chance of occurrence (p)"]
352 data = np.array([array_dir, array_wh, array_tm01, array_dd, array_fh, array_p])
353 # Optional: Add cell boundaries as row names?
354 # Columns = ["left boundary : right boundary"]
355 export_table = pd.DataFrame(data=data, index=columns)
356 export_table_transposed = export_table.transpose()
357
358 #pd.DataFrame(data=data, index=rows, columns=centres)
359 # Add the averages to the plot.
360 plt.plot(export_table_transposed['Wave Dir.'], export_table_transposed['Hm0'], '+', color='red')

```

```

361 plt.xlabel("Wave direction in degrees North [°]")
362 plt.ylabel("Wave height Hm0 [cm]")
363 plt.title(binned_wave_climate_name)
364
365 plt.savefig(save_location_figures + binned_wave_climate_name + ".jpg", dpi=100)
366 # %%
367 #export_table_transposed.sort_values(by=['Wave Dir.']).to_csv('wave_conditions_europlatform.csv')
368 export_table_transposed.to_csv(save_location_figures + wave_conditions_name_csv + '.csv', sep='\t')
369
370 # %%
371 # -----
372 # ADDITIONAL PLOTS
373 # -----
374
375 fig, (ax1, ax2, ax3, ax4, ax5) = plt.subplots(5)
376 fig.set_figheight(10)
377 fig.set_figwidth(10)
378 fig.suptitle(wave_reduction_name)
379
380 ax1.plot(df_merged['Th0'], df_merged['F_South'], '.', color='black', label='South directional factor')
381 ax1.legend(loc="best")
382
383 ax2.plot(df_merged['Th0'], df_merged['F_North'], '.', color='black', label='North directional factor')
384 ax2.legend(loc="best")
385
386 ax3.plot(df_merged['Th0'], df_merged['F_average'], '.', color='black', label='Average directional factor')
387 ax3.legend(loc="best")
388
389 ax4.plot(df_merged['Th0'], df_merged['Hss'], '.', color='black', label='$H^{2.5}$')
390 ax4.legend(loc="best")
391
392 ax5.plot(df_merged['Th0'], df_merged['Sy'], '.', color='black', label='Sediment Transport Proxy')
393 ax5.legend(loc="best")
394
395 plt.savefig(save_location_figures + wave_reduction_name + ".jpg", dpi=100)
396
397 # %%
398 # -----
399 # Plot wind- & wave rose Europlatform
400 # -----
401
402 ax = WindroseAxes.from_ax()
403 ax.set_xticklabels(['E', 'NE', 'N', 'NW', 'W', 'SW', 'S', 'SE'])
404 ax.bar(df_wind['DD'], df_wind['FH']*0.1, normed=True, nsector=36, opening=1.0, edgecolor='white')
405 ax.set_legend()
406
407 plt.title(windrose_name)
408 plt.savefig(save_location_figures + windrose_name + ".svg")
409
410 # %%
411 ax2 = WindroseAxes.from_ax()
412 ax2.set_xticklabels(['E', 'NE', 'N', 'NW', 'W', 'SW', 'S', 'SE'])
413 ax2.bar(df_merged['Th0'], df_merged['Hm0']/100, bins=np.arange(0,8,1), nsector=36, normed=True, opening=1.0, edgecolor='white')
414 ax2.set_legend()
415
416
417 plt.title(waverose_name)
418 plt.savefig(save_location_figures + waverose_name + ".svg")
419
420 # %%
421 # -----
422 # Sub-plots Europlatform
423 # -----

```

```
424 |
425 | fig, (ax1, ax2) = plt.subplots(2)
426 | fig.set_figheight(10)
427 | fig.set_figwidth(10)
428 | fig.suptitle(subplots_wavedata_name)
429 |
430 | ax1.plot(df_merged.index, df_merged['Hm0'], ',', color='black', label='Wave height')
431 | ax1.legend(loc="best")
432 |
433 | ax2.plot(df_merged['Th0'], df_merged['Hm0'], ',', color='black', label='Wave height')
434 | ax2.legend(loc="best")
435 |
436 | plt.xlabel("Wave direction in degrees North [°]")
437 | plt.savefig(save_location_figures + subplots_wavedata_name + ".jpg")
438 |
439 | #plt.plot(df_merged.index, df_merged['Hm0'], ',', color='black')
440 | #plt.xlabel("Wave direction in degrees North [°]")
441 | #plt.ylabel("Wave height Hm0 [cm]")
442 | #plt.title('Wave Europlatform, period ')
443 | # %%
444 |
445 | fig, (ax1, ax2) = plt.subplots(2)
446 | fig.set_figheight(10)
447 | fig.set_figwidth(10)
448 | fig.suptitle(subplots_winddata_name)
449 |
450 | ax1.plot(df_merged.index, df_merged['FH'], ',', color='black', label='Wind speed (0.1m/s)')
451 | ax1.legend(loc="best")
452 |
453 | ax2.plot(df_merged['DD'], df_merged['FH'], ',', color='black', label='Wind speed (0.1m/s)')
454 | ax2.legend(loc="best")
455 |
456 | plt.xlabel("Wind direction in degrees North [°]")
457 | plt.savefig(save_location_figures + subplots_winddata_name + ".jpg")
458 |
459 | #plt.plot(df_merged.index, df_merged['Hm0'], ',', color='black')
460 | #plt.xlabel("Wave direction in degrees North [°]")
461 | #plt.ylabel("Wave height Hm0 [cm]")
462 | #plt.title('Wave Europlatform, period ')
```

```

1 # %%
2 #####
3 #
4 #         Create .SWN SWAN files &         #
5 #         .bat batchfile for             #
6 #         (reduced) wave climate         #
7 #
8 #         Author: Detmar Dieleman        #
9 #         Last update: 23-03-2021       #
10 #
11 #####
12
13 import numpy as np
14 import pandas as pd
15 import os
16
17 ## INPUT FILES & FOLDERS
18 run_name = "1.Run_2019-2020"
19 wave_conditions_file = r"C:\Users\X\Google Drive\TU Delft\Master Thesis\Images, Graphs,
Tables\Results\Data analysis\Reduced wave climate Period 2019 - 2020 Location Europlatform.csv"
20
21 swan_install_location = r"C:\\Users\\X\\Google Drive\\TU Delft\\Master Thesis\\Model\\SWAN\\Old school
SWAN\\"
22 basefile_folder_location = r"C:\\Users\\X\\Google Drive\\TU Delft\\Master Thesis\\Model\\SWAN\\Old
school SWAN\\inputs\\Basefiles\\"
23
24 filename_grid_A = "Base_file_A.txt"
25 filename_grid_B = "Base_file_B.txt"
26 filename_grid_C = "Base_file_C.txt"
27
28 ## OUTPUT FILES & FOLDERS
29 save_location = r"C:\\Users\\X\\Google Drive\\TU Delft\\Master Thesis\\Model\\SWAN\\Old school SWAN\\"
+ run_name + "\\\"
30
31 if not os.path.exists(save_location):
32     os.makedirs(save_location)
33     os.makedirs(save_location + "/nests")
34     os.makedirs(save_location + "/output")
35     os.makedirs(save_location + "/SWNfiles")
36
37 # %%
38 df = pd.read_csv(wave_conditions_file, sep='\t', header=0, index_col=0)
39
40 # %%
41 save_name_runswan = swan_install_location + 'Runall'
42 with open('%s.bat' % save_name_runswan, "a+") as reset_runswan:
43     reset_runswan.truncate(0)
44
45 # Loop through all different reduced wave conditions
46 for i in range(len(df)):
47
48     # Open Base-file A
49     with open(basefile_folder_location + filename_grid_A, 'r') as file_in_A:
50         # Write Base-file A
51         data_A = file_in_A.read()
52
53         # 'Generate' a runnumber based on the variables to be used in the filenames
54         runnumber = 'D' + "{:05.0f}".format(df['Wave Dir.'][i]*100) + 'H' + "
{:03.0f}".format(df['Hm0'][i]*100) + 'P' + "{:03.0f}".format(df['Tm01'][i]*100) + 'S' + "
{:05.0f}".format(df['Wind Dir.'][i]*100) + 'WD' + "{:04.0f}".format(df['Wind Speed'][i]*100)
55
56         # Replace all placeholders with corresponding variables
57         data_A = data_A.replace(r'[windspeed]', str((df['Wind Speed'][i]*0.1).round(2)))
58         data_A = data_A.replace(r'[windir]', str(df['Wind Dir.'][i].round(2)))

```

```

59 data_A = data_A.replace(r'[dir]', str(df['Wave Dir.'][i].round(2)))
60 data_A = data_A.replace(r'[hs]', str((df['Hm0'][i]*0.01).round(2)))
61 data_A = data_A.replace(r'[per]', str(df['Tm01'][i].round(2)))
62
63 # Replace runnumber placeholder
64 data_A = data_A.replace(r'[runnumber]', runnumber)
65
66 # Define nest folder location
67 data_A = data_A.replace(r'[runmap]', run_name)
68
69 # Create output file with name based on variables
70 save_name_A = save_location + "SWNfiles\\" + 'A' + runnumber
71
72 # Save Base-File A
73 with open('%s.SWN' % save_name_A, 'w') as file_out_A:
74     file_out_A.write(data_A)
75
76 # Open Base-file B
77 with open(basefile_folder_location + filename_grid_B, 'r') as file_in_B:
78     # Write Base-file B
79     data_B = file_in_B.read()
80
81     # Replace all windspeed and winddirection placeholders
82     data_B = data_B.replace(r'[windspeed]',str((df['Wind Speed'][i]*0.1).round(2)))
83     data_B = data_B.replace(r'[windir]', str(df['Wind Dir.'][i].round(2)))
84
85     # Replace runnumber placeholder
86     data_B = data_B.replace(r'[runnumber]', runnumber)
87
88     # Define nest folder location
89     data_B = data_B.replace(r'[runmap]', run_name)
90
91     # Create output file with name based on variables
92     save_name_B = save_location + "SWNfiles\\" + 'B' + runnumber
93
94     # Save Base-File B
95     with open('%s.SWN' % save_name_B, 'w') as file_out_B:
96         file_out_B.write(data_B)
97
98 # Open Base-file C
99 with open(basefile_folder_location + filename_grid_C, 'r') as file_in_C:
100     # Write Base-file C
101     data_C = file_in_C.read()
102
103     # Replace all windspeed and winddirection placeholders
104     data_C = data_C.replace(r'[windspeed]',str((df['Wind Speed'][i]*0.1).round(2)))
105     data_C = data_C.replace(r'[windir]', str(df['Wind Dir.'][i].round(2)))
106
107     # Replace runnumber placeholder
108     data_C = data_C.replace(r'[runnumber]', runnumber)
109
110     data_C = data_C.replace(r'[runmap]', run_name)
111
112     # Replace [i] for .tab files with the wave condition number
113     data_C = data_C.replace(r'[i]', str(i))
114
115     # Create output file with name based on variables
116     save_name_C = save_location + "SWNfiles\\" + 'C' + runnumber
117
118     # Save Base-File C
119     with open('%s.SWN' % save_name_C, 'w') as file_out_C:
120         file_out_C.write(data_C)
121

```

```
122 | # Create the runswan.bat file. Fill with all 3 grids for every conditions.
123 | save_name_runswan = swan_install_location + 'Runall'
124 | with open('%s.bat' % save_name_runswan, "a+") as file_out_runswan:
125 |     file_out_runswan.write("call runswan.bat A" + runnumber + "\n")
126 |     file_out_runswan.write("timeout 10" + "\n")
127 |     file_out_runswan.write("call runswan.bat B" + runnumber + "\n")
128 |     file_out_runswan.write("timeout 10" + "\n")
129 |     file_out_runswan.write("call runswan.bat C" + runnumber + "\n")
130 |     file_out_runswan.write("timeout 10" + "\n")
```

```

1 # %%
2 #####
3 # #
4 #         Read SWAN .mat & .tab files, #
5 #         create UNIBEST .SCO files #
6 # #
7 #         Author: Detmar Dieleman #
8 #         Last update: 05-05-2021 #
9 # #
10 #####
11
12 import os
13 import scipy.io
14 import glob
15 import os
16 import pandas as pd
17 import numpy as np
18 import re
19
20 run_name = "1.Run_2013-2014"
21
22 ## INPUT FILES & FOLDERS
23 wave_conditions_file = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Images, Graphs,
Tables\Results\Data analysis\Reduced wave climate Period 2013 - 2014 Location Europlatform.csv"
24
25 tab_folder = r"C:\\Users\\detma\\Google Drive\\TU Delft\\Master Thesis\\Model\\SWAN\\Old school
SWAN\\" + run_name + "\\output\\"
26 raaien_file = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Model\UNIBEST\Raaien_RD_eind.csv"
27 tide_currents_file = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Model\UNIBEST\Tide
currents.csv"
28
29 ## OUTPUT FILES & FOLDERS
30 run_folder = r"C:\\Users\\detma\\Google Drive\\TU Delft\\Master Thesis\\Model\\UNIBEST\\UNIBEST
modellen\\" + run_name
31 sco_folder = r"C:\\Users\\detma\\Google Drive\\TU Delft\\Master Thesis\\Model\\UNIBEST\\UNIBEST
modellen\\" + run_name + "\\SCO files\\"
32
33
34 if not os.path.exists(run_folder):
35     os.makedirs(run_folder)
36     os.makedirs(sco_folder)
37 # %%
38 df_raaien = pd.read_csv(raaien_file, sep=';', header=0, index_col=None)
39
40 df_wave_cond = pd.read_csv(wave_conditions_file, sep='\t', header=0, index_col=0)
41
42 df_tide_currents = pd.read_csv(tide_currents_file, sep=';', header=0, index_col=0)
43
44 # %%
45 def atoi(text):
46     return int(text) if text.isdigit() else text
47
48 def natural_keys(text):
49     return [ atoi(c) for c in re.split(r'(\d+)', text) ]
50
51 # All tab-files in the tab_folder location. Important: sorted correctly by using natural keys
definition.
52 tab_files = [f for f in os.listdir(tab_folder) if f.endswith('.tab')]
53 tab_files.sort(key=natural_keys)
54
55 # Loop through each location (index in raaien-file)
56 for i in range(len(df_raaien)):
57
58     # First, create a .SCO file for each location and add the common lines (first 3)

```

```

59 save_name = sco_folder + str(df_raaien['Name'][i])
60 with open('%s.SCO' % save_name, 'w') as file_out:
61     data = "365      (Number of Days)" + "\n"
62     data += "[cond]      (Number of wave conditions)" + "\n"
63     data += "H0      Hsig      Tper      Alf      Duration" + "\n"
64     file_out.write(data)
65
66 wavecounter = 0
67 # Loop through all the .tab files in the folder
68 for file in tab_files:
69
70     # Define dataframe for each .tab file in folder, read the .tab file
71     importfile = tab_folder + file
72     columns = ['Hsig', 'Dir', 'Tm01', 'TPsmoo', 'Tm_10', 'Dspr', 'Depth', 'Watlev', 'Botlev', 'X-Windv', 'Y-
Windv', 'Wlen', 'dHs', 'dTm', 'Xp', 'Yp']
73     df = pd.read_csv(importfile, sep=r"\s+", names=columns, header=None)
74
75     # Get the number of the wave condition from the name of the .tab file
76     for s in file.replace('.', ' ').split():
77         if s.isdigit() == True:
78             wave_cond_num = s
79
80     # Find the chance of occurrence of that wave condition in the table, express in days per year
81     (*365) occur = df_wave_cond['Chance of occurrence (p)'][int(wave_cond_num)]*365
82
83     # Write to .SCO file in APPEND-mode
84     with open('%s.SCO' % save_name, 'a') as file_out_append:
85         # Check if the wave direction is directed off-shore (>90 degrees off), otherwise don't
86         add, since UNIBEST can't handle these
87         wave_check_norm = ((df['Dir'][i]-df_raaien['Orientation'].iloc[i]) %360)
88         wave_check_abso = np.minimum(360-wave_check_norm, wave_check_norm)
89
90         if wave_check_abso >= 90:
91             pass #print('OFF-SHORE DIRECTED: Wave direction: ' + str(df['Dir'][i]) + ', Raai: ' +
92             str(df_raaien['Name'].iloc[i]) + ', coastal orientation: ' + str(df_raaien['Orientation'].iloc[i]) )
93         else:
94             file_out_append.write(str(round(df['Watlev'][i],3)) + "      " + str(round(df['Hsig'
95             [i],5)) + "      " + str(round(df['TPsmoo'][i],3)) + "      " + str(round(df['Dir'][i],3)) + "      "
96             + str(round(occur,7)) + "\n")
97             wavecounter=wavecounter+1
98
99     # Add the two general current lines
100     with open('%s.SCO' % save_name, 'a') as file_out:
101         file_out.write("13      (Number of Tide conditions)" + "\n")
102         file_out.write("DH      Vgety      Ref. depth      Perc" + "\n")
103
104     # Loop through the tide currents in D3D-uitvoer file
105     for index, row in df_tide_currents.iterrows():
106         if index == df_raaien.index[i]:
107             with open('%s.SCO' % save_name, 'a') as file_out:
108                 file_out.write(str(row['DH']) + "      " + str(row['Vgety']) + "      " +
109                 str(df['Depth'][i]) + "      " + str(row['Perc']) + "\n")
110
111     # Rewrite the number of wave conditions, since some were removed based on wave angle. Otherwise
112     UNIBEST copies the last wave-condition X times.
113     with open('%s.SCO' % save_name, 'r') as file_in_replace:
114         data = file_in_replace.read()
115         data = data.replace('[cond]', str(wavecounter))
116
117     with open('%s.SCO' % save_name, 'w') as file_out_replace:
118         file_out_replace.write(data)

```

```

1 # %%
2 #####
3 #
4 #           D3D Tides to UNIBEST .SCO           #
5 #
6 #
7 #
8 #           Author: Detmar Dieleman           #
9 #           Last update: 23-04-2021           #
10 #
11 #####
12
13 import pandas as pd
14 import numpy as np
15
16 # INPUT
17 run_name = '9600'
18
19 file_velo = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Data\Tides\Base\velocity_" + run_name
20 + ".csv"
21 file_elev = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Data\Tides\Base\waterlevel_" +
22 run_name + ".csv"
23 file_angl = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Data\Tides\Base\angle_" + run_name +
24 ".csv"
25
26 raaien_file = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Model\UNIBEST\Raaien_RD_eind.csv"
27 # OUTPUT
28 output_folder = r"C:\\Users\\detma\\Google Drive\\TU Delft\\Master Thesis\\Data\\Tides\\"
29 # %%
30
31 # Get raaien info for raaien_file
32 df_raaien = pd.read_csv(raaien_file, sep=';', header=0, index_col=None)
33
34 df_velo = pd.read_csv(file_velo, sep=',', header=0, index_col=0)
35 df_elev = pd.read_csv(file_elev, sep=',', header=0, index_col=0)
36 df_angl = pd.read_csv(file_angl, sep=',', header=0, index_col=0)
37
38 # VARIABLES
39 raai_index = df_raaien.index[df_raaien['Name'] == run_name]
40 coast_normal = df_raaien['Orientation'][raai_index[0]] # Coastal normal for current tide-file. Look up
41 value in Raaien file.
42 threshold = 0.4 # Tidal threshold in m/s
43 max_bins = 16 # Maximum bin edges (= 2*bins for positive and negative values + 1) for 100 waves (=3000
44 max. wave conditions)
45
46 # Combine into one dataframe, assign column_names
47 df_merged = pd.concat([df_velo, df_angl, df_elev], axis=1)
48 df_merged.columns = ['velo', 'angl', 'elev']
49
50 # Remove the spin-up time (1 day, 24*3). Reset index. Define the total length.
51 df_merged = df_merged.iloc[72:,]
52 df_merged.reset_index(drop=True, inplace=True)
53 length = len(df_merged)
54
55 # Check if the point is increasing or decreasing in water elevation. Default = decrease, otherwise
56 check for increase.
57 df_merged['behv'] = 'decrease'
58
59 for i in range(len(df_merged)-1):
60     if df_merged['elev'][i+1] > df_merged['elev'][i]:
61         df_merged['behv'][i] = 'increase'

```

```

59 # Get the bin width from the min/max of the data and create the bins.
60 elev_min = df_merged['elev'].min()
61 elev_max = df_merged['elev'].max()
62
63 bin_array = np.linspace(elev_min, elev_max, num=max_bins, endpoint=True)
64
65 ## Filter the data
66 # Loop through the bin_array
67 for i in range(len(bin_array)-1):
68     # Find the indexes of the bin.
69     # Same height in bin AND same direction (in-/decreasing)
70     df_merged.loc[(df_merged['elev'] >= bin_array[i]) & (df_merged['elev'] <= bin_array[i+1]) &
(df_merged['behv'] == 'increase'), 'bin'] = str(i) + '_i'
71     df_merged.loc[(df_merged['elev'] >= bin_array[i]) & (df_merged['elev'] <= bin_array[i+1]) &
(df_merged['behv'] == 'decrease'), 'bin'] = str(i) + '_d'
72     # Alternative: df_merged.loc[(df_merged['elev'] >= bin_array[i]) & (df_merged['elev'] <=
bin_array[i+1]), 'bin'] = str(i) + '_i'
73     # Alternative: df_merged.loc[(df_merged['elev'] >= bin_array[i]) & (df_merged['elev'] <=
bin_array[i+1]), 'bin'] = str(i) + '_d'
74
75 # Group and average by the bins.
76 df_summary = df_merged.groupby(['bin']).agg(['mean', 'count'])
77
78 # Set default value for dir (-1 = south) and check where transport goes north (1)
79 df_summary['dir'] = -1
80 df_summary.loc[(df_summary['angl']['mean'] > coast_normal-180) & (df_summary['angl']['mean'] <
coast_normal), 'dir'] = 1
81
82
83 # Calculate the velocity
84 df_summary['velocity'] = df_summary['velo']['mean'].abs()*df_summary['dir']
85
86 # Calculate the chance of occurrence
87 df_summary['percentage'] = df_summary['velo']['count']/df_summary['velo']['count'].sum()
88
89 # Set column of summary dataframe to be equal to the means
90 df_summary['elevation'] = df_summary['elev']['mean']
91
92 # Reference depth is equal to the depth at the current location. Find reference depth in Raaien file.
93 # Find the depth of the current Raai
94 row_num = df_raaien.index[df_raaien['Name'] == run_name]
95
96 depth_val = df_raaien['Depth'][row_num[0]]
97
98 # Set the entire depth column to this value
99 df_summary = df_summary.assign(depth=depth_val)
100 print(df_summary)
101 # Make new export dataframe
102 df_export = df_summary[['velocity', 'percentage', 'depth', 'elevation']]
103
104
105 # Filter tides on the threshold value
106 df_export = df_export.drop(df_export[abs(df_export['velocity'])<threshold].index)
107
108
109 # Fill up the tides with dummy data, since 100% is always required
110 left_over = 1-df_export['percentage'].sum()
111 df_export.loc[-1] = [0, left_over, 0, 0]
112
113 # Export tide as name of Ray
114 df_export.to_csv(output_folder + 'Tide_' + run_name + '.csv', sep=',', header=False, index=False)

```

```

1 # %%
2 #####
3 # #
4 # CREATE .PRO FILES FROM .CSV #
5 # #
6 # #
7 # Author: Detmar Dieleman #
8 # Last update: 25-03-2021 #
9 # #
10 #####
11
12 import scipy.io
13 import glob
14 import os
15 import pandas as pd
16 import numpy as np
17 import re
18
19 ## INPUT FILES & FOLDERS
20 run_name = "1.Run_2013-2014_TEST1"
21 csv_file_raaien = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Model\Data\Onderhoud Maasvlakte
22 2\Raaien depth\BIP2013Q2.csv"
23
24 ## OUTPUT FILES & FOLDERS
25 pro_folder = r"C:\Users\detma\Google Drive\TU Delft\Master Thesis\Model\UNIBEST\UNIBEST
26 modellen\" + run_name + "\.PRO files\"
27
28 if not os.path.exists(pro_folder):
29     os.makedirs(pro_folder)
30
31 # Setup .PRO file
32 ref_coastline = 0
33 transport_boundary = -5
34
35 # %%
36 df_raaien = pd.read_csv(csv_file_raaien, sep=',', header=0, index_col=0)
37
38 # Find the unique name-values for the raaien in the file
39 raaien = df_raaien['Name'].unique().tolist()
40
41 for raai_num in raaien:
42     # Create a .PRO file for each raai
43     save_name = pro_folder + 'Location ' + str(raai_num)
44
45     # Filter the dataframe on the current raai_num, create new dataframe
46     df_cur_raai = df_raaien.loc[df_raaien['Name'] == raai_num]
47
48     # Force sort by index for current dataframe, reset index for use in calculations
49     df_cur_raai.sort_index(inplace=True)
50     df_cur_raai.reset_index(drop=True, inplace=True)
51
52     # Set the last X-coordinate (=last index*-2) as X-point dynamic boundary
53     x_point_dyn_bound = -2*(len(df_cur_raai)-2)
54
55     # Find first occurrence where depth = 0, set this X-value as the reference X-point coastline
56     value_coastline = df_cur_raai['RASTERVALU'] <= ref_coastline
57     x_point_coastline_index = next(iter(df_cur_raai.index[value_coastline].astype(int)), 'not exist')
58     x_point_coastline = x_point_coastline_index*-2
59
60     # Set the transport boundary
61     value_transport = df_cur_raai['RASTERVALU'] <= transport_boundary
62     x_point_transport_index = next(iter(df_cur_raai.index[value_transport].astype(int)), 'not exist')

```

```

62 x_point_transport = x_point_transport_index*-2
63
64 ### TEMPORARY, TESTING
65 print(str(save_name) + ', 0m NAP: ' + str(x_point_coastline) + ', x bound: ' +
66 str(x_point_dyn_bound) + ', -5m NAP at: ', str(x_point_transport))
67
68 # Write the first lines, add the variables
69 with open('%s.PRO' % save_name, 'w') as file_out:
70     data = " 1          (Code X-Direction: +1/-1 Landwards/Seawards)" + "\n"
71     data += str(x_point_coastline) + "          (reference X-point coastline)" + "\n"
72     data += str(x_point_dyn_bound) + "          (X-point dynamic boundary)" + "\n"
73     data += str(x_point_transport) + "          (X-point truncation transpor_CFSt)" + "\n"
74     data += " 1          (Code Z-Direction; +1/-1 Bottom-Level/Depth)" + "\n"
75     data += "0.0000          (Reference level)" + "\n"
76     data += " 3          (Number of points for Dx)" + "\n"
77     data += "X          DX" + "\n"
78     data += "0.0000          8.0000" + "\n"
79     data += str(x_point_dyn_bound/2) + "          8.0000" + "\n"
80     data += str(x_point_dyn_bound) + "          20.0000" + "\n"
81     data += " " + str(len(df_cur_raai)-1) + "          (Number of points for Profile)" + "\n"
82     data += "X          DEPTH (In any order)" + "\n"
83
84     file_out.write(data)
85
86     for i in range(len(df_cur_raai)):
87         file_out.write(str(i*-2) + "          " + str(-1*df_cur_raai['RASTERVALU'][i]) + "\n")
88
89 # %%

```

```

1 # %%
2 #####
3 # #
4 # Plot & Read .SCO files #
5 # #
6 # #
7 # Author: Detmar Dieleman #
8 # Last update: 07-05-2021 #
9 # #
10 #####
11
12 import os
13 import pandas as pd
14 import numpy as np
15 import matplotlib.pyplot as plt
16 import matplotlib.cm as cm
17 from matplotlib.pyplot import figure
18 from windrose import WindroseAxes
19
20
21 ## INPUT FILES & FOLDERS
22 run_name = "1.Run_2013-2014"
23 sco_folder = r"C:\\Users\\X\\Google Drive\\TU Delft\\Master Thesis\\Model\\UNIBEST\\UNIBEST modellen\\"
24 + run_name + "\\SCO files\\"
25
26 ## OUTPUT FILES & FOLDERS
27 save_location_figures = r"C:\\Users\\X\\Google Drive\\TU Delft\\Master Thesis\\Images, Graphs,
28 Tables\\Results\\SWAN\\Results SWAN per location\\" + run_name + "\\"
29
30
31 # %%
32 # All .SCO files in the sco_folder location
33 tab_files = [f for f in os.listdir(sco_folder) if f.endswith('.SCO')]
34
35 ## Loop through each file, get file_name (location name) and create dataframe
36 columns=['H0', 'Hsig', 'Tper', 'Alf', 'Duration']
37
38 # Loop through .SCO file
39 for file in tab_files:
40     importfile = sco_folder + file
41
42     # Create dataframe from .SCO file. Skip first 4 rows.
43     df = pd.read_csv(importfile, sep=r"\s+", names=columns, header=None, skiprows=[0,1,2,3])
44
45     # Only import wave conditions, not tides. Done by filtering on H0=0.0m, since number of wave
46     # conditions can vary based on wave angle.
47     #df = df.drop(df[df.H0 != '0.0'].index)
48
49     # Convert dataframe from string to float for calculation/processing
50     df = df.astype(float)
51
52     ##### PLOT WAVE ROSE #####
53
54     ## For the wave-rose: Repeat the wave conditions based on the chance of occurrence to get the
55     # realistic occurrence
56     # Create a new column for amount of times the wave conditions should be multiplied (round
57     (#Duration))
58     perc_onshore_waves = round(100*(df['Duration'].sum()/365))
59     df['multiply'] = round(df['Duration']*10)
60     df['multiply'] = df['multiply'].astype(int)
61
62     # Repeat each row based on the multiply value column

```

```
60 df = df.reindex(df.index.repeat(df['multiply']))
61
62 # Location name, without the .SCO part.
63 location_name = file.rsplit('.', 1)[0]
64
65 ax = WindroseAxes.from_ax()
66 ax.set_xticklabels(['E', 'NE', 'N', 'NW', 'W', 'SW', 'S', 'SE'])
67 ax.bar(df['Alf'], df['Hsig'], normed=True, nsector=36, opening=1.0, edgecolor='white',
bins=np.arange(0,5,1))
68 ax.set_legend()
69
70 plt.suptitle(str(run_name))
71 plt.title("Waverose SWAN-output at " + str(location_name) + ", " + str(perc_onshore_waves) + "%
onshore directed")
72 plt.savefig(save_location_figures + location_name + ".png")
73 plt.savefig(save_location_figures + location_name + ".svg")
74 plt.close('all')
```

```

1 # %%
2 #####
3 # #
4 # Plot Wave roses on map #
5 # #
6 # #
7 # Author: Detmar Dieleman #
8 # Last update: 06-05-2021 #
9 # #
10 #####
11
12 import numpy as np
13 import matplotlib.pyplot as plt
14 from mpl_toolkits.axes_grid1.inset_locator import inset_axes
15 import cartopy.crs as ccrs
16 import cartopy.io.img_tiles as cimgt
17
18 import windrose
19
20 from cartopy.io.shapereader import Reader
21 from cartopy.feature import ShapelyFeature
22
23 from matplotlib.offsetbox import AnnotationBbox, OffsetImage
24 from PIL import Image
25
26 ## INPUT FILES & FOLDERS
27 run_name = "1.Run_2013-2014"
28 save_location_figures = r"C:\Users\X\Google Drive\TU Delft\Master Thesis\Images, Graphs,
Tables\Results\SWAN\Results SWAN per location\\" + run_name + "\\"
29
30 ## OUTPUT FILES & FOLDERS
31 save_location_map = save_location_figures + "Wave rose map " + run_name
32
33 # %%
34
35 # Define the corners of the map plot
36 minx, maxx, miny, maxy = (53500, 62500, 435000, 447000)
37
38 # Set the projection as the RD_New/Amersfoort projection
39 proj = ccrs.epsg(28992)
40
41 # Set figure shape equal to A4-size
42 fig = plt.figure(figsize=(8.3/1.2, 11.7/1.2))
43
44 # Draw main ax on top of which the wave-roses are added
45 main_ax = fig.add_subplot(1, 1, 1, projection=proj)
46 main_ax.set_extent([minx, maxx, miny, maxy], crs=proj)
47 main_ax.gridlines(draw_labels=True)
48 main_ax.coastlines()
49
50 # Request the OpenStreetMap as baselayer.
51 request = cimgt.OSM()
52 main_ax.add_image(request, 12)
53
54 # Add the coordinates of the requested locations.
55 # TO DO: request locations directly from the Excel-sheet
56 name = ['200', '3000', '5200', '6400', '9000']
57 x = [61361.32028789907, 57825.586442191445, 56094.83857998719, 56063.048510478635, 56953.898093207 ]
58 y = [445667.65711699775, 445151.22427241, 443173.79203557986, 441285.7128791642, 438747.8144618873]
59
60 # For each location, retrieve the image, create an imagebox with a 0.1 level zoom and add the waveroses
61 for i in range(len(name)):
62     img = Image.open(save_location_figures + name[i] + '.png')

```

```
63     imagebox = OffsetImage(img, zoom=0.1)
64     imagebox.image.axes = main_ax
65     ab = AnnotationBbox(imagebox, [x[i], y[i]], pad=0, frameon=False)
66     main_ax.add_artist(ab)
67
68 # Plot handling and saving
69 plt.title('Modelled SWAN Wave roses for various locations')
70 plt.suptitle(run_name)
71 fig.savefig(save_location_map + ".jpg", dpi=400)
```

```

1 # %%
2 #####
3 #                                     #
4 #     Function:Interpolation from gridcell #
5 #     to coordinates from SWAN output    #
6 #                                     #
7 #     Author: Detmar Dieleman           #
8 #     Last update: 23-03-2021          #
9 #                                     #
10 #####
11 def get_grid(matrix_x, matrix_y, origin_x, origin_y, grid_dx, grid_dy, angle):
12     import numpy as np
13
14     # Create the return arrays
15     array_m = []
16     array_n = []
17
18     for i in range(len(matrix_x)):
19         x = matrix_x[i]
20         y = matrix_y[i]
21         x_o = origin_x
22         y_o = origin_y
23         alpha = np.radians(angle)
24
25         dx_grid = grid_dx
26         dy_grid = grid_dy
27
28         # Difference in x,y between point and origin: dx dy
29         dx = abs(x-x_o)
30         dy = abs(y-y_o)
31
32         # Distance between point and origin
33         s = np.sqrt(dx**2 + dy**2)
34
35         # Angle difference between point and turned axis  $\phi_{diff} = \phi - \alpha$ 
36         # Catch dx = 0: phi_diff= 0.5*np.pi if dx == 0
37
38         if dx == 0:
39             phi = 0.5*np.pi
40         else:
41             phi = np.arctan(dy/dx)
42         if x > x_o:
43             phi_diff = phi-alpha
44         elif x < x_o:
45             phi_diff = np.pi - phi - alpha
46         else:
47             phi_diff = 0.5*np.pi - alpha
48
49         # X and Y coordinates in tilted axis (m,n)
50         x_m = s*np.cos(phi_diff)
51         y_n = s*np.sin(phi_diff)
52
53         # Grid cell number (rounded down) (m,n)
54         m = np.floor(x_m / dx_grid)+1
55         n = np.floor(y_n / dy_grid)+1
56
57         array_m.append(m)
58         array_n.append(n)
59
60     return array_m, array_n

```

```

1 # %%
2 #####
3 # #
4 # Add tidal data to UNIBEST #
5 # wave climate .SCO #
6 # #
7 # #
8 # Author: Detmar Dieleman #
9 # Last update: 25-04-2021 #
10 # #
11 #####
12
13 import os
14 import pandas as pd
15
16 input_folder = r"C:\Users\X\Google Drive\TU Delft\Master Thesis\Model\UNIBEST\UNIBEST
modellen\SCO files\Waves_incl_Tides\1997_2020_MV2_methode\"
17 tides_folder = r"C:\Users\X\Google Drive\TU Delft\Master Thesis\Data\Tides\MV2\"
18
19 # Get the names of all the tidal files in the folder
20 tidal_files = [f for f in os.listdir(tides_folder) if f.endswith('.csv')]
21
22 # Open the .SCO file for the same Ray
23 for tidal_file in tidal_files:
24
25     # For each file in the tides_folder (not equal to all files in input-folder), create a dataframe.
26     column_names = ['Vgety', 'Perc', 'Depth', 'DH']
27     df_tides = pd.read_csv(tides_folder + tidal_file, sep=',', header=None, index_col=None,
names=column_names)
28     num_tides = len(df_tides)
29
30     # Get the number of the wave condition from the name of the .tab file
31     for s in tidal_file.replace('.', ' ').split():
32         if s.isdigit() == True:
33             raai_num = s
34
35     # Open the .SCO file & add the two general current lines
36     sco_location = input_folder + raai_num
37     print(sco_location)
38     with open('%s.SCO' % sco_location, 'a') as file_out:
39         file_out.write(str(num_tides) + " (Number of Tide conditions)" + "\n")
40         file_out.write("DH Vgety Ref. depth Perc" + "\n")
41
42     # Loop through the tide currents in the individual tide files
43     # Open the correct Tides-file based on the name
44     for index, row in df_tides.iterrows():
45         file_out.write(str(row['DH']) + " " + str(row['Vgety']) + " " +
str(min(19.000, row['Depth'])) + " " + str(100*row['Perc']) + "\n")

```