The effects of climate change on coastal management in the Hondsbossche Dunes

Analysis and modeling of aeolian sediment transport and dune growth

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by

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As a bachelor student in Civil Engineering, I came into contact with many subjects in the field. The subject of fluid mechanics, and the application of this subject in coastal areas, always stood out to me as particularly interesting and fun. Therefore, the choice for my Master studies in Hydraulic Engineering, and the specialization in Coastal Engineering was easily made. Because aeolian sediment transport is only lightly brushed upon during the courses at the university, I have had to start from scratch on this subject. Luckily, many concepts in aeolian sediment transport can be seen as analogous to the concepts used in hydrodynamic sediment transport.

I would like to thank my thesis committee members Prof. dr. ir. S.G.J. Aarninkhof, Dr. ir. S de Vries, Ir. P.M.G.J. Goessen and Ir. K.J. Reinders for helping me during the writing of this thesis, and for being willing to review my work. I would also like to thank Mark Broos, whom I've worked with during my internship at World Waternet in Amsterdam. He helped me come into contact with my now colleagues at HHNK, and thus helped me find this subject for my thesis work. Thanks to Petra Goessen for helping me on a near day-to-day basis at the office in Heerhugowaard, and thanks to Sierd de Vries for helping me out with modeling questions, and for lifting my spirit whenever I came by his office at the TU.

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Abstract

In 2003, it was established that the sea dike between Petten and Camperduin was insufficiently safe. To ensure the safety of the hinterland against flooding, this part of the Dutch sea defence system needed to be strengthened. During the design process, the most favourable variant was to construct a dune and beach system in front of the sea dike, which was constructed soon after, and finished in 2015. This changed the 'hard' sea defence to a 'soft' one, linking the beaches and dunes in the north and south with each other. Thereby not only increasing the safety of this part of the coast, but also providing a new area reserved for recreation and nature.

The change from a hard to a soft coastal system fundamentally changes the characteristics of the area. Where the old sea dike was a static structure, the newly constructed sandy beach and dune system is very dynamic in nature. The change in properties of this coastal defence stretch brings the question how the HD (Hondsbossche Dunes) can best be maintained to ensure its functions as a sea defence now and in the future. The answer to this question requires insight in the processes relevant to aeolian sediment transport in general, and for the HD in specific. With the knowledge of what processes are important for coastal dune growth in the HD, a model can be selected to make predictions on the likely development of the HD in the future.

Aeolian sediment transport, much like hydrodynamic sediment transport, can be described as a balance between forcing and resistance against forcing. The most important factors which govern the dynamics of dune growth as a consequence of aeolian sediment transport are: wind speed and direction, grain size, humidity, sediment availability, beach slope, and vegetation. Especially vegetation (marram grass) is important, as it stabilizes the dunes with its roots and rhizomes below ground, and by locally decreasing the wind velocity with the biomass above ground. The above ground component of the marram grass not only stabilizes the present sediment, it also accommodates a sheltering effect for any incoming sand grains. Dune growth rate is the sum of incoming and outgoing aeolian sediment transport rates. For a healthy dune system, this must be a positive value, as this process negates the effect of dune erosion as a consequence of storm events.

In the period between 2015-2018, positive dune growth rates have been observed. An alongshore dune growth velocity gradient has been found, with the highest growth rate being in the south. This is due to a combination of difference in vegetation health (being poorer in the north), and the orientation of the dunes in relation to the average wind direction (more onshore directed in the south). The dune growth rate has decreased over time, but has remained positive over the regarded period. This is due to the eroding beach, which decreases the sediment availability for aeolian transport. Another factor is the coarsening of the average grain size as a consequence of aeolian transport on the constructed coast, increasing resistance to aeolian transport. This largely explains the decreasing growth rates of the dunes, along with the fact that beach armoring starts to develop in the HD after construction.

The cellular automaton model DuBeVeg, developed at the University Wageningen, is used to model aeolian sediment transport, and the effect of vegetation in the HD. This model is chosen over other models like AeoLiS and Aeolus, as DuBeVeg is capable of modeling vegetation growth both in surface area and effectiveness against erosion as a result of vegetation density. Several improvements have been made to the model. Non-erodible elements have been implemented, which allows the user to model the effects of the presence of objects such as the old sea dike behind the dunes, or pavement on top of the dunes. Mass balance has been implemented in the model, with an option to define a sediment flux in the marine area of the model as a consequence of cross-shore and/or long-shore sediment transport. A dynamic erosion profile on the beach is implemented, based on the erosion profile of Vellinga. Climate change in the form of sea level rise and changes in wind velocity have been modeled.

Sea level rise affects aeolian transport rate and coastal dune development by influencing the sediment availability on the beach. Higher water levels increase the reach of hydrodynamic processes, which result in higher beach erosion rates. To ensure sediment availability for aeolian sediment transport, nourishments are an effective measure. Higher sea level rise asks for a shorter interval between nourishments to ensure sediment availability. Higher and lower wind velocities generally result in higher

and lower aeolian sediment transport rates respectively. Higher aeolian sediment transport rates don't necessarily result in higher dune growth rates, as the stabilizing effect of vegetation against aeolian erosion must be present to prevent aeolian transport out of the dune area. Marram grass has an optimum accretion rate at which the plant grows best, and therefore stabilizes the dune most efficiently at this dune growth rate. Therefore, an optimum dune growth rate exists.

To ensure the HD can maintain its functions as a sea defence, nature reserve and recreational area, it is important for the dunes to grow under average conditions. To ensure this, sediment needs to be available on the beach which is ready for aeolian sediment transport toward the dunes. Enough vegetation needs to be present on the dune surface to protect the dunes against aeolian erosion by sheltering, lowering the local wind velocity at the surface. Thereby inhibiting aeolian transport in the dune itself. The sediment availability can be ensured by nourishing the beach or foreshore. The presence of enough healthy vegetation can be ensured by providing the right abiotic conditions for the vegetation to thrive. Increasing the biodiversity in the area makes the HD more robust to changes in the climate, such as sea level rise and changing wind climates which results in different rates of accretion in the dunes.

Increasing the biodiversity enhances the HD's other functions as a nature reserve and recreational area as well. Biodiversity helps with the robustness of the ecosystem, and makes the area more enjoyable for recreational purposes. The nourishments ensure the presence of a wide beach, ensuring enough room is available for a recreational day on the beach.

Contents

List of symbols

Symbol	Description	Units
A	Surface area	[m^2]
C_{grad}	Coefficient relating to the grain size distribution	[-]
$C_{Shields}$	Shields parameter	[-]
D	Reference grain diameter	[m]
d	Actual grain diameter	[m]
H_0	Deep water wave height	[m]
h_s	Slabheight	[m]
g	Gravity acceleration	[m/s^2]
k	Bed roughness	[m]
k'	Ripple factor	[m]
L_0	Deep water wave length	[m]
L	Jump length	[m]
n	Iterations per year	[-]
p_d	Deposition probability	[1/iteration]
p_e	Erosion probability	[1/iteration]
Q	Aeolian transport rate	[m^3/m/year]
q	Aeolian transport rate	[kg/m/s]
$R_{2\%}$	2 percent max wave run-up	[m]
u_*	Friction velocity	[m/s]
u_t	Threshold velocity	[m/s]
u_{t*}	Threshold friction velocity	[m/s]
u_z	Wind speed at height z	[m/s]
z	Height above bed	[m]
α	Conversion factor between wind velocity above the bed to shear velocity at the bed	[-]
β_f	Foreshore slope	[-]
ρ_a	Density of air	[kg/m^3]
ρ_s	Density of sand	[kg/m^3]
τ	Shear force	[N/m^2]

1 Introduction

The province of North-Holland in the Netherlands is protected from the sea by natural defences like dunes, and man-made defences like dikes. The coastal area between Petten and Camperduin however, is protected by man-made dunes in front of an old sea dike. The area is called the Hondsbossche Dunes (HD), after the old sea dike the 'Hondsbossche Pettemer Zeewering' (HPZ). See figure 1.1.

(a) Hondsbossche Pettemer zeewering (b) Hondsbossche dunes

Figure 1.1: Comparison of the Hondsbossche Dunes area before and after construction

In 2004, the old dike had been found to be insufficiently safe to protect the hinterland. The design process took many factors in consideration in addition to safety against flooding. Interests like nature preservation and recreational activities ended up being factors in the design considerations. The end result is a multifunctional design which provided safety against flooding, room for nature development, and recreational areas.

Construction of the HD started in 2014. Large quantities of sediment were dredged from various locations in the North Sea. The locations were selected on the basis of location, quality of the sediment (e.g. shell content) and grain size. Though the locations of dredge sites was also influenced by other things, such as the encounter of unexploited explosives on the sea floor during construction. As a result of natural variation and differing dredging locations, the median grain size used in the construction and maintenance nourishment of the Hondsbossche Dunes varies in cross shore and alongshore direction.

The dunes and beach are subject to forcing in the form of wind and waves. These forces can both cause sedimentation and erosion, depending among other things, on the magnitude and direction of the forces, the properties of the sediment, vegetation and topography of the area. This dynamic system therefore fluctuates in the amount of sediment it contains, which partly determines the safety the system provides against flooding of the hinterland. Adding to these natural fluctuations, human interventions play a role in the developing topography of the HD as well. Bicycle and footpaths are maintained, and meeting places like the pavilions in the north and south end of the HD are voided of sand to maintain their functions.

When the HD contain too little sediment to provide adequate safety against flooding, sediment can be added to the system. For the water board it is important to understand what will happen to the HD on the long term (~50 years), during and after a storm, and what will happen to the HD when a nourishment cannot be carried out. The nourishments can be part of regular maintenance works, or repair works after a storm event. In the case of maintenance works, it is important for the contractor to know the time intervals in which the work needs to be in order to make efficient management plans for the area.

After storm events, the dynamic system may or may not be able to recover on its own. Though in the design of the HD, overall erosion is expected, and regular nourishments are part of the design. In general, interventions like nourishments are unfavorable for natural systems, as it disrupts the ecosystems located on the seafloor where the sand is dredged, and the location where this sediment is placed. On the long term however, the flora and fauna in the HD area is helped by the added sediment in the beach and dunes. As without the nourishment, there wouldn't be a dune and beach system between Petten and Camperduin to begin with. In addition, the HD connects the beaches on the north and south side of the area together, forming a link between these two coastal areas. Thereby not only increasing the total area of this coastal area type, but also forming one large coastal stretch. This is a positive development for nature development. On top of that, the dynamic nature of the dunes makes it possible to grow the sea defense more easily with sea level rise compared to hard sea defenses like the old sea dike. By simply adding sediment to the area.

The water board Hoogheemraadschap Hollands Noorderkwartier (HHNK) is responsible for the safety the HD system provides against flooding. Concretely this means HHNK makes sure there is a sufficient amount of sand above the calculated water depth of the design storm (once every 3.000 years). However, the measures HHNK employs to ensure the safety aren't limited to the area above this water line. The measures include the placement of screens, extra vegetation and nourishments on the beach or foreshore (though the foreshore nourishments are the responsibility of Rijkswaterstaat (RWS)).

1.1. Functions of the Hondsbossche Dunes

As introduced in the section above, the HD has three main functions. It serves as a protection from the sea, as a nature reserve, and a recreational area. These different functions result in different requirements for the HD to function well. The requirements for each function are described below.

1.1.1. Sea defence

The function as a sea defence, which is arguably the most important, or main function, requires a certain minimum amount of sand in the dunes. The amount of sand acts as a buffer against dune erosion during storm events, and it is expressed in m^3/m in long shore direction. This minimum required amount of sand in the dunes has to be maintained, and is actually mandated by Dutch law, and depends on the design storm and local topography.

Vegetation on the dunes improves the stability of the sea defence. Therefore, healthy vegetation and a high amount of vegetation coverage are important factors for the functioning of the HD as a sea defence. A fast growing and common species of dune vegetation is marram grass. This species is abundantly planted in the HD, as it can grow up to a meter per year, stabilizing incoming wind transported sand in the process.

1.1.2. Nature reserve

Important factors for a nature reserve is the variety in flora and fauna, or the amount of different plant and animal species. The amount of animal and plant species can be increased by improving the quality of the abiotic conditions in the HD. These abiotic conditions include the amount of fresh, salt, and brackish water in the dunes, rainfall, sunshine, wind exposure temperature and soil composition. Parts of the HD are closed off to the public, in order to protect the vegetation and animals. This allows the plants to grow, and animals like birds to be able to rest, feed and breed. To help the nature reserve in its function, the contractor has included in the contract that no nourishments will be carried out in the nature zone reserves for the first period after construction.

1.1.3. Recreational area

The HD is a recreational area where people go to the beach and swim in the sea. There also are foot and bicycle paths for people to walk and cycle through the dunes themselves. These paths can become covered in sand during sand due to wind driven sand transport, causing these paths to be difficult to navigate, see figure 1.2.

Figure 1.2: Buried bicycle/footpath in the Hondsbossche Dunes as a result of high velocity onshore directed winds. Hondsbossche dunes, 3-2-2016 [Fortuijn and Van Egmond, 2018]

For recreation on the beach of the HD, a certain minimum width and maximum slope of the foreshore is desirable. This ensures an attractive area for people to recreate, and gives an opportunity for an economical boost in the area. In the contract with the contractor, a minimum beach width of 50 meters is established. This width will be maintained by nourishing the beach as needed [Bakker, 2015].

1.2. Design

The HD was designed by the contractors Boskalis and Van Oord. In total, the HD consists of 35.000.000 m^3 of sand, including a buffer of 9.200.000 m^3 of sand which is placed to postpone the need for maintenance suppletions. The design of the HD isn't uniform in the alongshore direction. Five different profiles have been designed for the HD area which are presented in the figures below. The location of the boundary between these two profile types is somewhat arbitrary, as all profile types gradually morph into each other in alongshore direction.

Profile type 1- Lookout dune

This dune profile is located in the north of the HD, near Petten. The main feature of this dune is the lookout dune, which has its highest point at NAP +26.20 m. It is the highest point in the whole project area, and with a slope of 1:1.70, this profile also has the steepest slope of the HD. The main reason for this high point is for recreational use, providing sights for tourists and locals alike.

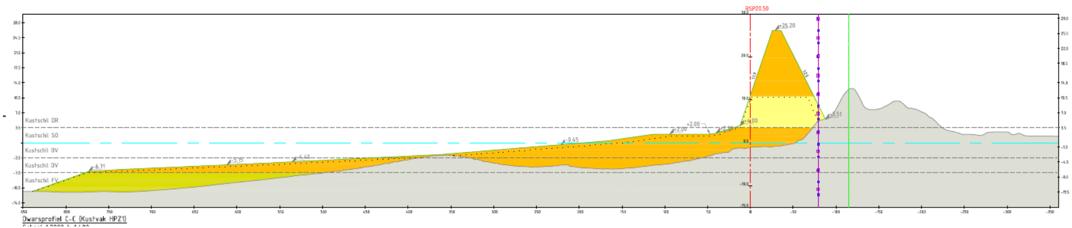


Figure 1.3: Dune profile 1 [Leenders and Smit, 2016].

Profile type 2- High dunes

This profile type is found just south of the lookout dune, and just north of profile 5, the lagoon. It consists of a single dune row, which is relatively constant in profile when compared to natural dunes. The highest point in this profile lies at NAP +12.50 m, and a dune slope of 1:2.10. Vegetation has been planted on the dune crests and slopes. Next to the main use of being a sea defence, this profile, just like all other profiles, contains a bicycle path, footpath and a horse track for recreational use.

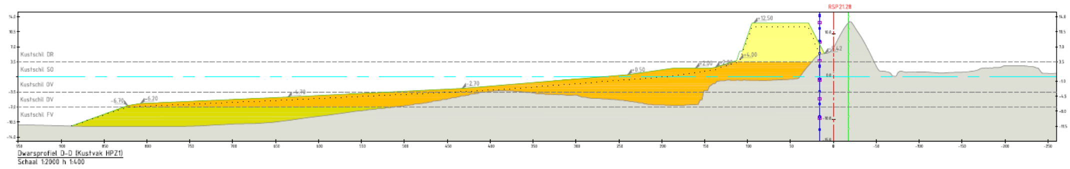


Figure 1.4: Dune profile 2 [Leenders and Smit, 2016].

Profile type 3- High dunes with fore dune

This profile type is connected to the high dunes without fore dunes. The highest point in this profile type is found at NAP +10.00 m and a slope of 1:1.8, with the fore dune at NAP +5.50 m and with a slope of 1:4.

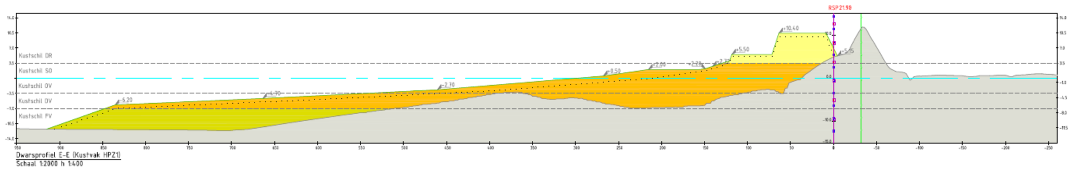


Figure 1.5: Dune profile 3 [Leenders and Smit, 2016].

Profile type 4- Dune valley

The dune valley is found in the middle of the HD, and is jammed in between the areas where profile type 3 is found. This profile consists of two dune rows, with a valley in between which contains open water. The landward dune row is a continuation of the dune rows found in the other profiles, and consist of a main crest and a to the seaward side. The highest point of this dune row is at NAP +11.00 m, and a slope of 1:1.1. The seaward dune is a continuation of the fore dune found in profile type 3. The highest point is at NAP +6.00 m, with a more gentle maximum slope of 1:3.

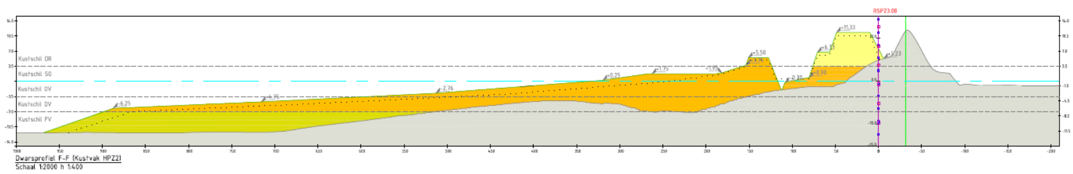


Figure 1.6: Dune profile 4 [Leenders and Smit, 2016].

Profile type 5- Lagoon

The lagoon is located at the southern most end of the HD. It consists of a constructed dune row in front of natural dunes, with a lagoon in between. The constructed dunes have a height of NAP +5.00 m, with a slope of 1:2.

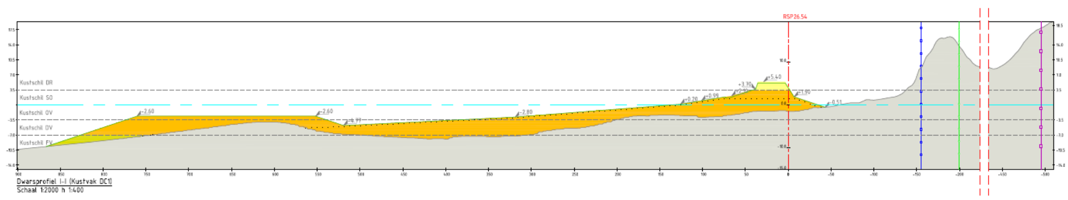


Figure 1.7: Dune profile 5 [Leenders and Smit, 2016].

Maintenance

The contractors maintain the HD for 20 years after construction has finished. During this period, three maintenance events are planned as shown in table 1.1.

	Time after completion [years]	Recreation zones [Mm^3]	Nature zones [Mm^3]	Total [Mm^3]
Nourishment I (2023)	8	1.6	0.0	1.6
Nourishment II (2026)	11	0.0	1.5	1.5
Nourishment III (2030)	15	1.1	0.0	1.1
Total		2.7	1.5	4.2

Table 1.1: Planned nourishments of the original design application of Van Oord and Boskalis.

Together with the buffer of 7.0 Mm^3 of sand, a total of 11.2 Mm^3 of sand has been incorporated in the design to counteract the effects of erosion. But practice has proven this planning to be insufficient, as will be apparent in the problem definition of this thesis.

1.3. Problem definition

Because the HD is a morphologically dynamic system with its development depending on many factors, it is hard to predict the system's response to climatic forcing. This can cause many problems for the management of the area. For example, after its construction had been finished in 2015, the first nourishment was on the beach face planned for 2023. However, the first nourishment is being carried out at the time of writing this document (March 2018, 5 years earlier than planned). Though the nourishment was necessary to maintain the minimum beach width, not the dunes in the HD, this still indicates that accurate predictions regarding the morphology and growth of the HD isn't available.

1.4. Goal & research questions

The goal of this thesis is to be able to make more efficient maintenance and management plans for the HD. Aeolian processes which govern the dynamics of the HD must be better understood to be able to make mid, to long term prediction on the behaviour of the HD system. The intended result of this thesis is to develop a model which provides insight in the relevant processes and factors which govern the development of the HD. The model is also able to predict the likely growth or decline of the dunes in the HD area under different circumstances. The insight, and the predictions this model offers can then be used to improve the efficiency of management plans of the HD, and possibly provide mitigating measures after a storm event which has damaged (part of) the HD. From this goal, the main question follows:

- How can the HD system best be maintained to ensure its functions as a sea defense now and in the future?

With the associated sub-questions:

- What are the main processes which govern the long term growth and decline of coastal dunes?
- What types of models for dune development are available, and what are the main differences and commonalities regarding their operation, input, output and performance?
- What is the added value of improving or coupling models, and if it's worth it, how can these models be improved or coupled to produce a model which accurately predicts the behavior of the HD?
- What processes with their associated parameters have the biggest influence on the behavior of the HD?

1.5. Project scope

The spatial scope of this thesis is from Camperduin to Petten (see figure 1.8), and the HPZ to the water line (see figure 1.9). This excludes profile type 5 (the lagoon), as in this area marine processes are the more dominant type of forcing. This demarcation only includes the area of the HD where aeolian processes and its associated factors are dominant. The focus of this thesis in on the dunes in the HD system, which have been defined as above the level NAP +3.50 m [Olijslagers and Bakker, 2015]. Hydrodynamic processes also have a large influence on the HD, these influences are taken into account, but aren't considered in great detail. The inter tidal zone is a grey area, as this can both act as part of the aeolian subsystem and the hydrodynamic subsystem.

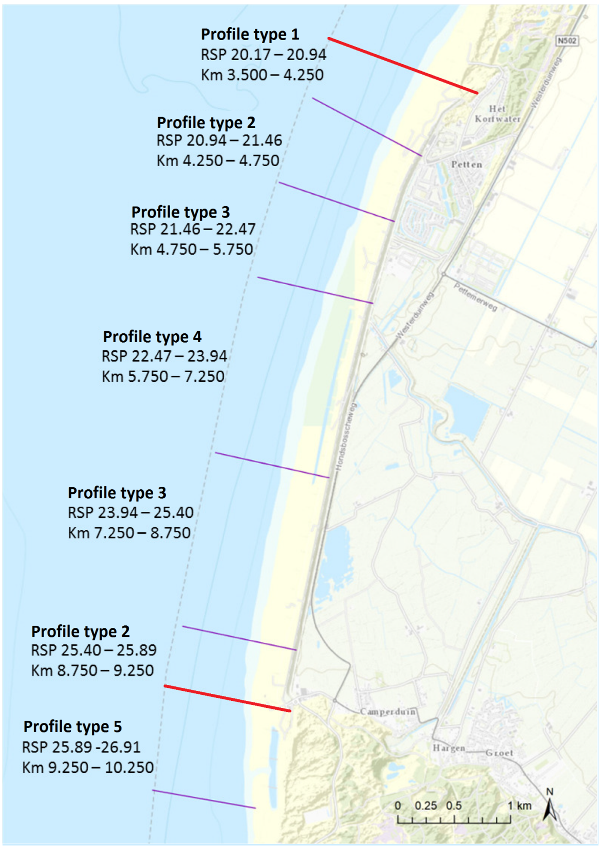


Figure 1.8: Aerial view of the HD, with along shore domain borders indicated in red.

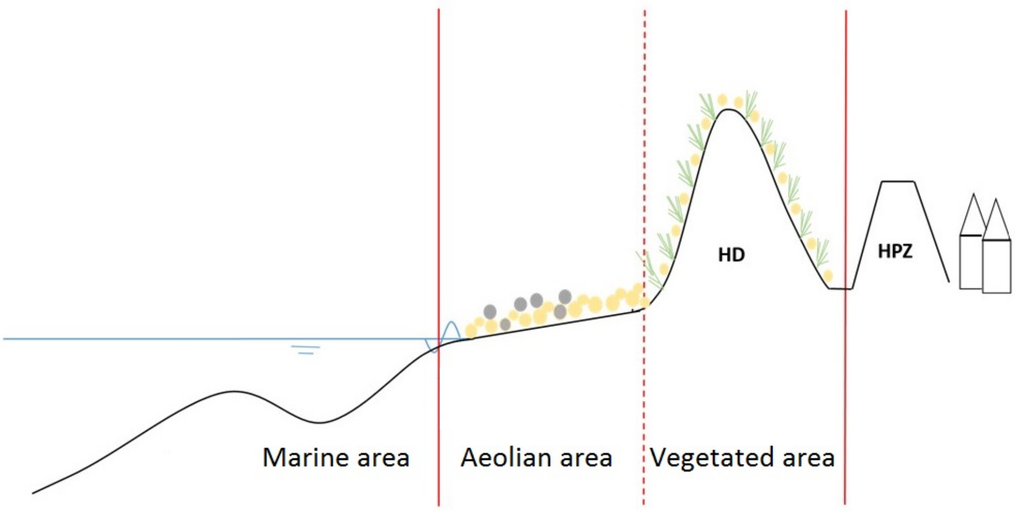


Figure 1.9: Cross shore schematization of the HD.

The temporal scope of this thesis is from the completion of construction (2015) to 50 years into the future (2065). Data from the historic temporal scope will be used to make statements on the HD in the future temporal scope.

Aeolian processes is the main focus if this thesis. Processes which influence aeolian sediment transport are taken into account, which will be discussed in chapter 2. Hydrodynamic processes are taken into account, but not in great detail. Meaning that the consequences of hydrodynamic processes are quantified, which have an effect on aeolian sediment transport.

1.6. Thesis outline

The general outline of this thesis is given below:

- **Introduction** The introduction contains the history of the Hondsbossche-Pettemer zeewering, and its transition into the Hondsbossche Dunes. This chronological story introduces the considerations which have led to the decisions that have been made in the area.

  The goal, problem definition, research questions and project scope (including the topics which won't be part of the thesis report) are also introduced in this section.
- **Literature study** The relevant physical processes in dune growth and decline are introduced and discussed in this section.

  The various available numerical models which model (part) of a coastal dune system are introduced and discussed regarding method of calculation and accuracy. A choice of model(s) is made as a conclusion to this section.
- **Method** In the method, the general approach of the data analysis and the model study is discussed. This includes spatial and temporal definitions used in both the data analysis and model study
- **Results** The results of the data analysis and model study as described in the Method section is discussed.
- **Discussion** The approach and results of this study are reflected on, and issues which could have (easily) been done better are discussed.
- **Conclusion** A summary of all conclusions in this report is given, including advice on maintenance and management. Adding to this, a transfer of data and a short manual of how to use the intended product of this thesis.

2

Literature study

Coastal dunes are dynamic systems which are highly reactive to outside forcing. The main constructive force is aeolian sediment transport, and the main destructive force is wave attack from the sea. This premise isn't entirely true, as these forces have a dual nature. Aeolian forcing can also have the opposite effect on dune development, and waves can indirectly cause dunes to grow. In this chapter, the overall process of dune development is introduced, and the characteristics of aeolian sediment transport and the effect of vegetation is discussed. The main questions of this chapter are:

- What are the main processes which govern the long term development of coastal dunes?
- What types of models for dune development and sediment transport are available, and what are the main differences and commonalities regarding their operation, input, output and performance?
- What is the added value of coupling models, and if it's worth it, how can these models be coupled to produce a model which accurately predicts the behavior of the HD?

2.1. Aeolian sediment transport

Aeolian sediment transport is the transport of sediment caused by wind forcing. The wind is characterized by its speed, turbulence (fluctuations of the wind speed) and direction. This process of aeolian sediment transport can be divided in three main stages, which are in order:

1. Initiation of motion
2. Transport
3. Deposition

In idealized coastal dune growth, sediment is supplied in the inter tidal zone by hydrodynamic processes. During low tide, the newly available sediment dries up, and motion is initiated by wind forcing and is transported in cross shore direction toward the dunes. After transport over the beach, the sand is deposited in the vegetated dune area which then grows in volume.

In reality however, start of motion, transport and deposition occurs in all coastal zones indiscriminately. Wind speed and direction isn't constant, causing sand particles in motion to settle on the beach, get picked up again, move in alongshore direction or the particles are transported back to the sea. It is therefore important to be able to describe these processes and the wind forcing accurately, regardless of their location.

In this section, first the forcing is discussed, and then the three stages of aeolian sediment transport.

2.1.1. Wind forcing

Wind exerts a shear force on sediment, which can cause the sediment to move if its magnitude is large enough. The shear force can be rewritten in the form of a velocity (see equation 2.1), which is called the friction velocity. This friction velocity cannot be measured in a particular location at or above a sand grain, but it is useful in describing shear forcing of wind on sand grains.

$$u_* = \sqrt{\frac{\tau}{\rho_a}} \tag{2.1}$$

where:

τ	=	shear pressure	[N/m2]
ρ	=	density of air	[kg/m3]
u_*	=	friction-, drag- or shear-velocity	[m/s]

The shear velocity isn't easily determined using equation 2.1. A more easily applicable approach of determining the shear velocity is proposed by Bagnold. The wind speed at a certain height, and the roughness of the bed (i.e. a measure of grain size in the case of a sand bed) are needed for the calculation with the following formula [Bagnold, 1941]:

$$u_z = 5.75 u_* log \frac{z}{k} \tag{2.2}$$

where:

k	=	bed roughness	[m]
u_z	=	wind speed at height z	[m/s]
z	=	height above bed	[m]

This relation is based on the fact that the drag velocity is directly proportional to the rate of increase of the wind velocity with the log-height [Bagnold, 1941]. The drag velocity and the log-height have a linear relation, which was found to be a factor of 5.75. Together with the density of air, this formula can be used with formula 2.1 to determine the shear force on any given surface.

2.1.2. Initiation of motion

Motion of sediment starts when the driving force exceeds the resisting force of the sand grain in magnitude in a certain direction. The initiating force in aeolian sediment transport can be the wind itself, which is comparatively continuous. It can also take the form of transmission of kinetic energy, which is more incidental in nature. The impact of other grains of sand, animal and human activity are all examples of forces which can initiate motion. Once motion has started, it tends to keep going downwind as a result of the chain reaction of grains impacting other grains.

Because of the long downwind dimensions in the case of alongshore aeolian sediment transport, incidental, or infrequent, initiation of motion is enough to maintain a steady alongshore aeolian sediment transport situation. Initiation of motion in alongshore aeolian sediment transport is a less important criterion for this reason. But in the case of cross shore aeolian sediment transport (which is the main focus of this report), this criterion is very important. Therefore it is important to understand the initiation of motion in aeolian sediment transport when studying coastal dune development.

As explained in the previous section, wind exerts a shear force on the sand grains. When this force is high enough, motion is initiated. The wind forcing must exceed a threshold value, which is expressed in the quality of a shear velocity. The following expression relates the density of the air and sand and the grain size to the shear velocity threshold.

$$u_{*t} = C_{shields}\sqrt{\frac{\rho_s - \rho_a}{\rho_a} gd} \tag{2.3}$$

In which u_{*t} is the threshold velocity, $C_{shields}$ is an empirical coefficient based on the shields equation, ρ_s & ρ_a are the densities of the sand and air respectively, g is the gravitational acceleration, and d is the diameter of the sand grain.

This equation describes the initiation of a certain sand grain diameter. Though in reality, bodies of sand rarely consists of sand with a single grain size. Other factors such as water content and local topography are also limitation which aren't described in this formulation. These effects are described below.

Beach armoring
The larger the grain diameter, the higher the shear velocity threshold to initiate motion. A situation where the top layer of the beach consists of relatively coarse material, which prevents finer materials below it to start moving. This is called an armored beach, and this effect directly influences the sediment availability in aeolian sediment transport.

Beach armoring occurs when a beach consists of heterogeneous materials. Wind forcing erodes the finer particles away, while the coarser elements remain in their location. This coarser material can be larger grains of sand, but it can also be made up of shells or other large particles with a comparable density to the surrounding sand.

Moisture
Dry sand particles don't cohere to each other, but wet sand particles do. This extra resisting force increases the threshold of motion of sand particles. Moisture can be found in the form of precipitation, surface water, and groundwater.

Precipitation and surface water inhibit the movement of sand particles at the surface. Groundwater can do the same, but the groundwater level needs to be high enough for the surface to be in the capillary zone. The shear velocity threshold of dry sand can be described accurately by formula 2.3.

Beach slope
The formula above assumes a flat bed. In reality however, a beach is never completely flat. A slope upward in downwind direction increases the shear velocity threshold, as the slope introduces more friction between the sand grains.

2.1.3. Transport

Once initiation of motion of the sand particles has set in, the actual transport of the grains has started. The transport of these grains comes in three basic modes depending on the ratio of the forcing by the wind, and the resisting forces of the sand grain. These modes are suspended transport, saltation and surface creep. See figure 2.1 for clarification. These transport modes will be discussed in detail in the following subsections, as well as the transport formula relevant to the Hondsbossche Dunes.

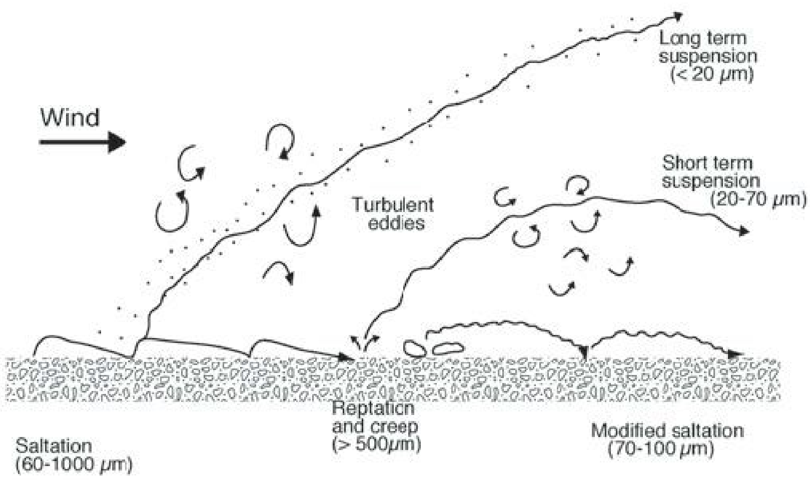


Figure 2.1: Modes of aeolian sediment transport. [Lancaster, 2009]

Suspended transport
Suspended aeolian transport is the transport of sediment through the air. Long term suspension, traveling over tens of kilometers, is associated with very small grain sizes (<20 μm [Lancaster, 2009]). Short term suspension, traveling hundreds of meters, is associated with slightly larger grain sizes (20-70 μm [Lancaster, 2009]). Both of these grain sizes can be regarded as silt. In the context of coastal

dune development, this transport mode isn't very relevant because the grain sizes associated with this transport mode don't manifest themselves in these areas. Also, the travel distances are so great, that the sand particles are likely to travel over the dunes, and out of the system during a single suspended transport event.

Saltation
Saltation is the transport of sediment through the air over small distances before coming returning to the bed. This transportation mode occurs when the grain size is too large for the wind to keep the sediment in the air (70-1000 µm [Lancaster, 2009]). When the grains come down and crash into the bed, the momentum it transfers initiates motion in other grains causing a chain reaction. This transport mode is most common, and is responsible for most of aeolian sediment transport volumes.

Surface creep
Surface creep describes the movement of grains forced by wind, but they never leave the bed. The grains are too large for the wind to lift them from the bed (>500 µm [Lancaster, 2009]). Instead, the grains roll and slide over each other in the direction of the wind as a result from wind force and impact forces from other grains.

Transport formula
Bagnold was the first to describe aeolian sediment transport, and also the first to propose a relation between the wind forcing and characteristic properties of sediment to the transport, see equation 2.4.

$$q = C_{grad}\sqrt{\frac{d}{D}}\frac{\rho_s}{g}{u_*}^3 \tag{2.4}$$

In which q is the sediment transport rate in kg/s/m, C_{grad} is an empirical coefficient relating to the grading of sand (1.8 for sand in dune areas), and D is reference grain size (0.25 mm). This relation describes sediment transport as a consequence of saltation and surface creep. But this relation doesn't take initiation of motion into account. Therefore it isn't applicable in situations where wind forcing is low, and where initiation of motion thus isn't continuous.

To incorporate the threshold of motion, Bagnold used a modified version of formula 2.2:

$$u_z = 5.75 u_* log\frac{z}{k'} + u_t \tag{2.5}$$

Where k' is a characteristic height above the bed (roughly 1 cm for normal dune sand [Bagnold, 1941]), and u_t is the wind velocity at that location. When formula 2.4 is combined with formula 2.5, formula 2.6 is obtained.

$$q = \alpha C_b \frac{\rho_a}{g}\sqrt{\frac{d}{D}}(u_z - u_t)^3 \tag{2.6}$$

with

$$\alpha = (\frac{0.174}{log\frac{z}{k}})^3 \tag{2.7}$$

In which α is a factor which converts the measured wind velocity near the surface to the shear velocity at the bed.

This formula describes aeolian sediment transport in kg/s/m and incorporates the initiation of motion criterion (u_t), using measurable velocity parameters, bed roughness and one empirical parameter (C_b). The formula assumes unlimited sediment availability.

2.1.4. Deposition

Deposition is the laying down of sediment which is in transit. Sand accumulates in locations where the forcing doesn't exceed the resistance to movement for a long enough time to reach the bed. This can be caused by the forcing being weakened, the resistance against forcing being strengthened, or a combination of the two. Several situations which can cause sedimentation are discussed in this section.

Reduced forcing
The most simple form of reduced forcing, is the laying down of the wind. Lower, or no wind speed means less to no force on sand particles. Gravity is now stronger than the wind forcing, and the sand particles settle down on the bed.

Another less trivial example of reduced forcing is downwind sheltering. Sand grains are protected from the wind on the lee side (shadow zone [Bagnold, 1941]) of a structure. This structure can be a sand dune, vegetation, a fence or anything else which protrudes from the bed. Vegetation is a special case,

Increased resistance
An uphill slope increases the resistance of a grain to movement. The steeper the bed slope, the more likely it is that grains deposit. This additional needed force increases as the slope steepness increases.

Another example of increased resistance to movement is surface moisture. Sand particles in a saltating or creeping transport mode experience an increase in drag when moving into a damp patch of the bed The moisture introduces cohesion to the particles, which increases the resisting force on the particle. The moisture content can be removed by for example exposure to the sun, high velocity winds, or drainage of the soil.

2.2. Dune dynamics

Sand dunes develop where there is a sufficient amount of sand available, and where there is wind which exerts a shear force strong enough to move sand grains around. A sand dune can form around a disturbance where wind streamlines contract and expand. Contraction causes higher wind velocities, which cause higher shear forces on the grains, inducing movement. Expansion of streamlines lowers the wind velocity and shear force, allowing moving grains to settle. These differences in wind speed cause different areas to lose or accumulate sediment, forming a dune.

Erosion occurs where less sediment comes in than goes out, and deposition occurs where more sediment comes in than goes out. The dynamics of a sand dune forced by wind is shown in figure 2.2. When the deposition is larger in magnitude than the erosion, the sand dune grows and moves in the direction of the wind. If the erosion and deposition are equal and non-zero, the sand dune is in balance and doesn't grow in volume, but it still migrates in the direction of the wind.

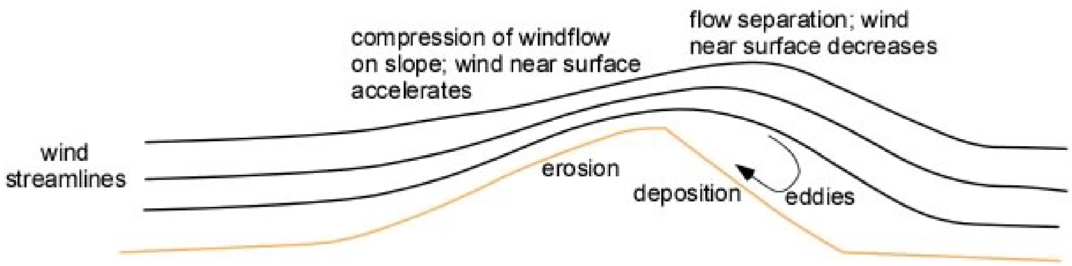


Figure 2.2: A sand dune forced by wind. The wind comes in from the left. [Wittebrood, 2017]

Coastal dunes often have vegetation growing on them. The presence of vegetation has a stabilizing effect, causing erosion rates to go down and sedimentation rates to go up. Coastal dunes therefore don't tend to move in the direction of the wind. A vegetated upwind side of a dune can experience deposition of sediments, as the vegetation traps incoming sand.

Because of their location, coastal dunes are subject to hydrodynamic forces from the sea. Though coastal dunes are only affected by these forces during storm events, as the typical location of these dunes is several meters above mean sea level. During these events, the waves from the sea can take large quantities of sediment away from the dunes in small amounts of time.

Next to destructive storm events, the sea also helps dunes to grow in an indirect way. During calm conditions, sediment is deposited in the inter tidal zone during high tide. At low tide, this sediment is picked up by the wind, and in the right conditions it is deposited in the dunes. In stable coastal dune environments, the destructive forces of the sea and the constructive forces of aeolian sediment transport are in a dynamic balance.

2.3. Vegetation

Vegetation is an important factor in the development and stability of coastal dunes. Because of its properties, it has a large impact on the dynamics of sand dunes. The above ground part of the vegetation provides sheltering, encouraging sedimentation. The underground roots and rhizomes of the plants stabilize the sand in the dunes (see figure 2.3). The most common dune vegetation in the Netherlands, and in the HD, is marram grass (Ammophila Arenaria). This grass species is abundantly available along the Dutch coast, and has favourable properties for coastal dune development [Ecomare, 2018].

Figure 2.3: Marram grass showing its stabilizing effects on coastal dunes [Ecomare, 2018].

Marram grass has long roots, stabilizing the sand dunes effectively. The plant isn't resistant to submergence in salt water coming from the sea, but it can handle salt ground water. Though it grows faster and healthier in the presence of fresh groundwater. Salt spray is common in coastal dunes, the balancing force is precipitation, which washes the salt left by salt spray off the vegetation.

The bloom period of the species Ammophila Arenaria (European marram grass), is in spring (March-May). During this period, the plant grows at its highest rate. During the summer (June-August), growth is also high, though a bit slower than in spring. In autumn (September-November) growth slows down, and in winter growth is at its lowest. Though growth during winter (December-February) is minimal, marram grass never stops growing [Huiskes, 1979].

The species procreates through seeds, but also through rhizomes. Rhizomes are modified below ground stems of plants that send out roots and shoots from its nodes. New specimens of the species result from this underground expansion, as they can survive on their own when they are disconnected.

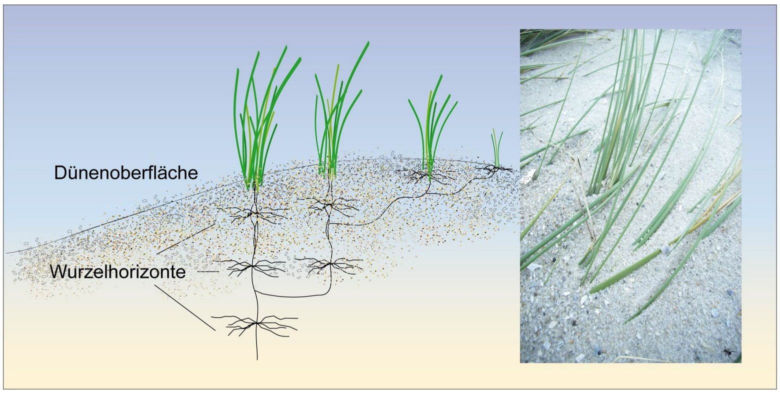


Figure 2.4: Schematic view of horizontal roots and rhizomes (located between the horizontal roots and above ground vegetation). Translated from German: Dünenoberfläche = dune surface, Wurzelhorizonte = horizontal roots.

Vegetation growth speed, and coverage area is highly influenced by seasonality. Marram grass grows fastest in spring, and slowest in winter. A sedimentation speed of roughly 0.5 m per year is most favourable for marram grass to grow [Maun, 2009] [Van der Putten, 1993]. And accumulation speeds of up to 2.0 m per year have been observed with marram grass narrowly keeping up. So an area with healthy vegetation indicates a positive dune growth speed of roughly 0.5 m per year, with a maximum of 2.0 m per year.

2.4. Hondsbossche Dunes

After construction, the HD has been monitored regarding the topography of the beach and dunes. With this data, the topographic change in the area can be quantified, and with the use of additional (climatic) data, these changes can be explained. From the previous work done by Wittebrood [2017], some important parameters can be identified which influence the development of the coastal dunes in the HD area. These factors include:

- Orientation of the dunes in relation to wind direction
- Beach width
- Beach slope
- Median grain size
- Dune geometry

Because more data has come available since the last study of the area, the same analysis will be carried out on the newly available data. In addition, the effects of vegetation, groundwater, tide and waves are taken into account. The marine forcing just mentioned are mainly used as an input for the models discussed in chapter 2. This is because these factors indirectly influence dune development by increasing or decreasing the available sediment for aeolian transport. For a short summary of the previous work, see appendix A.

2.5. Numerical models

There is a wide selection of models available which can model a coastal area, all with different focuses and varying degrees of accuracy. In this chapter, a selection of different models are compared to each other, and a choice is made in what models will be used to make more accurate predictions regarding the development of the HD system.

2.5.1. AeoLiS

AeoLiS is a physics and process based model based on the programming platform Python, developed by Bas Hoonhout and Sierd de Vries of the Delft University of Technology [Hoonhout and de Vries, 2016]. The hydrodynamic and aeolian processes relevant to the development of coastal dunes are incorporated in this model. AeoLiS distinguishes between transport limited, and availability limited sediment transport. In other words, when wind conditions allow sediment to be moved, the model checks whether there is any sediment available to move. The domain in AeoLiS is discretized into horizontal grid cells and vertical bed layers. The top bed layers are subject to wind forcing in a deterministic way, using mathematical formulas as described in chapter 2.1. The transport of sand particles is from one cell to the next.

AeoLiS can handle non-uniform grain size distributions. This means that phenomena like beach armoring and hydraulic mixing can be modeled using AeoLiS.

Aeolian processes

AeoLiS calculates the sediment transport capacity using the mathematical equations introduced in chapter 2.1. These relations only calculate the transport capacity for a uniform grain size distribution. To calculate the total transport capacity of a non-uniform grain size distribution, the grain size distribution is discretized into fractions. The transport capacity is calculated for each fraction, and multiplied with the use of a weighing factor. Otherwise the increase of fractions taken into consideration would increase the total transport capacity, which is physically not correct.

The grain size distribution as a result of wind forcing is stored in the bed layers in the vertical. The bottom layer is modeled as having an infinite thickness, and a grain size distribution which doesn't change. This means that when a cell with a certain grain size distribution which deviates from the starting condition receives a lot of sedimentation, this grain size distribution can be lost to the bottom layer.

Marine processes
Hydraulic mixing influences the sediment availability in AeoLiS. The affected cells are mixed together in the vertical by averaging out the grain size distribution in these cells. During high water, the soil in the affected cells increase in moisture content. The moisture causes the velocity threshold to increase temporarily. The drying up of the soil by retreating water level and evaporation is modeled in AeoLiS using a modified version of the Penman-Monteith equation which relies on meteorological data.

Vegetation
Vegetation isn't modeled in AeoLiS as such, but it can be implemented in the model with the use of a 'mask'. This has in fact been done by M. Wittebrood in her thesis about the HD, of which this is a continuation. This mask mimics the effects of vegetation by preventing erosion in certain places. This approach to modeling the effects of vegetation is very good in an area where the vegetation cover remains constant in time. But vegetation cover in coastal areas isn't constant in time, as growth and death of plants are inherent properties of vegetation.

2.5.2. DuBeVeg

DuBeVeg is a cellular automata model based on the programming platform Matlab, developed at Wageningen University [Keijsers et al., 2016]. This model incorporates the hydrodynamic, aeolian and biotic processes relevant to coastal dune development in its calculations. DuBeVeg discretizes the domain into discrete cells of sediment, which are subject to wind forcing. The wind picks up these slabs of sand, and on the basis of probability, erosion and deposition of this sand is determined. This means that two runs with the same starting and boundary conditions do not necessarily return the same results. These probabilities are influenced by various factors, including vegetation. The presence of vegetation in a cell increases the probability of deposition, and decreases the probability of erosion of that cell. DuBeVeg makes use of a uniform sand distribution, and the wind forcing is assumed as unidirectional (onshore directed), uniform and steady [Keijsers et al., 2016].

The aeolian process is at the basis of DuBeVeg. In each iteration of the aeolian sediment transport, every cell is checked for erosion and deposition. The model takes several aeolian and marine processes into account. The marine processes determine deposition and erosion of sediment in the inter-tidal area each spring-neap tidal cycle. After a certain amount of iterations, a simulated time period of one year has passed, and the vegetation in the domain is updated using the results of the aeolian processes.

Aeolian processes
Wind is the driving force of aeolian processes, and in this model, the wind is assumed as constant, and onshore directed. This simplification allows the wind to be parameterized into probabilities of erosion and deposition. The potential aeolian sediment transport rate is given by the formula:

$$Q = h_s L \frac{p_e}{p_d} n \tag{2.8}$$

In which Q is the potential aeolian sediment transport rate in m^3/m/yr, h_s is the slab thickness, L is the hop length of a slab in meters, p_e and p_d are the probabilities of erosion and deposition of a given slab, and n is the number of iterations per year.

The wind speed determines the base probability of erosion of a slab of sediment [Keijsers et al., 2016]. This probability is further modified the amount of sheltering the slab experiences, the occurrence of avalanching, the presence of groundwater, the ground level in relation to maximum wave run-up, and the presence of vegetation on the slab.

The amount of sheltering a slab experiences is determined by the amount of sediment in the neighbouring upwind slabs. When and upwind slab has a higher amount of sand associated with it, the downwind slabs experience a zero probability of erosion. The occurrence of avalanching is simulated by enforcing the angle of repose between neighbouring cells. This angle is increased in the presence of vegetation, so steeper slopes can be maintained in vegetated dunes. The chance of erosion is further decreased when the slab is situated below sea level, or below groundwater level.

Marine processes

The maximum water level in each spring-neap tidal cycle is determined using the astronomical tide, wind set up, and wave run up. The set up and run up are determined using the formula derived by Stockdon et al. [2006], formula 2.9.

$$R_{2\%} = 1.1\Big(0.35\beta_f\sqrt{H_0L_0} + \frac{1}{2}\sqrt{H_0L_0(0.563\beta_f^2 + 0.004)}\Big) \tag{2.9}$$

The water level resulting from this calculation is converted to a unit of hydrodynamic energy, by multiplying it by a factor called F_{energy}. This energy is dissipated over the beach and dune topography which is inundated during the spring-neap tidal cycle. To determine the amount of erosion and/or deposition, the energy which has dissipated is multiplied by the difference in the actual topography, and the equilibrium topography. When this equals or exceeds the value of 1, the topography is reset to the equilibrium value, with erosion or deposition as a result. Depending whether slabs need to be added or removed to reach equilibrium again. When the value of hydrodynamic energy is zero, the amount of sediment in the cell remains as is. This process also influences any vegetation present in the inundated area, though in this case, only removal of vegetation is possible.

Vegetation processes

The presence of vegetation in this model increases the probability of sedimentation, and decreases the probability of erosion in the cells. Also the maximum angle of repose is increased, stabilizing slopes and decreasing the occurrence of avalanching. This way, dunes are stabilized in DuBeVeg. In the starting conditions, a certain amount of vegetation must be present, as the model doesn't allow spontaneous creation. The vegetation in DuBeVeg grows in each cell depending on the amount of sedimentation and erosion in the cell. Lateral expansion of vegetation is possible, also depending on erosion and sedimentation, depending on the vegetation type. There are two types vegetation modeled in DuBeVeg. They are called pioneer species (marram grass) and stabilizer species (buck-thorn type vegetation). This terminology deviates from other literature, where marram grass isn't considered a pioneer species. The pioneer species grows well in conditions with high amount of sedimentation. The stabilizer species prefers neutral conditions (neither erosion or sedimentation). Erosion of sediment negatively influences both plant classes. Seasonality isn't included for the vegetation, as effects like sunshine, temperature and precipitation aren't taken into account in modeling vegetation growth.

2.5.3. Aeolus

Aeolus is a model in development at the department of coastal morphodynamics at the University of Utrecht. The model is even more so in development as the other models, in the sense that it isn't ready for use yet. In contrast to AeoLiS and DuBeVeg, this model isn't focused on morphological change. Instead, the aim of this model is to accurately predict the amount of aeolian sediment transport in the interface between the beach and dune. With this model, the effects of changing boundary conditions such as changing wind climate, sea level rise and tide on coastal dune development can be studied. This model takes the following factors in aeolian sediment transport into account: wind angle, beach geometry, fetch effects, surface moisture and groundwater, and grain size.

Aeolus consists of two modules: A beach groundwater and surface moisture model, and an aeolian sand transport model. At the time of writing, the groundwater and surface moisture module is finished. This module is based on the non-linear Boussinesq equation for the groundwater level, including the effect of wave run-up. The surface moisture is modeled after a Van Genuchten soil water retention curve.

The aeolian module is based on the Hsu model. This model will be re-formulated to include the effects of grain size on aeolian sediment transport. Aeolus will be able to take the effects of fetch into account. Also, the effects the fore dune has on the wind characteristics will be taken into account [Ruessink, 2018].

2.5.4. Model choice

Each model has their weak and strong points, depending on the model approach, the way forcing is introduced in the system, the focus of the model, and what processes they take into account. The choice of model therefore depends on what processes and factors are likely most of interest for the goal of this thesis. All considered models model aeolian processes, and hydrodynamic processes to some extent, though in different ways (see table 2.1).

	Grain size	Bed slope	Armoring/ Hydraulic mixing	Vegetation	Sheltering	Surface moisture	Ground water
AeoLiS	✓	✓	✓	✓*		✓	
DuBeVeg	✓*			✓	✓		✓
Aeolus	✓	✓			✓	✓	

Table 2.1: Considered models with the associated processes and parameters taken into account. (* indicates the process or parameter is taken into account implicitly or with a rough approximation).

AeoLiS models more processes which are of importance to accurate predictions regarding aeolian sediment transport. While DuBeVeg appears to be more adept in modeling the growth of vegetated dunes. Aeolus could be an interesting option with which to model the HD, in the sense to gain understanding in the dynamics of the beach and dune interface. But for practicality (the model isn't ready for use), this model won't be used in this thesis.

Since the focus of this thesis is on dune development, DuBeVeg is the first choice for modelling the HD. DuBeVeg models the dynamic nature of vegetation, varying the vegetation cover in both space and time. Whereas AeoLiS can only model the effects of vegetation in user defined locations, which are static in time.

Though it isn't possible to directly implement various physical properties relevant to aeolian sediment transport, these properties can be implemented indirectly by adjusting the probabilities of erosion and sedimentation. As is the case with all numerical models, calibration and validation is very important for the performance of the model. Though with this model, the parameters for calibration are more abstract than with process based models.

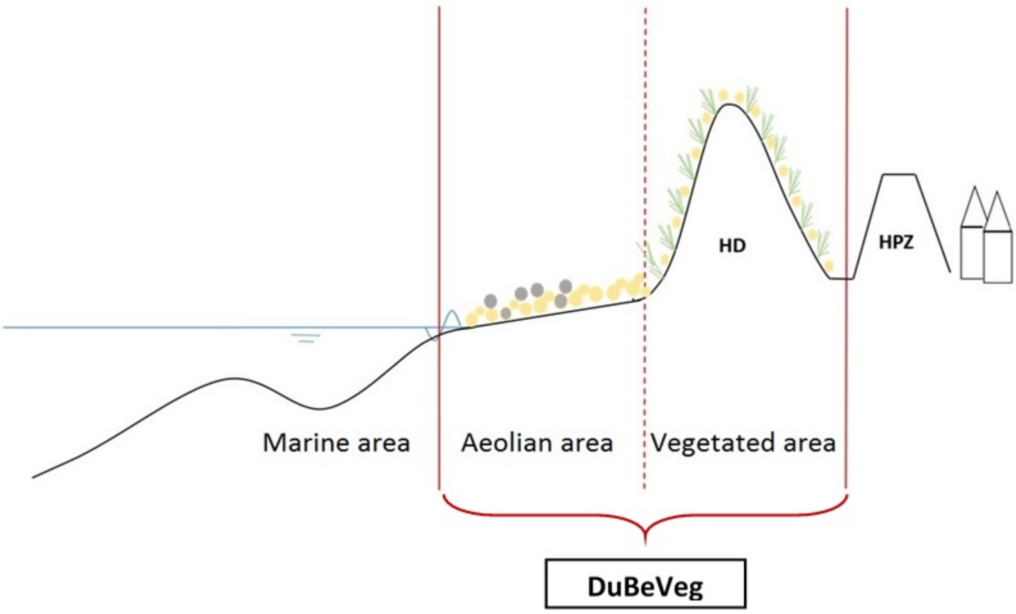


Figure 2.5: Model schematization using DuBeVeg.

3 Method

In this chapter, the method with which the research questions are answered is discussed. The method consists of two main parts, the data analysis and the model study. The processes which are analyzed, and the model which is used have been introduced in chapter 2. The data which is used in both parts of this thesis is gathered from various sources. An overview of the data is shown in table 3.1 below. More details about the climatic and spatial data can be found in Appendices C and D.

	Period	Interval
Topography	2015-2018	~4 months
Vegetation	2015-2017	Irregular
Grain size	2015 & 2018	Incidental
Groundwater	2015-2017	Irregular
Tide	1977-2017	10 min
Waves	1989-2017	1 hour
Wind	1971-2018	1 hour

Table 3.1: Available climatic and spatial data regarding the Hondsbossche Dunes.

Before the methods used in the data analysis and model study are discussed, first the spatial and temporal definitions used in this thesis are introduced.

3.1. Definitions

The spatial and temporal scope has already been defined in section 1. In this section, subdivisions in the spatial and temporal scope are defined in more detail.

3.1.1. Spatial definitions

The domain of this thesis is divided in profile types (alongshore), and coastal zones (cross-shore). The definitions are described in the sections below.

Alongshore divisions

The project domain is divided into profiles in alongshore direction. These profiles have been introduced in chapter 1. In the work of which this is a continuation, alternative profile definitions have been used. Though the differences of the definitions are small, the original profile definitions are more suited for analysis. This is because the definitions used in this thesis better reflect the transition between profile types. (The wet dune valley is not located on a profile border anymore). Also, the results from analyses made by third parties can be more easily compared to the analyses in this thesis. This standardization of profile definitions makes cooperation between researchers easier as it prevents confusion in terms defined for this area.

The profile definitions have been introduced in chapter 1. The characteristics of each profile has been discussed there, and a plan view of the profiles is shown in figure 1.8. The exact borders of the profiles are shown in table 3.2. The reference system is based on Rijksstrandpalen (RSP, government beach poles). The unit is hectometers.

	RSP [hm]
Profile 1	2017-2094
Profile 2 north	2094-2146
Profile 3 north	2146-2247
Profile 4	2247-2394
Profile 3 south	2394-2540
Profile 2 south	2540-2589

Table 3.2: Definition of profiles based on RSP (Rijksstrandpalen, government beach poles).

Cross shore divisions

In cross shore direction, the domain is divided into four different areas. Namely the dune, beach, intertidal zone and the sea. These coastal zones are defined by elevation, resulting in horizontal slabs as shown in figure 3.1.

The dune begins where the beach ends. Though the transition between beach and dune area is gradual, and this area is called the dune foot. For the purposes of this thesis, a clear definition of this border must be defined. As defined by HHNK, the dune foot is located at an elevation of NAP +3.50 m, and the volume of sediment above this height is defined as the dune volume. Though the location of the dune foot isn't static, and therefore, the border between the beach and dune area also isn't static. The location of the dune foot is governed by both aeolian and hydrodynamic processes, and therefore changes as a response to changes in these two types of forcing. In the case of sea level rise, the location of the dune foot migrates with the elevated sea level [Stive and Bosboom, 2015]. Therefore, the dune foot is defined at NAP +3.50 m + SLR (Sea Level Rise).

The beach is defined as the area between the sea and the dunes. Because the dunes are defined to start at an elevation of NAP +3.50 m + SLR, this is the border between the two coastal zones. In this thesis, the water line is defined at MHW (Mean High Water), which has been found to be at a level of NAP +0.84 m [RWS, 2013]. This border also migrates with SLR, and therefore is defined as NAP +0.84 m + SLR.

Below this level, the intertidal zone is located. This zone is between MLW (mean low water) and MHW, again migrating with sea level rise. So the intertidal zone is located between NAP -0.76 m + SLR, and NAP +0.84 m + SLR [RWS, 2013].

Below the mean low water level, the sea is defined. Due to the focus of this thesis, the definition of the hydro-dynamically active part of the shore isn't divided into further areas such as breaker zone, near shore zone, and offshore zone. These zones are grouped as the 'sea' group.

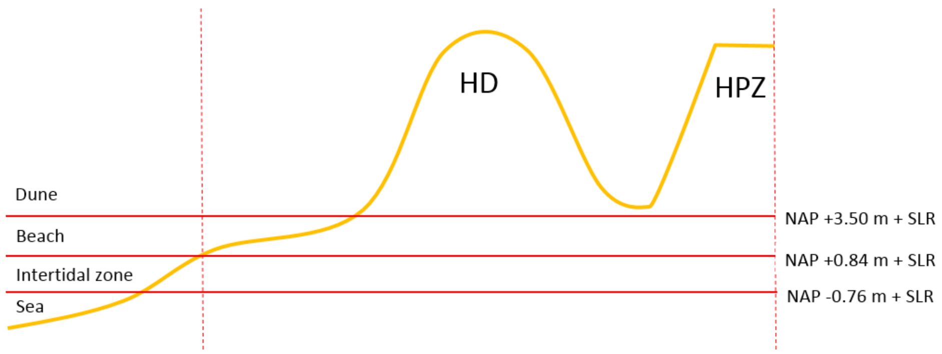


Figure 3.1: Overview of the different profile types, and locations of the borders.

Finally, the grensvolume (border volume) is defined as the volume above the calculated normative water level. The height above which this volume is defined is variable along the dutch coast, and thus variable in the domain of the HD. The calculated normative water levels per profile area are shown in 3.4, and a further description of the normative water level is given in section 3.3.1.

3.1.2. Temporal definitions

To be able to carry out the analysis, and do it efficiently, a time path must be defined. Because the main focus of this thesis is the development of the dunes, the topographic data is leading. The data collection dates of the topography of the HD is shown in tab 3.3.

Moment	Date
T0	24-05-2015
T1	28-12-2015
T2	21-03-2016
T2.5	18-07-2016
T3	01-09-2016
T4	05-12-2016
T5	19-04-2017
T5.5	22-06-2017
T6	11-08-2017
T7	06-12-2017
T8	19-03-2018

Table 3.3: Dates of LiDAR measurements of the Hondsbossche Dunes.

As can be seen in table 3.1, not all data sets reach up to T8, and some data sets have a higher or lower resolution on the temporal scale. This limits the analysis of the dune development during some time periods. Per situation, the consequences of the lacking data will be assessed.

Also note the half time steps, T2.5 & T5.5. These definitions are used in the vegetation analysis, as will become apparent in chapter 4.

3.2. Data analysis

Because of the abundance of factors influencing coastal dune growth, and the interaction between these factors, there are multiple ways to start analyzing the available data. In this thesis, first the climatic data will be considered, and then the spatial data. This method is chosen because climatic data has more influence on the topography, than the topography has influence on the climatic forcing. Especially since the wind and wave data used in this thesis is obtained from sources outside of the spatial domain of the HD. Though both the wind and the topography dynamically influence each other locally. The order of analysis of the different data sets is shown below:

1. Wind
2. Waves
3. Tide
4. Groundwater
5. Grain size
6. Vegetation
7. Beach
8. Dune

As can be seen, first the driving force in aeolian sediment transport is discussed. After that all factors with varying degrees of influence on dune dynamics are treated. The main focus of this thesis is saved for last. This way, all findings from the previous analyses can be used to explain the growth or decline of dune volumes. The available data is shown in table 3.1. Here the time period over which the data is available, and the interval between measurements is shown.

As can be seen, the bathymetry isn't part of the analysis as it falls outside of the spatial domain of this thesis. But, when the influence of local bathymetry has a dominating effect on any of the other parameters, the effect of the bathymetry will be taken into consideration.

3.2.1. Climatic data

The climatic data is both quantitatively and qualitatively analyzed. The data is obtained from four different data stations, which are operated by different institutions. The locations of data collection are shown in figure 3.2.

The tidal data is obtained from a tidal station in Petten Zuid (RWS). The wind data is gathered from a meteorological station in IJmuiden (KNMI), and the wave height and direction data is obtained from the offshore buoy called the 'IJgeul munitiestort 2' (RWS). Measurements regarding groundwater levels have been taken at the dune foot inside the HD domain (HHNK). These data stations are chosen on the basis of suitability of the data, for use in the analysis of dune development in the HD. Factors such as location, and environment of the data station is taken into account in this choice. For more information about the choice of data stations and the data itself, see Appendix C.

Figure 3.2: Locations of data sources for climatic data collection with the location of the HD indicated in red.

The tide and wave data is analyzed to gain insight into the sediment balance, or sediment availability for aeolian sediment transport. The groundwater is analyzed to determine how much the groundwater level influences the resistance of the grains to aeolian transport rates. And the wind characteristics are analyzed as it is the driving force in aeolian sediment transport, and thus has a large influence on the topographic changes in the HD.

3.2.2. Spatial data

The spatial data, just like the climatic data, is analyzed qualitatively and quantitatively. The data sets are obtained from different sources, including HHNK, the contractor (Boskalis and Van Oord), Beeldmateriaal Nederland, and my own measurements and observations.

First, the grain size distribution is analyzed in spatial and temporal dimensions. The data about grain sizes is obtained from Boskalis and Van Oord (the contractors), and my own measurements in the field. The grain sizes are analyzed for spatial variation, in both cross shore and alongshore direction, and for changes in the distribution in time.

The data on vegetation comes from aerial photographs, both infrared and visible light, interviews with the area manager, measurements on the location of vegetation after construction, an excursion to the area with experts on ecology, and my own observations in the field. All these sources are used to analyze the spatial and temporal variations in vegetated area and the health or efficiency of the vegetation.

The analysis of the topographic LiDAR data is divided in two parts, namely the beach and the dunes. As one of the conclusions from the previous work states, the condition of the beach is an important boundary condition for aeolian sediment transport toward the dunes in the HD. Therefore, the beach is not only analyzed for changes in volume, it is also analyzed for changes in beach slope. Quantitatively, the dune topography is analyzed for changes in volume using GIS, for each time period and each profile. Qualitatively, the locations of sedimentation and erosion are determined by making difference maps of the topography in the HD. For more information about the spatial data, see Appendix D.

3.3. Model study

The model study is aimed at answering the main question of this thesis; how to maintain the functions of the coastal area effectively now and in the future. Several scenarios regarding future forcing in the model are modelled, and these scenarios are discussed in this chapter. As introduced in chapter 2, the model used in this model study is DuBeVeg. Because the model is in development, improvements can still be made to DuBeVeg. These improvements are aimed at increasing the accuracy of the model, such that the results of the model can be used for engineering purposes. These improvements are introduced and discussed in this section.

The initial state and climatic forcing implemented in the model are introduced and discussed in this section. These settings are based on the data introduced in this chapter, and on the results of the data analysis. The model is calibrated, and validated using the data sets briefly introduced at the start of this chapter, and the results of the analyses which are discussed in chapter 4. The results of this calibration is shown in this section as well.

3.3.1. Scenario's

Because the state of climatic forcing in the future is uncertain, several different scenarios for the future state of the forcing are modeled in DuBeVeg. These scenario's are divided in scenario's where nourishments are implemented in the simulation, and scenarios where no nourishments are applied. These two base scenario's, and all other scenario's, will span a period of 50 years between 2015 and 2065. The details of these scenario's are discussed below.

Base scenario - no nourishments

In this scenario, no nourishments are applied. The calibrated model is run for 50 years for every profile. The results show what would happen to the different profiles in the HD when no nourishments or any other interventions would be applied to the HD. Though this is unrealistic, as nourishments will certainly be applied to the HD, the results are very useful in determining what effect nourishments have on the development of the HD.

Base scenario - nourishment

As introduced in chapter 1, three nourishments have been planned for the HD in 2023, 2026 and 2030. These nourishments are planned to ensure the safety the HD provides to the hinterland (dune volume minimum), and to ensure the HD can fulfill its function as a recreational area (beach width minimum). Though the first nourishment in profile 2 south has already taken place in march 2018. Therefore, the original planning isn't up to date anymore, and another nourishment planning can be made.

Safety requirement The HD needs to be able to withstand a storm with a return period of 3000 years. The required dune profile, and the corresponding sediment volume, is determined using the program Morphan. Morphan requires boundary conditions (significant wave height and period, calculation water level e.d.) to calculate the safety profile, and the corresponding volume. The boundary conditions resulting from the design storm is determined using the program RisKeer. Using these values, Morphan calculates the minimum required sediment volume above storm surge level in the dunes. In the calculation, the border profile and volume, erosion volume, and a buffer volume is determined. These three volumes together form the minimum amount of sediment required to provide safety to the hinterland.

As defined in the contract with the contractor, the minimum required sediment volume in the safety profile must be guaranteed. This is done by linearly extrapolating the volume trend of the safety profile. When it is determined that this minimum volume is undercut within the next 1.5 years, a nourishment is carried out within the next half year. This is modeled in DuBeVeg by implementing the nourishment 1 year before the minimum required sediment volume is undercut. See table 3.4 below for the calculation levels and minimum required volumes for each profile.

	Calculation level [m]	Required volume [m^3]
Profile 1	4.56	280
Profile 2N	4.57	400
Profile 3N	4.60	359
Profile 4	4.62	159
Profile 3Z	4.64	202
Profile 2Z	4.65	292

Table 3.4: Calculation levels and minimum required dune volumes for each profile in the domain.

Recreational requirement Recreation is one of the three functions of the HD. To ensure this function, a minimum average beach width of 50 meters over 250 m of beach, and a minimum width of 40 meters locally is required in the profiles which function as a recreational area Olijslagers and Bakker [2015]. The recreational area consists of Profiles 1, 2 North, 3 North and 2 South. Profile 4 and 3 South fall in the zone reserved for nature, and therefore don't have to have a minimum beach width of 50 meters Olijslagers and Bakker [2015]. A nourishment will be carried out when it is found that the beach width will be undercut within the next 1.5 years, with a reaction period for the contractor of half a year. Therefore, this requirement is modeled in DuBeVeg by implementing the nourishment 1 year before the minimum required sediment volume is expected to be undercut.

Nourishment design The design of the nourishments are based on the suppletion carried out in March 2018 in Profile 2 South, the base designs for the planned nourishments as described in chapter 1, and the requirements for these nourishments as described in the management and conservation plan, written by the contractor [Bakker, 2015]. The basic shape of the nourishment is therefore a flat surface at NAP +3.00 m, which extends cross shore direction toward the sea. The edge of the nourishment slopes down to the bottom with a slope of 1 in 20, or gentler [Bakker, 2015]. Based on the nourishment applied in march 2018, the nourished volume is set at 600 m^3/m. This volume is set as the standard nourishment volume in the simulations, and determines the length of the flat surface from the dune toward the sea.

Sea level rise

Due to climate change, the average sea level is rising. It is not exactly known how fast or by how much it is going to rise. Though the accelerated nature of sea level rise is measurable. The sea level rise has been measured to be 2.7 mm/year during the period 1993-2004, and it has been 3.5 mm/year in the period 2004-2015. Because of the uncertainty of the exact sea level rise, three sea level rise scenarios will be modeled in this thesis. The spread of the expected sea level rise is shown in table 3.5 below, where the sea level rise in the year 2100 corresponding to three scenarios is shown.

	sea level rise in 2100
Upper bound	3.17 m
Average	1.95 m
Lower bound	0.75 m

Table 3.5: Values of sea level rise by the year 2100 as predicted, displaying the upper bound (95%), median (50%) and lower bound (5%) of the sea level rise prediction [D. le Bars, 2015].

These scenario's are based on projections of the consequences of melting antarctic ice. The actual sea level rise in the next hundred years lies between the upper and lower bound with a certainty of 90%. Each profile will be subject to these scenarios, with and without the application of nourishments.

Wind climate

As introduced in chapter 2, the wind climate in the North Sea displays a decadal scale variation in wind speed. Because wind is the direct driving force of aeolian sediment transport, it is very important to understand the effects these decennial variations in wind speeds have on the development of the dunes in the HD area. Because no concise period of this variation is known, the effect of wind speed on aeolian sediment transport is modelled by simply increasing and decreasing the wind speed by ten percent for each model run.

Because aeolian sediment volume transport is related to the wind speed by the third power (see equation 2.4 and 2.6 in chapter 2), a decrease of 10 percent in wind speed would decrease the potential sediment transport rate by 27.1 %, and an increase of 10 percent leads to an increase in potential aeolian sediment transport of 33.1%. To implement the change in wind speed, the calibration formula (equation 2.8) is used.

Two scenario's are run in DuBeVeg. A scenario in which the wind speed is increased by 10 percent, and one in which the wind speed is decreased by 10 percent. These scenarios are applied to every profile, with and without the application of nourishments.

Overview of model scenario runs

The scenarios as described above will be run in DuBeVeg. An overview of the scenario's is shown in table 3.6 below, and apply to every profile inside the domain of the HD.

No nourishment	Nourishment
Base	Base
SLR - low	SLR - low
SLR - high	SLR - high
Windspeed - low	Windspeed - low
Windspeed - mid	Windspeed - mid
Windspeed - high	Windspeed - high

Table 3.6: Overview of model runs for each profile area in the HD.

The scenario's are divided in situations where no nourishments to the beach are simulated, and simulations where these nourishments do occur. Thereby assessing the effect and effectiveness of nourishments on aeolian sediment transport in the HD, and the effect of different sea level rise scenarios, and differing wind climates.

3.3.2. Model improvements

Because DuBeVeg is a model which is still in development, improvements can be made. These can come in the form of added functionality, or by increasing the accuracy of the simulations. In this section, the improvements made to the model for the study in the HD are discussed. Namely, the addition of non-erodible elements, an improved beach update algorithm, and the implementation of a controllable alongshore mass flux.

Non-erodible elements

The original DuBeVeg model could only model every grid point in the domain as an erodible element (i.e. areas where only loose granular material is present). Though in most cases, non-erodible objects can be found on the beach. In the HD, these include foot,- and bicycle paths, and the old sea dike behind the constructed beach and dunes. Therefore, to get a more accurate representation of the HD in the simulations, non-erodible elements have been implemented in the model with the help of scripts made by prof. dr. K.M. Wijnberg of the University of Twente.

The non-erodible elements are modeled by disallowing sedimentation and erosion in the non-erodible cells, or grid points. Any incoming sediment is transported further downwind until a normal erodible cell is encountered. From here on, the regular rules imposed by DuBeVeg apply again. This implies that incoming sediment cannot stay on top of a pavement, or any other non-loose granular surface. Which in reality of course can happen, introducing a small amount of inaccuracy. Though the increased accuracy the implementation of non-erodible elements provides likely outweigh the inaccuracies of this effect.

Beach update

The original beach update is improved on, by implementing a sediment balance, and the possibility of defining a trend in the sediment volume in the domain. The changes are discussed in the paragraphs below.

Dynamic profile & conservation of mass In DuBeVeg, whenever the energy of the waves in the sea exceed a certain value, the beach resets to a certain static equilibrium topography. This in itself is a very good approximation in the case of a stable coastal system, as the location of the shoreline is set at a more or less constant location. But in the case of systems where the equilibrium profile isn't known, or is more dynamic, this approximation isn't very useful. This is the case in the HD, where the beach profile changes don't indicate that an equilibrium in it's position has been reached. Therefore, to be able to simulate the HD accurately, the equilibrium profile needs to be defined in a different, more dynamic way.

The new approach for the beach update works similarly to the original script used in DuBeVeg. Every beach-update, the maximum water level and the average water level is determined. The maximum water level is the highest water level during each spring-neap tidal cycle, and the average water level is set at 0 in the case of no sea level rise. When sea level rise is introduced into the model, the average water level per time step is equal to the sea level rise. The area between these water levels defines the intertidal zone. For each beach update, a new equilibrium profile is calculated, and imposed in the same manner as in the original script. The difference in sediment volume is distributed over the area below average sea level, thus conserving the sediment mass or volume in the simulated domain.

The equilibrium profile of the intertidal zone is determined by using the formula formulated by Vellinga. According to Vellinga [Stive and Bosboom, 2015], the beach profile is defined by equation 3.1.

$$h = A * (x')^{0.78} \tag{3.1}$$

Where h is the water depth, x' is the offshore distance from the high water line, and A is a calibration parameter which is determined by the fall velocity of the sediment. A can be determined using formula 3.2.

$$A = 0.39 w_s^{0.44} \tag{3.2}$$

The formula is empirical, and is derived with the use of experiments on different scales. In these experiments, Vellinga used sediments with a D_{50} between 90 µm and 225 µm. As will become apparent in chapter 4, the sediment in the HD has a diameter which is larger than the diameters in that range. Though this approximation can still be used, as the parameter A can be adjusted accordingly, using formula 3.2.

In figure 3.3, the principle of this approach is illustrated. $V_{intertidal}$ is the volume which is eroded or sedimentated between the high and mean water level in each period. This is deposited to the area below mean sea level, enforcing a sediment mass balance. A trend can be added to the simulation, by adding a certain volume of sediment each beach update. Here indicated by V_{trend}, which is further explained in the next paragraph.

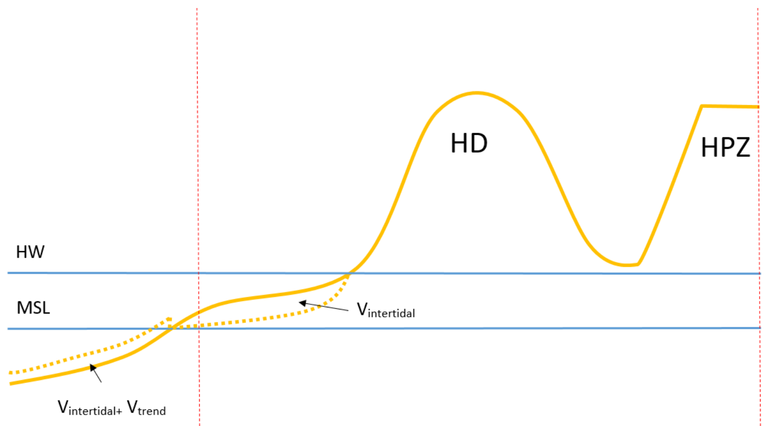


Figure 3.3: New beach update approach, showing the Vellinga profile in the dashed line between high water and mean sea level, and the location below mean sea level where the eroded sediment is transported.

Mass flux With the implementation of the dynamic beach profile, the beach update of DuBeVeg now has a sediment balance which is set at 0. But in practice, the sediment balance in the intertidal zone and deeper areas of the HD isn't zero, see Appendix E and Brandeburg [2018]. A combination of cross shore and alongshore sediment transport provides the area with a surplus or shortage of sediment. The magnitude of this sediment flux varies in both time and location along the shore. The sediment source is implemented in DuBeVeg by allowing the user to define the flux per beach update in the model. Per time step, a pre-defined volume of sediment is added or taken away from the hydrodynamic part of the simulated profile of the HD. This volume flux can be defined for each profile, and for each time step in the simulation. Therefore, the sediment in- or out flux in the model is a calibration parameter for every profile.

3.3.3. Initial state

As introduced in section 2.5.2, DuBeVeg needs several data files as starting conditions. These include a topographic map at t=0, a vegetation map at t=0, and a map of non-erodible elements, and a groundwater map. Due to the changes in the beach update approach, a static, pre-defined equilibrium profile isn't needed in this version of DuBeVeg.

Topography

The topography of the HD has been measured with the use LiDAR scans, as introduced at the beginning of this chapter In some locations the laser scan hasn't been able to obtain useful data, so the topographic scans contain holes. These holes have been filled using a linear interpolation technique in GIS. The data has a resolution of 0.5x0.5 m. This gives a relatively high definition picture of the topography in the HD. When using this data as is in DuBeVeg, very long calculation times can be expected. To limit the calculation time, the topographic data is downgraded to a grid size of 5 m. This downgrade results in a resolution which is high enough to get a clear picture of the behaviour of the dunes in the HD, while drastically shortening calculation times in DuBeVeg. When the model has been calibrated, the grid size can be made finer again if it is necessary to get a more detailed view of an area.

The bathymetry of the HD isn't part of the LiDAR data-set, but this part is important for the simulations. Therefore, the bathymetry is estimated using the Bruun rule (see equation 3.3 [Stive and Bosboom, 2015]).

$$h = A * (x')^{2/3} \tag{3.3}$$

Though this is a rough approximation of the actual bathymetry in the HD, the emphasis of this thesis is on the volume and form of the dunes. The state of the beach is calibrated on the amount of sediment the intertidal area provides for aeolian sediment transport toward the dunes. This makes the equilibrium topography of the HD area a calibration parameter, next to being a part of the initial state of the model.

Vegetation

The vegetation cover in the HD has been surveyed right after construction by HHNK. This map of the vegetation has been used as input for the model. Though only the location had been measured without taking notes on the density or health of the vegetation. In the analysis regarding vegetation in chapter 4, an estimation of the initial vegetation cover is made. With higher concentrations in profile 2 south, 3 south and 4, and lower concentrations in profile 3 north, 2 north and profile 1.

Vegetation other than Marram grass has developed in the HD since construction. Though these species haven't been planted, and no data is available on the location of these plan species. To be able to implement these species in the HD, a small portion of this vegetation is added to the initial state of the vegetation. After one iteration of the vegetation cycle, most of this initial vegetation dies out, resulting in a plausible vegetation map of this secondary plant species group.

Non-erodible elements

In the domain, several elements exist which aren't made up of sand, or vegetation. These areas include a bicycle path, footpath, and the old sea dike. Because these elements aren't made up of loose granular material, they don't behave as such. In DuBeVeg, these elements are treated as non-erodible elements in which no sedimentation and erosion can occur. This is an add-on developed by Prof. dr. K.M. Wijnberg from the university of Twente. This means that any incoming sediment is transported further downwind until a cell which isn't non-erodible is encountered. Here, standard rules of DuBeVeg apply, and sedimentation or erosion may occur again. So sedimentation on the bicycle and footpaths, which does occasionally happen in the HD, cannot be simulated in this model. This isn't a very big problem, as this effect doesn't have a huge impact on the total transport in the domain.

Groundwater level
Groundwater level has a huge effect on the results of a DuBeVeg model-run. Slabs of sediment below groundwater level in DuBeVeg act as non-erodible elements, thereby making transport of these slabs impossible. As the model was previously calibrated on different areas of the Dutch coast with high groundwater levels, the model first returned odd results for the purposes of the HD. After the groundwater level in the HD had been found to be only at NAP +0.70 m at the foot of the dune, instead of a similar number below the surface, the model returned much more usable numbers. The correct calibration of the groundwater level has proven to be an important parameter to get right.

Dune valley
Open water like the dune valley in profile 4 can act like a sediment sink for aeolian sediment transport, and sediment can also be transported over the water. This poses a problem for DuBeVeg, as open water in the dune profile isn't a standard feature in the model. To model this valley in DuBeVeg, two approaches have been thought out.

The first option is to simply ignore the valley and input the topographic data as is. The transported sand will likely sedimentate in the area behind the first dune row, as this is the shadow zone. Sheltered from the wind. The incoming sand will show up as an elevated bed level, where in reality it would sink to the bottom of the wet dune valley. This will continue until enough sediment has accumulated in the valley to reach the groundwater level. When this point is reached, the wet dune valley converts to a dry dune valley. The landward side of the dune valley can however erode, due to the water being modeled as sand in DuBeVeg. Though this effect is expected to be countered by the shadow zone produced by the first dune row. It is still possible that the dune valley farthest downwind from the dune row will erode. These effects will be taken into account when analyzing the results.

The second option is to model the wet part of the dune valley as non-erodible elements. This way, elevation in the 'bed'-level of the wet valley is prevented, leading to a more natural result. The downside is that the sediment is passed through to the second dune row, instead of accumulating in the water of the dune valley, leading to inaccuracies. Though this inaccuracy is expected to be small. Therefore, it is chosen to model the valley as dry sand in the model. In the interpretation of the simulation results, the effects the wet dune valley might have on aeolian sediment transport will be taken into consideration.

3.3.4. Climatic forcing

The climatic forcing imposed in DuBeVeg are the water level, and the wind. The wind characteristics implemented in DuBeVeg is the average wind speed and direction of the period T0 to T8. The wind climate is discussed in the chapter 4, for the value see table 4.1. Because of the simplified nature of the hydrodynamic module in DuBeVeg, only one water level data point is needed for every spring-neap tidal cycle. Which is one data point per approximately 2 weeks. Therefore, the available data must be modified to facilitate the needs of DuBeVeg. Wind set up and wave run up are accounted for using formula 2.9. The output from this formula is added to the data from the astronomical tide, and that is used as input for the climatic forcing in DuBeVeg.

There are two main approaches in implementing the wind direction in DuBeVeg. One is to change the wind direction itself, and the other is to simply rotate the input topography instead. To change the wind direction itself is very difficult, and introduces a lot of numerical problems. DuBeVeg models transport in a rectangular grid, and in one direction. When the direction of transport changes, the distance between the grid points, or cells, changes. To implement the directional change of aeolian sediment transport, the jump length of a transported slab must be converted from a constant value, to a variable dependent on the wind direction. The wind directions possible in this situation with a jump length short enough is dependent on the grid size of the domain. Experiences from previous users of the models indicate that rotating the topography is the best way to change the wind direction in DuBeVeg. As it isn't very laborious, and the results are accurate. Any inaccuracies caused by rounding errors from the rotation of the map are very small, and are negligible.

3.3.5. Calibration

The model is calibrated with the use of formula 3.4 of Nield and Baas. This formula relates several numerical parameters to each other which as explained in chapter 2.5.2. Other than the parameters appearing in this formula, the probability of sedimentation in vegetated cells, the groundwater level and initial vegetation density are parameters which have to be calibrated. Parameters such as the growth curve of marram grass, angles of repose of bare sand and vegetated sand and shadow zones are parameters which can be measured, and thus don't need to be calibrated.

Calibration formula
The calibration formula is used to determine and relate the potential maximum aeolian sediment transport in the domain. The parameters and overall explanation of this formula can be found in chapter 2, formula 2.8.

$$Q = h_s L \frac{p_e}{p_d} n \tag{3.4}$$

Several parameters have been chosen beforehand. The jump length (distance a slab travels when it is determined that it erodes) is set at the same size as the grid. This way, it is ensured that each eroded slab travels toward the downwind located cell, and doesn't overshoot. The iteration frequency is set at 52 per year. This is approximately one iteration per week, which fits nicely in the predefined iteration frequency of the beach update which is once per two weeks (roughly a spring-neap tidal cycle).

This leaves only the potential aeolian sediment discharge, slab height and the probabilities of erosion and deposition of an non-vegetated cell. The slab height has a bandwidth of realistic values, which is between 0.077 and 0.13 m [Nield and Baas, 2007] Because the bandwidth of the allowed slab height is so narrow, the slab height is set at a value of 0.10 m, decreasing the amount of calibration parameters even further. After eliminating another calibration parameter, the formula is rewritten to a form where the probability of erosion is determined by the values of the other parameters to make sure the calibration equation is satisfied.

Groundwater
As described in chapter 4, the groundwater table in the HD is relatively low lying. Therefore, the effects of groundwater presence is very low. The implementation of the groundwater level in DuBeVeg is as a fraction of the local topography. The groundwater measurement has shown that this level was at NAP +0.70 m at the dune foot, which results in a groundwater level at 0.2 at this location (dune foot is defined as NAP+3.50)

Beach update
As described in the model improvements, the beach update is based on the Vellinga erosion profile for beaches. The calibration parameter is based on the fall velocity of the sediment which the beach is made of. With larger fall velocities resulting in a higher parameter for the Vellinga erosion profile.

Because the grain sizes measured in the HD are relatively large, the Vellinga parameter is correspondingly large as well. But, not every spring-neap tidal cycle contains a period of storm conditions, leading to a smaller value for this parameter. Therefore, the value of this parameter is uncertain, and the parameter is calibrated for each profile individually.

Incoming sediment below sea level is based on the findings of Inge Arends. One of the conclusions of her work was that the trend in sediment balance decreased in magnitude over time. Therefore, the magnitude of the imposed volume change of the below water area is decreased over time.

3.3.6. Validation
The results of the model runs are validated using the results of the data analysis as discussed in chapter 4. The volume changes of the beach and dunes from the model runs are compared to the actual volume changes which have taken place in the HD during the period since construction. Instead of comparing the measured volumes to the calculated volumes, percentages of growth are compared to each other. These growth percentages are based on the T0 measurement and the T8 measurement, as described in chapter 4. The development of the vegetation is used as a validation tool. The data used in the validation for the vegetation is obtained from the infrared analysis as discussed in chapter 4. The data points from this data set are from different dates (T2.5 & T4.5). Since DuBeVeg is set at 52 iterations per year, the closest week in which the infrared pictures were taken are used as validation data points. The same approach is used in the validation of the changes in beach and dune volumes.

The domain which is used for each profile is determined by the profile area itself, and the upwind distance to a deep enough area so the improved beach update can work properly. The results of the calibrations are shown in table 3.7 below:

		Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3S	Profile 2S
Beach	Measured	-2,9%	-11,0%	-11,3%	2,8%	-0,6%	-18,8%
	Model	-2,9%	-10,5%	-11,0%	2,6%	-0,7%	-18,7%
Dune	Measured	2,3%	4,8%	10,0%	11,2%	17,0%	8,7%
	Model	2,4%	4,8%	10,0%	11,4%	17,0%	8,7%
Vegetation	Measured	112,1%	26,1%	6,2%	60,7%	-23,4%	-28,8%
	Model	-18,4%	-7.3%	-33,9%	-18,0%	-33,5%	-23,8%

Table 3.7: Comparison between model results, and data analysis results volume changes per coastal zone.

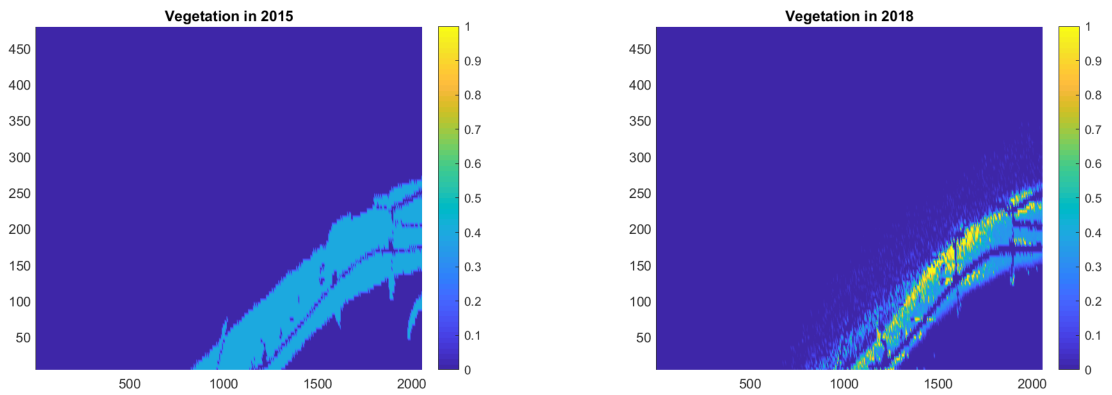
Beach & dunes

The measured and modeled volume changes of the beach and dunes in the profiles correspond very well to each other. The dunes is the most important growth rate to get right.

Vegetation

The development of the vegetation in the model runs doesn't correspond to the numbers obtained from the infrared analysis of the vegetation from chapter 4. As discussed in that chapter, the data obtained from this analysis isn't too reliable due to the limitations of infrared vegetation analysis in coastal areas.

But vegetation development is still a very important for the validity of the model. The results of the vegetation development must therefore still be assessed, albeit qualitatively. From the data analysis, it was concluded that the vegetation on the seaward crest of the dunes grows at the highest speed, and embryonic dunes have formed in front of the dunes. In figure 3.4, the starting conditions and the situation in 2018 is shown.



(a) Vegetation state in profile 2 north at t=0 (2015)

(b) Vegetation state in profile 2 north at t=3 (2018)

Figure 3.4: Development of vegetation in the HD in profile 2 north, showing increased growth rate in the seaward crest, and embryonic dune development in front of the dunes. In this figure, the sea is located in the top left corner, and the hinterland in the bottom right corner. North is situated toward the upper right corner.

The results above show higher growth rates in the vegetation on the seaward crest, and scattered vegetation seaward of it. This is qualitatively consistent with the observations made in the HD area. For the vegetation state after three years for all profiles, see appendix G.

4

Results

In this chapter, the results from the data analysis and the model study are discussed. First, the results from the data analysis are discussed. The characteristics of the forcing and the spatial data available for the HD are presented, and insights gained from this analysis is used in the model study using DuBeVeg. Phenomena found in the spatial data will be explained using the climatic data which forces the domain of the HD.

4.1. Data analysis

4.1.1. Wind

Wind forcing directly influences the magnitude and direction of aeolian sediment transport in the HD. The plot in figure 4.1 shows that the wind has a diffusive character. It shows that the wind has come from every direction at least a couple of times, but there are some wind directions which appear more often than others. In appendix C figure C.2 and C.3 the wind roses for each time period is shown. These wind roses illustrate perfectly how irregular wind direction is in this area

The wind data shows that the dominant wind direction comes from the south-west. This is a somewhat favourable dominant wind direction for aeolian sediment transport toward the dunes. The wind coming from this direction has both an onshore and a alongshore component, in which the onshore directed component is most favourable for dune growth. Another spike is from the land toward the sea, coming from the east. Wind coming from this direction is unfavourable for dune growth in the HD, as it is offshore directed. This wind direction is of a lesser magnitude than the most dominant wind direction.

This shows that the dominant wind direction is mostly alongshore directed.

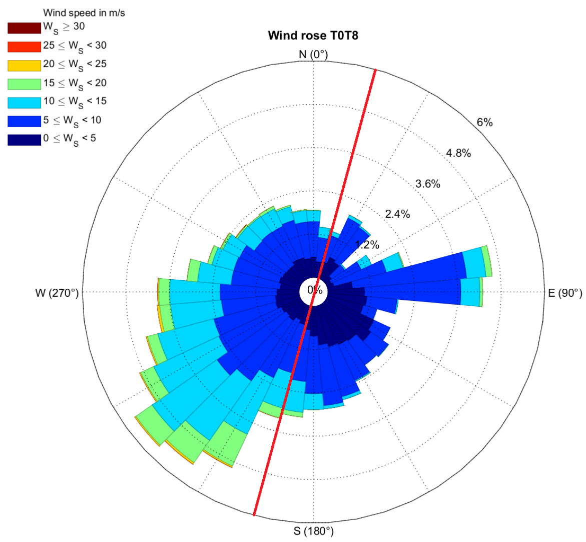


Figure 4.1: Wind direction measured at the IJmuiden weather station (T0-T8), with the red line representing the average orientation of the HD shore line. (See appendix C for wind roses for each time period).

The average wind velocity and wind direction have been calculated, and are shown in table 4.1 below. The data shows that in the period between T0 and T8, the average wind direction varies between 100 degrees and 172 degrees. (roughly coming from the west to the south).

	Average wind direction [°]	Average wind speed [m/s]
T0-T1	233	7,8
T1-T2	215	8,3
T2-T3	262	6,8
T3-T4	190	6,5
T4-T5	223	7,0
T5-T6	251	6,8
T6-T7	255	8,0
T7-T8	211	8,6
T0-T8	237	7,4

Table 4.1: Average wind directions and velocities per time period between topographic measurements. (90° = east, 180° = south, 270° = west, 360° = north).

Figure 4.1 shows all data points measured since the construction of the wind station. Wind speed varies strongly minute to minute and year to year, but no trend in wind speed has been found in this area [KNMI, 2018b]. The focus of this thesis is on the long term development of the HD, so the average wind conditions are most suitable for this study.

North sea wind climate

The overall wind in the North sea travels from west to east. This is due to the rotation of the earth, and the resulting Coriolis effect. Because of the latitude in which the north sea lies, and the direction of earth's rotation, wind at the latitude where the north sea is converges in the direction stated above. This dominant wind direction can indeed be seen in the data discussed above. The wind direction is locally influenced by surface roughness differences, being less at the sea, and higher on the land.

Though the overall wind direction is relatively stable, the wind velocity is very variable. Over the scale of decades, low and high energy periods can be distinguished. Though larger scale trends over the past 130 years haven't been observed [A. Sterl and Winter, 2014]. These decennial variations of wind speed can have a great effect local aeolian sediment transport characteristics.

4.1.2. Waves

The wave buoy is located offshore in the North Sea (see figure 3.2). This means that the buoy can measure waves going in westward direction, as can be seen in figure 4.2. This wave directions is physically impossible at the HD, as that would mean that these waves would come from land. For that reason, all data from waves on the east side of the red line in figure 4.2 is rejected. The incoming waves at the HD are further manipulated by effects such as shoaling, refraction and depth induced breaking. These effects aren't worked out in detail, as the main focus of this thesis is about aeolian sediment transport. Not about the effect waves have on the intertidal zone. But the geometry and amount of sediment in the intertidal zone influences the sediment availability for aeolian sediment transport. Therefore, waves are still an important forcing to consider when studying aeolian sediment transport.

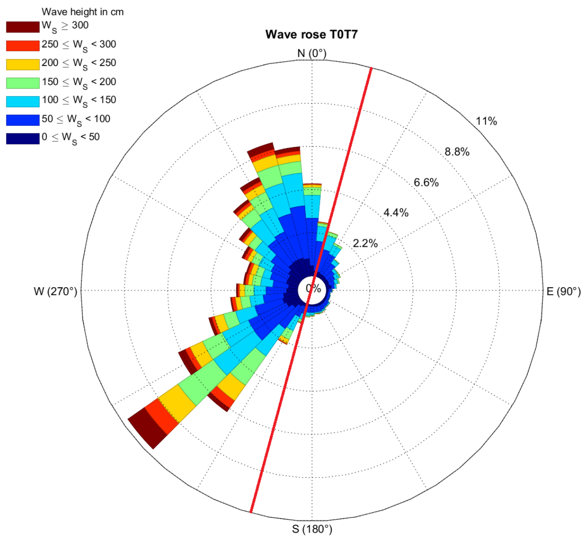


Figure 4.2: Wave direction measured at the offshore wave buoy (T0-T7), with the red line representing the average orientation of the HD shore line.

(Note that the wave data reaches from T0 to T7. This is due to data availability at the time of writing). As can be seen in figure 4.2, the wave direction has a less diffusive character than the wind has. There are two dominant wave directions, namely S-W and N-N-W. This is due to the geometry of the North Sea. Waves are generated by wind, and need a large fetch distance to grow large. Toward the NNW the North Sea continues, and toward the SW, the channel is located. Toward the West, the United Kingdom is located, and toward the east, the Netherlands is situated. Both these landmasses limit the fetch distance for wind to have an effect on the development of waves.

These dominant wave directions cause alongshore sediment transport in the north and south direction respectively. The lower intensity onshore directed waves cause cross shore sediment transport in the intertidal zone. The amount of sediment transport caused by these waves, and the direction of this transport is highly influenced by local topography.

4.1.3. Tide

The tide in the North Sea is dominated by an M2 and an S2 tide. These two tide constituents interfere with each other, resulting in a spring-neap tide cycle with a period of 14 days, 18 hours and 22 minutes. The tide moves from South to North with a period of 12 hours and 25 minutes. Though the direction of the tide is negligible, as the wavelength of the tide is much longer than the alongshore dimension of the HD. MHW (mean high water) is at a level of NAP +0.84 m. This value is used as the water line which defines border of the domain of the HD in this report. For more characteristic values of the tide at Petten Zuid, see appendix C.

4.1.4. Groundwater

The presence of groundwater in a beach or dune can have a large influence on aeolian sediment transport rate. The presence of ground water decreases the sediment availability for aeolian sediment transport. The presence of moisture increases the needed force to initiate motion of a grain, thus lowering the amount of grains which are mobilized at a given wind velocity. Other than decreasing sediment availability for aeolian sediment transport, groundwater can also stabilize or destabilize dunes, depending on the groundwater level. At very high levels, the groundwater can start to flow out of the dune. This can lead to high porous flow, which can cause sediment to be transported away from the dune through the toe. The way groundwater influences coastal dune growth indirectly is by influencing vegetation growth. Marram grass (like any other species of vegetation) needs fresh water to thrive, or even survive. The water source can either be in the form of precipitation, groundwater or irrigation. Thus a high enough groundwater level, which doesn't exceed a certain concentration of salt, can help the growth of coastal vegetation by providing water.

The groundwater level in the HD has been measured since construction up to 2017. During this period, the average groundwater level has been found to be at NAP +0.70 m in the dune foot [Caljé and Schaars, 2017]. The low groundwater level implies that the marram grass on the dunes take their water from precipitation, as the groundwater level is very low. Though the roots of the vegetation may have grown to this level since construction, in the period after construction it was certainly the case that water source of the marram grass was almost exclusively precipitation.

Furthermore, it is shown that the groundwater in the HD has elevated concentrations of chloride when compared to 'standard' groundwater. The added saltiness of the water makes the water less suitable for vegetation to use. The higher level of chloride is due to the origin of the sand in the HD, which comes from the North Sea Bed. Desalination of the groundwater in the HD can not be proven with the available data on groundwater in the HD [Caljé and Schaars, 2017].

4.1.5. Grain size

After construction of the HD was finished, the contractor had taken samples along the entire stretch of the HD area. The samples are taken 125 m apart in March of 2015. Some additional samples were taken in April 2015 to account for some abnormal samples. Additional data from my own field research and lab analysis at the VU under supervision of Dr. Maarten Prins. The samples of this research have been taken on May 14th 2018 and some additional samples on June 5th 2018, by myself with the use of a shovel and a manual auger. The additional samples taken on June 5th were necessary because the sample location was below sea level due to high tide on May 14th. The transects where the samples were taken are shown in figure 4.3 below. For more exact sample locations, see Appendix D.

Figure 4.3: Locations of samples taken in 2018 for the sieve analysis of the sand in the Hondsbossche Dunes. North is to the right in this picture.

In this section, the spatial and temporal variability of the grain size distribution is discussed. Because the data sets have been obtained with different methods, and different amounts of samples, it expected that only general trends can be obtained from this analysis.

Spatial variability (2015)

During construction, the sediment has been dredged from several different locations. As a consequence, the grain size varies over the domain. The contractor has determined the grain sizes over the domain, and calculated the d_{50} over three main areas. The results for the corresponding profile types are shown in table 4.2

	Profile 2 south	Profile 3 south	Profile 4	Profile 3 north	Profile 2 north	Profile 1
Swash	278	278	320	274	274	274
Beach	229	278	341	327	327	327
Dune foot	229	229	341	327	327	327
Dune seaside	259	259	357	358	358	358
Dune land side	-	-	357	-	-	-

Table 4.2: Average d_{50} of each measured profile determined by Boskalis and Van Oord after completion of the HD in 2015.

This table shows that the grain size varies both in cross shore and alongshore direction. The cross shore variation shows a coarsening of the grains moving land inwards. The alongshore variation shows a coarsening of the sediment in northward direction in the dunes. In the dune foot, beach and intertidal zone, the d_{50} increases in magnitude from south to north until Profile 4. Going north from here, the grain size decreases in size toward Profile type 1. In the intertidal zone, the profiles north and south of Profile 4 have very comparable grain sizes. While the grain sizes found on the beach and dune foot are significantly larger north of profile 4 compared to the area south of profile 4.

Spatial variability (2018)

As can be seen in table 4.3, the HD area now shows more natural characteristics in the regard of spatial grain size gradients. With the exception of the panorama dune in Profile 1, the cross shore variation now shows gradient closer to a natural system; finer grain sizes in the dunes, and coarser in the beach and intertidal zone.

	Profile 2 south	Profile 4	Profile 3 north	Profile 2 north	Profile 1
Swash	304.76	376.32*	574.04*	305.98	326.60
Beach	300.79	307.35	353.66	440.76	401.34
Dune foot	254.68	390.31	377.42	349.62	320.08
Dune seaside	238.06	357.18	417.23	331.85	428.56*
Dune land side	-	281.45	-	-	-

Table 4.3: Measured d_{50} at each location on the surface. (* indicates the presence of (very) coarse gravel in the samples).

The grain sizes at 1 m below the surface are shown in table 4.4 below.

	Profile 2 south	Profile 4	Profile 3 north	Profile 2 north	Profile 1
Swash	271.67	490.62	620.47*	385.97*	410.25*
Beach	344.28	388.20	487.71*	359.75	453.82
Dune foot	275.53	303.71	317.98	289.59	269.68*
Dune seaside	252.13	281.50	381.60	308.76	480.60
Dune land side	-	430.80*	-	-	-

Table 4.4: Measured d_{50} at each location at 1m depth. (* indicates the presence of (very) coarse gravel in the samples).

Temporal variability

The average grain size in the HD has changed due to climatic forcing. Depending on the location, the dominant forces responsible for this change is either hydraulic or aeolian in nature. The temporal changes on the surface (comparison between 2015 - 2018) are shown in table 4.5, and the grain size diameter changes are shown in table 4.6. Note that at Profile 2 south a suppletion had just carried out. The other profiles have remained undisturbed by human interventions of such a scale. Therefore, Profile 2 will be analyzed apart from the other profiles

	Profile 2 south	Profile 3 south	Profile 4	Profile 3 north	Profile 2 north	Profile 1
Swash	27	-	56	300	32	53
Beach	72	-	-34	27	114	74
Dune foot	26	-	49	50	23	-7
Dune seaside	-21	-	0	59	-26	71
Dune landside	-	-	-76	-	-	-

Table 4.5: Difference in d_{50} at each location on the surface between 2015-2018.

	Profile 2 south	Profile 3 south	Profile 4	Profile 3 north	Profile 2 north	Profile 1
Swash	-6	-	171	346	112	136
Beach	115	-	47	161	33	127
Dune foot	47	-	-37	-9	-37	-57
Dune seaside	-7	-	-76	24	-49	123
Dune landside	-	-	74	-	-	-

Table 4.6: Difference in d_{50} at each location at 1m depth between 2015-2018.

Profile 2 (suppletion) Profile 2 south shows an overall coarsening of the grain diameter, except in the dunes. The samples were taken just after a suppletion had been carried out on the beach and the intertidal zone. Therefore, the changes in grain size in the intertidal zone and the beach can be explained with human intervention. The coarsening in the dune foot and the refining of the grain size in the dune can be attributed to aeolian transport. Since construction, the grains in the dune foot have increased in size, and the diameter in the dunes has decreased. This can be explained by the properties of aeolian transport, where fine particles are transported further and higher in elevation than coarser grains.

Inter tidal zone & beach The intertidal zone and the beach show an overall increase in grain size diameter both on the surface and at depth. Except the beach on the surface of Profile 4. The coarsening is caused by aeolian sediment transport where finer sediments have been transported toward the dunes, leaving only the coarser particles behind.

The refinement of the particle size on the beach in Profile 4 can be attributed to local variation, alongshore transport, or human intervention (recreational digging). The extreme increases in grain size in Profile 3 north in the intertidal zone is likely a local effect. The original grain size in this area has more than doubled compared to the data obtained by Boskalis and Van Oord. During construction, this area has likely been built using particularly coarse materials which haven't been moved much due to its properties.

Dune & dune foot The dune foot and the dune itself show an overall coarsening at the surface, and a refining at a depth of 1 m. After construction, fine sediment particles were available at the surface, which have quickly been transported toward the dunes. The supply of fine sediment particles steadily declined, and the sediment transport toward the dunes consisted of more coarse particles than before. Therefore, the accreted sediment at 1.0 m depth consists of relatively fine material, and at the surface the material is somewhat coarser.

The coarsening of the dune in Profile 3 north has to do with a coarse sediment supply. The local grain size in the intertidal zone of this transect is very coarse, thus only providing coarse sediment for cross shore aeolian sediment transport. Because the sediment in the dunes was large to begin with, the increase in grain size isn't that high. The decrease in grain size at the dune in Profile 2 north, and at the dune foot in Profile 1 can be attributed to the supply of fine particles at the start of construction was locally higher, elongating the time period in which this effect was active. The coarsening of the grain size in the panorama dune in Profile 1 is due to erosion of this dune profile (see section 4.1.8. The erosion due to aeolian sediment transport first picks up the finer particles, leaving coarser particles behind which in turn increases the mean sediment size.

Conclusion grain sizes

The sand supplied to construct the HD system is in-homogeneous in grain diameter. The spatial variability is high in both cross shore, alongshore and in the vertical direction since construction has been complete. The climatic forcing has had its influence on the surface of the HD system, which now (2018) shows more natural spatial variability in grain size distribution when compared to the starting situation. Measurements taken at a depth of 1 m in locations where no significant sedimentation has taken place, show unexpected grain sizes when looked at from a natural processes point of view. These grain sizes are explained by the spatial variability which was present right after construction. Locations where significant sedimentation has taken place, the samples taken from 1 m depth show more expected grain sizes when viewed from a natural processes perspective.

So, the trend in the HD area is that the grains coarsen in the beach and intertidal zone, and in the dunes the d50 becomes smaller. Any measurements that don't follow this trend can be explained by variability in the grain size of supplied sand during construction.

4.1.6. Vegetation

As introduced in chapter 2.1, vegetation has a stabilizing effect on coastal dunes, and thus helps coastal dunes to grow. Therefore, healthy vegetation is very important for the safety which coastal dunes can provide. The most prominent species of vegetation in the HD is marram grass. This plant has been planted in the HD, but it is not the only vegetation type which is present in the area. Other types of bushy vegetation grows mainly on the landside of the HD. Though the main focus of this analysis is on marram grass.

The vegetation planted during the construction of the HD has been harvested from the Dutch coast between Petten and Den Helder (north of the HD area). The harvesting has been done using two methods, thinning out the vegetation and harvesting entire areas. Between these two methods, there is no difference in the quality of the harvested marram grass [HHNK/TU Delft and HHNK, 2018].

Though vegetation is very important for a good sandy coastal protection, not much data is available on the quantity and quality of vegetation in the HD area. After construction, the locations of vegetated areas were mapped, but no notes were taken on the health or density of the present vegetation. To be able to make an analysis of the vegetation development, three sources have been called upon. Namely, aerial photographs, infrared aerial photographs, and an interview with the area manager of the HD.

The LiDAR scans used to determine the topography of the HD, also provides us with aerial photographs of the area. The data of these photographs contains a red, green and blue band. For the purposes of a vegetation analysis, infrared photographs are needed. Therefore, the photographs taken at the same moment as the LiDAR scans aren't suitable for a quantitative vegetation analysis. But the global development of vegetation can be derived from the pictures by eye. Though the results of this type of analysis is hard to quantify, and only global trends can be derived from this data set.

In 2016 and 2017, infrared aerial photographs have been taken of the area which can be used to make a vegetation analysis. This data will be analyzed on two properties of the vegetation, namely: vegetation density, and vegetated area. So this data set can be used to have a more detailed view of the vegetation in the HD, though the time steps between the data points are longer, and the amount of data points is low.

Another data source is the measurements made right after construction. These measurements represent the starting conditions of the HD area with respect to the state of the vegetation. This data source has been used in the initial state and calibration of the model in chapter 3.

The final source of information is an interview with the area manager of the HD Martien Witte. His insight and experience in the HD is very valuable for understanding why the vegetation in the HD has developed the way it has. His remarks have helped explain the findings from the aerial photographs, both visible light and infrared,

Visible light data analysis

In this analysis, the aerial photographs available of the HD area are compared to each other in chronological order. This analysis provides insight in the overall growth pattern of the marram grass in the HD, but doesn't provide any numbers regarding the total vegetated surface, or the density/health of the vegetation.

T0-T1 This period spans the summer, and the start of winter. During this period, the marram grass is still being planted in profile 3 north to profile 1 on top of the dunes, and from the top of the dunes toward the dune foot over the entire domain. Other than the active addition of marram grass, the planted vegetation seems to have grown in this period. Though this increase in density is very small.

T1-T2 During this period, some vegetated areas in the southern part of the HD seem to have disappeared. This can be attributed to incoming sediment, and decreased growth rates due to the season. During this period it is winter, in which higher rates of sedimentation, and lower vegetation growth rates are to be expected.

T2-T3 The vegetation in areas which has been buried in the previous period has returned during this period. During this period it has been spring and summer, which comes with higher growth rates of marram grass, and relatively lower expected sedimentation due to seasonality. The increase of vegetated area can be seen on the aerial photos, where the color contrast between the sandy and vegetated areas is higher, and the vegetated area has expanded seaward in the form of embryonic dunes. This growth is most notable in the south, and less so in the north as can illustrated in figure 4.4.

(a) Aerial photo of profile 1 and 2 north

(b) Aerial photo of profile 2 south

Figure 4.4: Comparison of vegetation cover in the north and south of the HD domain, showing healthier vegetation in the south.

T3-T4 During this period, the situation regarding vegetated area hasn't changed much. The growth, and burial rate seem to be roughly in balance. This is due to the period itself, being autumn. In this time of year, vegetation growth rates slow down, and aeolian sediment transport rates are expected to go up. During this period these effects have balanced each other out.

T4-T5 During this period, a lot of vegetation disappears from view. Embryonic dunes in profile 2 North, 3 North, and seaside part of the dunes in profile 3 south and 2 south have disappeared, likely buried by incoming sediments. Also at higher elevations in the larger dunes this effect is observed.

T5-T6 The embryonic dunes and seaside parts of the dunes which seemed to have lost vegetation coverage and density in the previous period, now have increased vegetation cover and area. Because of this, it can be concluded that these areas have experienced high amounts of sedimentation in the previous period, and in this period, the marram grass has grown with the sedimentation from the previous period.

T6-T7 The same effect can be seen in the period as in the period T4-T5, in which certain areas of vegetation seem to have disappeared. Because the aerial photograph of T7 is the latest available photo, it cannot be proven that is the same effect, but when looking at the topographic data, it can be seen that a high amount of sedimentation has taken place at these locations.

Infrared data analysis
For this analysis, infrared pictures of the HD area from 'Beeldbank Nederland' have been analyzed using a NDVI function. This function uses red and infrared light, and based on their intensities it determines whether vegetation is present in the regarded cell or location. This method only assesses the amount of vegetation at the surface, whereas a large amount of the biomass (roots and rhizomes)

of marram grass is below surface. The density of the vegetation is hard to quantify, as factors such as the amount of sunlight, clouds, rain and other climatic effects influence the intensity of the red and infrared light captured by the camera. For this reason, the intensities and boundary values for vegetated and non-vegetated cells for each infrared aerial photograph differs. No known values for vegetation density are known in the surrounding area of the HD which can be used to calibrate the density scale of the vegetation analysis. For this reason, the vegetation density of the cells in the vegetation analysis couldn't be obtained. But the total area of vegetated cells in the HD has been found, and presented in table 4.7. The time frame indication is a bit odd, at half intervals. This is because the infrared pictures have been taken on July 18th 2016 and June 22nd 2017. These dates fall in between T2-T3 and T5-T6, hence the indication T2,5 and T5,5.

	T2,5 [m^2/m]	T5,5 [m^2/m]
Profile 1	45	96
Profile 2 north	47	60
Profile 3 north	42	45
Profile 4	58	94
Profile 3 south	100	76
Profile 2 south	89	63
HD	66	75

Table 4.7: Vegetated area in the HD

In the table, it can be seen that the total surface area of vegetation has increased. Though not all profiles show an increase in vegetated surface area. Profile 2 south and profile 3 south show a decrease in vegetated surface area. The decrease in surface vegetation in these profiles can be attributed to high rates of sedimentation in these locations. The marram grass has been buried in these profiles, and therefore they don't show up on the infrared photographs. But, the vegetation is still there, and after some time the vegetation grows back to above the surface. Therefore, this data source is difficult to use and to analyze. The results are not very useful, as it can only measure vegetation at the surface, while a lot of biomass is below surface due to high rates of sedimentation.

Interview area manager

North south differences can be attributed to 3 factors. The first is the time of planting the marram grass. During construction, the marram grass was first planted in the south, and the work was continued northward until completion. A constant density of nine seedlings per m^2 had been planted in the dunes of the HD. The work started at the beginning of the growth season, and by the time the north was reached, the optimum time of plantation had passed [HHNK/TU Delft and HHNK, 2018].

The second contributing factor is the method of extracting the marram grass from harvesting sites. For healthy transplantation of marram grass, a certain amount of roots and growth nodules need to stay intact. The quality of the transplantation of the marram grass deteriorated over time. This is due to the excavation depth of harvesting marram grass staying constant, while the harvesting area experienced sedimentation. To accommodate for this effect, deeper excavation is needed. This measure hasn't been implemented during construction, resulting in lower quality, marram grass [HHNK/TU Delft and HHNK, 2018].

A third cause of the alongshore variation can be traced to the breeding habits of birds. The harvesting locations of the marram grass used in the HD also function as a breeding ground for certain types of birds. Because access to this area is restricted during this time, the marram grass was harvested at a high rate of speed. The marram grass was then stored for plantation later. The storage method was insufficient to ensure the health of the marram grass, resulting in lower quality vegetation. This effect had more influence later in the construction period, which equates to the north of the domain due to the construction method [HHNK/TU Delft and HHNK, 2018].

In cross shore direction, the marram grass tends to expand toward the sea. This can be explained by the fact that marram grass needs an influx of sediment to grow properly. Generally sediment in coastal areas travels from the sea toward the dunes, hence the optimum vegetation growth being located at the dune foot.

Excursion HD

On the 4th of June 2018, Ecoshape organized an excursion to the HD to monitor the developments in the area. I have taken part in this yearly organized excursion, to see the state of the vegetation first hand. The experts present that day have shared their knowledge and expertise to help explain the observations in the HD, also regarding the interaction of the vegetation with aeolian sediment transport. The analysis is about more than only marram grass, and included many plant species. The report resulting from these yearly excursions have been used in this thesis.

The observations from the site visit indicate that the vegetation on the seaward side of the HD is mainly made out of marram grass. The marram grass has established further toward sea in the form of embryonic dunes. A north south divide in the health of the vegetation (not only marram grass), has been observed. One of the identified reasons for this divide is that the sediment in this area is less rich in calcium, an important nutrient for vegetation [W. Bodde, 2018].

On the landward side of the HD, other species have established themselves. These species don't necessarily need incoming sediment to thrive as marram grass does. So these species live in different habitats in the HD, and they stabilize these areas against aeolian transport, or erosion.

Conclusion - vegetation

Overall, it can be concluded that the marram grass in the HD grows steadily. However, there is variation in the health and growth rate of the vegetation over the domain. Though the observations from the different sources seem to contradict each other. The analysis of the aerial photographs and the interview with the area manager conclude that the health of the vegetation is better in the south, and gets worse traveling in northward direction. But the infrared analysis seems to contradict these statements, and this analysis concludes that it is the other way around; better vegetation health in the north, and worse in the south.

As said before, infrared analysis cannot measure biomass which is present under the surface (roots and rhizomes). It is therefore possible that the vegetation in the southern profiles was buried in transported sediments, decreasing the accuracy of the observations in this analysis. This is also the case in the analysis of non-infrared aerial photographs. Though there are more of these photographs available, in which the return of the marram grass above the surface is observed. Therefore, it is concluded that the marram grass in in the south is of a better quality than the vegetation in the northern profiles.

The vegetation other than marram grass is steadily growing on the land side area of the HD. These species are also important, as they grow in areas where marram grass can't. Thereby stabilizing areas in the HD which otherwise would be unprotected from aeolian erosion.

4.1.7. Beach

As introduced in section 3, the dry beach volume is the volume between NAP +0,84 m and NAP +3,50 m. The domain is further divided into profiles, which have been introduced in chapter 1, and further defined in section 3. In this section, the differences in beach volume, slope and width are presented for each subsequent time period. The change during the entire period since the first measurement and last is also discussed. For the absolute beach volumes of each measurement date, see Appendix D.

The LiDAR data used in this analysis has some missing data points. This is a result of scatter, the presence of buildings and other objects among other things. To be able to use this data, these gaps are filled with the use of linear interpolation.

Beach volume

Beach volume is important for the growth of dunes in the sense that the beach acts as a source sediments, and as a conveyor for aeolian sediment transport. Thus, it is important to have some understanding of what goes on on the beach in terms of volume changes. If there is no to very little transportable sediment present on the beach, dune growth is likely to be very small. A high amount of sediment availability on the beach doesn't necessarily mean that dunes will grow at a high rate, as wind speed and direction, and grain sizes have an equally important influence on the aeolian sediment transport on the beach. But the amount of available sediment is a good indicator for the potential aeolian sediment transport. The changes in beach volume over the periods per profile is shown in table 4.8 below.

	T0-T1	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6	T6-T7	T7-T8	T0-T8
Profile 1	-48	-16	19	-25	-24	28	67	-33	-6
Profile 2N	-71	-12	29	-38	-28	18	-31	-10	-21
Profile 3N	-62	42	-3	-23	-56	-6	-53	19	-24
Profile 4	25	44	14	11	-17	-4	-41	8	6
Profile 3S	-9	-8	17	23	-16	10	-16	-9	-1
Profile 2S	-36	-120	13	-4	-106	10	-106	-25	-43
HD	-33	-11	15	-9	-41	9	-30	-8	-15

Table 4.8: Beach volume changes per time period in m3/m/year

T0-T1 (24-05-2015 - 28-12-2015) During this period, erosion is experienced in all profiles except profile 4. In the profiles which experience erosion, the erosion isn't uniform, as locally accretion is observed on the beach. The dominant wave direction is from the southwest, which induces an alongshore sediment transport toward the north. The eroded sediments from profile 2 south and 3 south travel toward profile 4. These sediments accumulate here, causing the local accretion. Because the sediment transport stops here, or hasn't had enough time to travel further, the profiles north of profile 4 don't have much incoming sediments. Therefore these downstream profiles have an increased erosion rate.

Also, these erosion/sedimentation rates are from the period right after construction. Therefore, high amounts of transport are expected during this period.

T1-T2 (28-12-2015 - 21-03-2016) In this period, profiles 4 and 3 north show accretion. profile 1 and 2 north and 3 south still show erosion, but on a decreased rate. Profile 2 south however, shows a dramatically increased erosion rate of 120 m^3 per meter per year. This can be attributed to the wave attack and the orientation of this profile to the waves. The waves are more intense during this period, though in direction very comparable to the previous period (see Appendix C). Some of the sediments eroded from profile 2 south has likely ended up north in the HD. This partly explains the accretion and decreased erosion rates in the profiles north of profile 2 south.

T2-T3 (21-03-2016 - 01-09-2016) All profiles show accretion during this period, except profile 3 north which shows a small erosion rate. The dominant wave direction is different during this period, coming from the northwest instead of the southwest like in the previous periods. There is still a peak from the southwest, but not as large or intense as the peak from the northwest. Also, the wave height is lower than during the previous periods. This wave direction induces an opposite alongshore sediment direction, going south instead of the average direction north. This causes the the sediments transported from the HD to the north to return. The lower wave heights encourage cross shore sediment transport toward the HD, causing a net import of sediment on the beach.

T3-T4 (01-09-2016 - 05-12-2016) During this period, profile 4 and 3 south show accretion, and the other profiles show erosion. There is a large spread of incoming waves during this period, coming from the northwest, southwest, and some high waves coming in roughly perpendicular to the beach orientation. The wind during this time has had an offshore character, transporting sediment from the dunes toward the beach. Due to the orientation of the beach and dunes, this effect has more influence on the northern dunes. These profiles are more east-west orientated than the other profiles. These factors combined explain in part why the profile of accretion and erosion occurred as it has.

T4-T5 (05-12-2016 - 19-04-2017) During this period, the highest erosion rates have occurred in the HD. This is because of the high intensity waves during this period. The waves came in from both dominant wave directions (northwest, and southwest). Because these wave directions induce opposing alongshore sediment transports, cross shore transport has likely caused the erosion measured during this period.

The highest erosion rate has been measured in profile 2 south. This is due to a gully in front of the coast which migrates to the north. This gully has been filled during the construction of the HD, but due to hydrodynamic processes, it slowly returns in the bathymetry. See appendix E for more information. Because this has been a high energy period, the gully migrated at an accelerated pace, causing high rates of erosion to occur.

In the south of profile 4 and 3 south, local sedimentation of the beach has been observed. This can be attributed to the fact that the erosion in this locations have mostly taken place below the defined dry beach profile. Thus influencing the sediment balance in these locations, with a measured sedimentation as a result.

T5-T6 (19-04-2017 - 11-08-2017) All profiles show a low amount of accretion, except profiles 3 north and 4, which show a low amount of erosion. During this period, the wind speeds and wave heights were relatively low, which can be seen in the low amount of aeolian and hydrodynamic activity in the HD. The dominant wave direction is from the southwest during this period, inducing an alongshore sediment transport rate towards the north. As can be seen in figure 4.10, profile 5 has lost a lot of sediment volume. A fraction of this sediment has been transported toward the north, and has accumulated in profile 2 and 3 south.

The accretion in profile 1 and 2 north can partly be accredited to the eroded sediments from profile 3 north coming into the profiles via alongshore sediment transport. The overall sedimentation of the domain indicates that positive cross shore sediment transport has occurred, or more sediment has come in in alongshore direction than has gone out.

T6-T7 (11-08-2017 06-12-2017) The average erosion rate during this period has been the second highest. High erosion rates over the domain, except in profile 1. This profile actually shows high rates of accretion. The dynamic nature during this time can be attributed to high intensity waves coming from the southwest and northwest. Profile 2 south again shows a high erosion rate due to the migrating gully in the south.

T7-T8 (06-12-2017 - 19-03-2018) Profile 3 north 4 show accretion, and the other profiles show erosion. Especially the beach in profile 2 south has lost a lot of sediment during this period. Just below the dune foot there, local erosion has decreased the height of the beach with more than 2 meters. During this period, a storm had taken place which is the cause of the beach erosion.

T0-T8 (24-05-2015 - 19-03-2018 As can be seen in table 4.8, the beach overall erodes over the entire domain. Though some periods of accretion can be seen (T2T3 & T5T6). These periods contain large parts of the summer in 2016 and 2017 respectively. During summer, the wave conditions are generally less energetic compared to winter periods. When looking at the wave roses in Appendix C, this is indeed the case. The only profile which shows accretion over the entire temporal scale, is profile 4.

The overall erosion of the beach was expected in the design of the HD. This is due to the fact that the HD protrudes of the Holland coast. This causes a discontinuity in the coastline, which interferes with the northward directed average alongshore sediment transport. Because of the direction of this average hydrodynamic sediment transport, profile 2 south is especially vulnerable.

Another cause of the systematically higher erosion rates of profile 2 south, is a underwater gully which migrates from toward the HD from the south. This is caused by the bend in the local shoreline orientation, and the fact that the gully of a near shore sand wave is slowly coming closer. This eats away sediment, destabilizing the beach, which causes the high speed of sediment loss in this profile.

Beach slope

As concluded in the previous work on the HD, the beach slope is an important parameter in dune volume growth. The beach width is equivalent to this parameter, because the beach area is defined as the area of elevations between NAP +0.84 m, and NAP +3.50 m. In appendix D a table with the beach widths and changes in beach width is shown.

Following from previous research [Wittebrood, 2017], the gentler the beach slope, the easier, and faster sediment is transported toward the dunes. The average beach slope is determined for each regarded profile in the HD, by computing the actual beach surface, and the projected beach surface on the horizontal plane. These surfaces are divided over the length of the profile, and using trigonometry, the average beach slope is obtained. Table 4.9 below shows the temporal changes in beach slope, with a positive number indicating a steepening beach slope, and a negative number indicating that the beach is getting a gentler slope.

	T0-T1	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6	T6-T7	T7-T8	T0-T8
Profile 1	1,24	-0,63	0,86	0,25	-1,08	2,12	-0,47	-1,61	0,25
Profile 2N	-1,01	1,96	0,51	0,64	-0,80	2,23	-0,98	1,72	0,29
Profile 3N	-0,36	3,48	0,43	-0,34	-0,95	2,47	1,41	-1,36	0,42
Profile 4	1,09	1,22	-1,03	0,04	-0,01	1,11	0,80	-1,60	0,22
Profile 3S	-0,75	-0,92	0,82	-0,31	-0,75	1,49	0,02	1,33	0,07
Profile 2S	-0,95	-0,07	1,86	-2,00	1,03	3,00	3,90	15,73	2,39
HD	-0,12	0,84	0,57	-0,29	-0,43	2,07	0,78	2,37	0,61

Table 4.9: Beach slope changes, average for each profile in degrees/year

The beach in all profiles get steeper, with relatively comparable rates. Except profile 2 south. The average steepening of the beach in profile 2 south over the entire measurement period is an order of magnitude larger than in the other profiles. Especially in the period T7-T8. This is caused by the same influences which caused the volume changes in the beach in T6-T7. It appears that the beach slope responds to these effects with a delay in time.

Conclusion - beach
The sediment supply for aeolian sediment transport toward the dunes in the HD steadily declines, as the beach volume declines in all profiles except for one. In profile 4 the sediment supply actually increases over the period since construction, facilitating a more suitable climate for dune growth.

The beach slope is a measure for resistance to aeolian sediment transport toward the dunes. This resistance steadily increases, as all profiles in the HD increase in slope. Inhibiting the transport of sediments toward the dunes

4.1.8. Dunes

As previously described, the dunes are defined as the volume of sand which resides at NAP +3,50 and higher. The dune volumes of the data sets have been analyzed, and compared to each other. The changes in dune volumes have been calculated for the time periods between each consecutive measurement date, and for the whole period of data collection. The volume changes have been normalized to a change in volume per alongshore meter, per year. This way, the change in dune volume per profile per period can be easily compared to each other (see table 4.10). The below plots are somewhat distorted spatially, as the curvature of the shoreline isn't taken into account. But these plots are useful in providing insight in the alongshore dune growth nonetheless. Also note that the surrounding area of the domain of this thesis (profile 1 to profile 2 south) is shown in the plots. Other than profile 5, the surrounding area is made up of more natural dunes

	T0-T1	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6	T6-T7	T7-T8	T0-T8
Profile 1	8	2	8	26	-32	14	53	-9	9
Profile 2N	24	28	10	27	7	12	9	17	17
Profile 3N	47	35	12	30	21	10	19	30	25
Profile 4	19	8	20	36	35	30	42	46	29
Profile 3S	58	57	34	33	44	24	65	65	47
Profile 2S	56	43	25	35	29	10	32	0	29
HD	35	29	18	31	17	17	37	25	26

Table 4.10: Dune growth per time period in m^3/m/year

The data shows that the dunes (nearly) constantly grow in volume during the time of data collection. Only dune profile 1 shows a decrease in dune growth in the periods between T4-T5 & T6-T7. And Profile 2 South shows a stationary behavior during the last period between measurements. The dune volume changes are described per period below.

T0-T1 (24-05-2015 - 28-12-2015)

The first period after construction shows an above average dune growth speed, and is positive in every profile in the HD. The growth rate is highest in profile 3 south, and lowest in profile 1. As can be seen in figure 4.5, local sediment losses are observed profile 1. These losses can be found at the panoramic dune in this profile.

The wind speed and direction is very close to the average conditions measured during the time since construction. The high dune volume accumulation speed can be attributed to the fact that this is the first measured period after construction. The effects of grainsize distributions and beach geometry in time are discussed below.

The highly dynamic nature during this period can be attributed to the sediments still being well mixed. The effects of sediment sorting haven't had sufficient time to establish after construction, so a relatively high amount of fine sediment is available at the surface, which is picked up more easily by the wind.

As concluded from the previous section, the beach is steadily eroding and the beach slope is steepening. As is the case with sediment sorting, this effect hasn't had enough time to establish properly. Therefore, the resistance a steep beach slope induces on aeolian sediment transport still is at a low level.

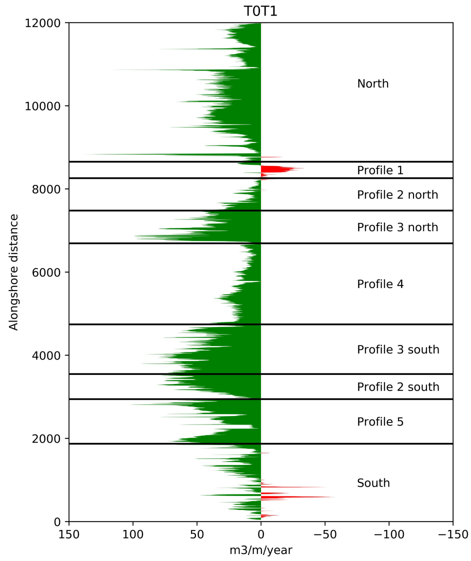


Figure 4.5: Dune volume change in period T0-T1

The effects of vegetation are roughly the same in the entire domain. The marram grass has just been planted, and the differences in vegetation health, and therefore effectiveness of the vegetation, haven't had time to establish yet.

T1-T2 (28-12-2015 - 21-03-2016)

In this period, here is a significant drop in overall dune growth speed compared to the previous period. Though the dune growth speed is still slightly above the average of the entire measured scale. In profile type 1, local erosion of the panorama dune has slowed down, but is still significant. In profile 4, accretion of the dune profile has occurred in the dune valley, and local erosion at the seaside dune. The change in dune volume varies a lot in alongshore direction in profile 4. Profile 3 north experiences local erosion in the south of the sub-domain.

This can be attributed to the wind direction during this period The percentage of offshore directed wind is relatively high. Offshore winds don't provide the dunes with sediment, as there is no sediment source in the hinterland. Therefore, these winds can only erode the dunes. In this period, the amount and speed of the offshore winds is lower than the onshore directed winds. Therefore, the dunes are still accreted during this period.

In the previous period, the beach slope has increased in profile 1, and 4. These profiles show the largest decrease in accretion rates of the dunes, reducing the growth of the dunes to less than half compared to the previous period.

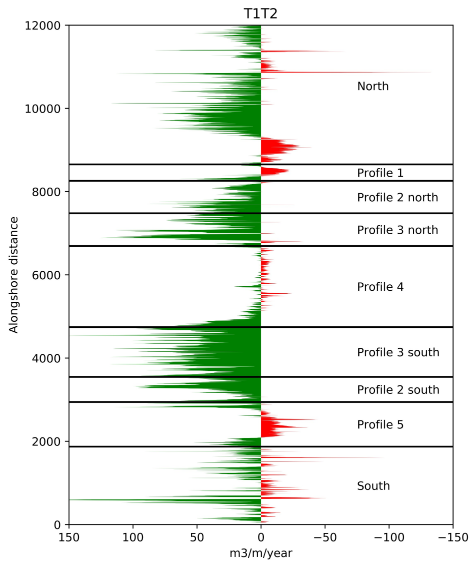


Figure 4.6: Dune volume change in period T1-T2

The effects of the grain size distribution and vegetation have had little time to establish. Especially the marram grass, as this period falls outside the growth season.

T2-T3 (21-03-2016 - 01-09-2016)
The dune growth speed during this period is significantly below average. All profiles have had a decreased sedimentation rate compared to the previous period, except profile 1. Small local volume losses are observed in profile 4, 3 north, 2 north, and again large losses in the panorama dune in Profile 1. The volume losses in profile 1 are compensated by accretion in the lower dune areas in this profile.

During this period, the wind has been calm, and it has come mainly from the south west. The low velocities of the wind explain the low activity during this period, and the favourable wind direction explains that the volume differences have been mainly positive.

The effects of the steepening beach can again be noticed in the accretion rates of the different profiles. Especially in profile 1, where the beach has decreased in slope and despite the lower wind velocities, the dune accretion rate has gone up.

This is the first period which spans the growth season of the marram grass. As concluded in the previous section, the growth in the south of the domain has been more positive than in the north. This effect can be seen in the divergence of growth speeds in the northern and southern profiles. Dune growth speeds have decreased in all profiles, but this rate is fastest in the northern profiles. Indicating that the effect of vegetation health differences start to have an effect. Though other factors contribute to this effect also.

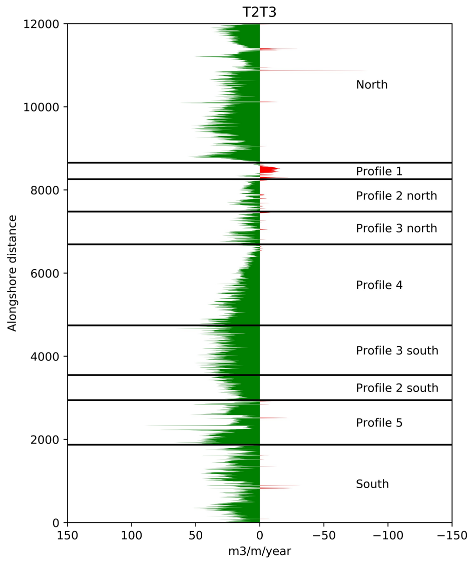


Figure 4.7: Dune volume change in period T2-T3

The local losses can be attributed to unfavourable dune geometry in profile 1, and the small local losses in the northern profiles can be attributed to less favourable wind direction in relation to the dune orientation.

T3-T4 (01-09-2016 - 05-12-2016)
Again, during this period dune accretion has been positive along the entire domain of the HD, as can be seen in figure 4.8. The panoramic dune has again been eroded, though the surrounding lower dunes accreted at a higher rate. Therefore, the losses of the panoramic dune don't clearly show up in figure 4.8.

The wind during this period has mostly been directed offshore. But the wind velocity of these winds have been very low, while the low amount of onshore directed winds have had a higher velocity. Since aeolian sediment transport is determined by the cube of the wind speed, the low amount of high speed onshore directed wind trumps the high amount of low velocity offshore directed winds in this situation. Hence the net inflow of sediment into the dunes during this period.

The beach is now steeper than the previous periods. This event should inhibit transport toward the dunes, but this cannot be observed in the data. Profiles where the beach has steepened, and profiles where the beach has flattened show similar growth rate changes. Therefore, the effects of wind characteristics and vegetation seem to have had more effect on the aeolian transport in this period.

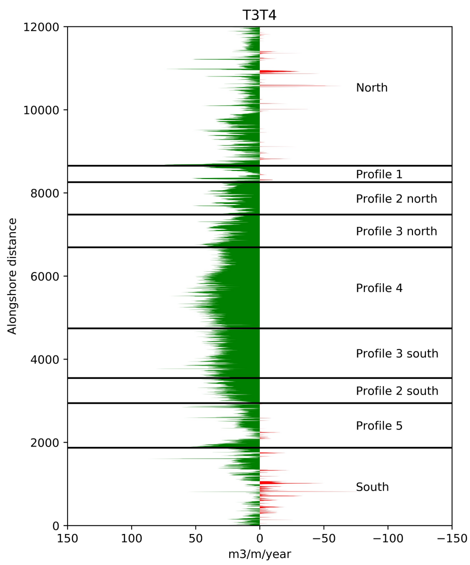


Figure 4.8: Dune volume change in period T3-T4

The marram grass has now had time to settle and grow (as discussed in the vegetation analysis). This increase of vegetation has stabilized the dunes, and inhibits outflow of sediment. Again helping to keep the net sediment transport positive in the dunes. The difference in vegetation health can now be seen in the dune growth rates. Dune accretion is faster in the southern profiles, when compared to the northern ones.

The north south divide isn't only caused by the difference in vegetation density, the orientation of the dunes also has a major influence. The northern profiles dune orientation is more oblique to the dominant wind direction than the southern ones. Especially in profile 1, where the dominant direction is nearly parallel to the dune crest.

T4-T5 (05-12-2016 - 19-04-2017)

During this period, the average dune growth speed has dropped significantly. This is mostly due to the loss of dune volume in Profile 1 in the north (see figure 4.9), and low accretion rates in profile 2 north. The local volumetric losses can be attributed to sedimentation of the footpath and bicycle path in this area. A lot of sand had been deposited on these paths by the wind, and it had been removed to ensure the function of these roads.

The wind has had high velocities, with the dominant wind direction coming from the south west. Due to the orientation of the dune profiles, the wind comes in obliquely onshore in the southern profiles, and more alongshore directed toward the northern profiles. This partly explains the sediment loss in the dunes in profile 1. As the wind transports wind from the upwind dunes into profile 1. The marram grass in these profiles, although of low quality and growth density, still resist aeolian transport more than sediment on the beach. Low amounts of incoming sediment, and a higher amount of outgoing sediment has lead to the decrease of sediment volume in this profile. The panoramic dune even shows accretion on the upwind (south) side, indicating that the low amount of sediment coming into the profile comes from the dunes of the upwind profiles.

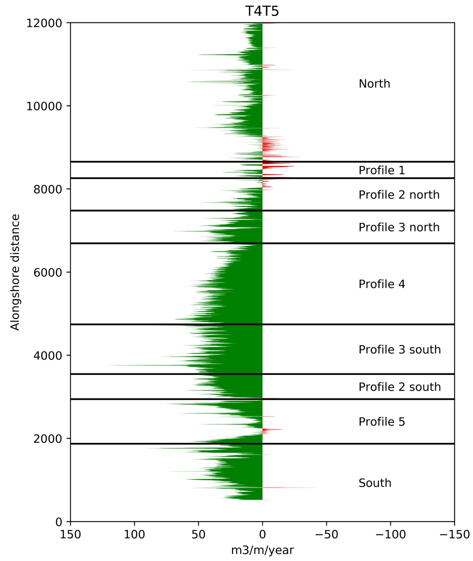


Figure 4.9: Dune volume change in period T4-T5

The increased growth rate in profile 3 south, and stable growth rate in profile 4 and 2 south can be attributed to the gentler beach slope during this period. The effect of the gentler beach seems to counteract the effects of the alongshore wind conditions during this period.

T5-T6 (19-04-2017 - 11-08-2017)

The overall dune growth speed over the domain is equal to the one in the previous period. But the alongshore variation of the change in volume is distributed differently. Profile 1 shows overall accretion, but local erosion at the panorama dune, and the bicycle parking lot.

During this period, the wind has a more onshore directed character, with a lower velocity compared to the previous period (see table 4.1. This is especially favourable for the dunes in the northern profiles, because of their orientation. The dune growth rates in the southern profiles are lower, because of the lower average wind speed during this period.

During this period, the beach has steepened at a high rate everywhere in the domain (see table D.12.

The effect of the diverging vegetation quality in the south and north can now be clearly seen. The accretion rates in the northern profiles is systematically lower than in the southern ones.

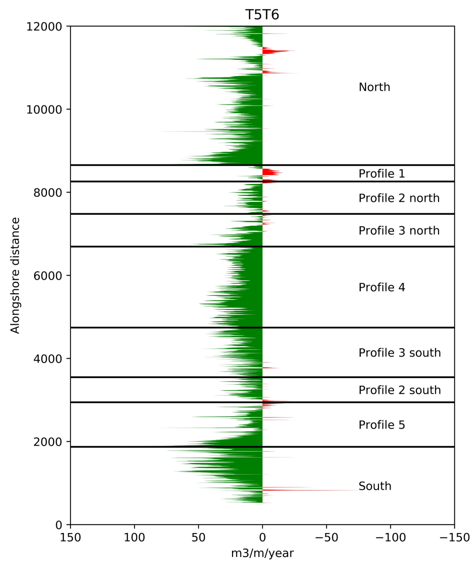


Figure 4.10: Dune volume change in period T5-T6

T6-T7 (11-08-2017 06-12-2017)
In this period, the highest average dune growth rate has been observed. Also, the highest accretion rate for a profiles has been observed during this period, in profile 3 south, which is actually matched in the following period.

The high dune growth rates van be attributed to the very favourable wind direction and speed. A large part of the wind was onshore directed, with the dominant wind direction coming from the west. Some offshore winds have been measured, but these were of a small magnitude.

The effects of well mixed sediment caused by the construction has now decreased in its influence. Therefore it is reasonable to assume that less sediment is available for transport on the beach and intertidal zone.

During this time, the beach in all profiles except profile 1, show erosion. This indicates that the sediment source for the dunes accretion is at least in part the beach. In profile 1 however, the sediment doesn't come from the beach during this period. It is likely that the sediment accreted in this profile came from the beaches and dunes from the downwind, southern profiles.

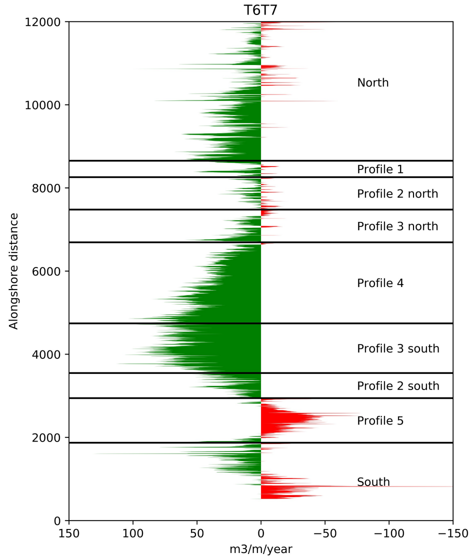


Figure 4.11: Dune volume change in period T6-T7

The vegetation has now had more than 2 years to grow and stabilize the dunes. The north-south difference in density and vegetation health is now very much present. This low health vegetation explains how the accretion of both the dune and beach in profile 1 is possible. The grains in the profiles north of profile 4 are more mobile, due to the low amount of healthy vegetation. The wind can therefore transport the sand toward profile 1. Because of the transport mode, likely being saltation and surface creep, it takes some time to travel out of profile 1. Therefore, the accretion has been measured in profile 1.

T7-T8 (06-12-2017 - 19-03-2018)
The overall dune accretion rate of the HD is very nearly on the average over the entire time period of measurements since construction, at 25 m^3/m/year. The spatial variability of accretion rates is very strong during this period, as shown in table 4.10 and figure 4.12, and it is positive over most of the terrain. In profile 2 south shows a dynamic balance over the domain, where the dune growth rate is around zero. The only profile which shows loss of sediment in the dunes is profile 1.

The average wind direction is onshore directed, but there is also a significant portion of the wind offshore directed. The offshore component of the wind during this period has a smaller velocity compared to the onshore directed wind. Due to the nature of aeolian sediment transport, the onshore wind induces more sediment transport thanks to the higher speeds.

The effects of the construction of the HD in regards to the well mixedness of the sediment have now largely died out. Therefore the behaviour of the dunes now more closely resemble a more natural system.

Beach steepened,

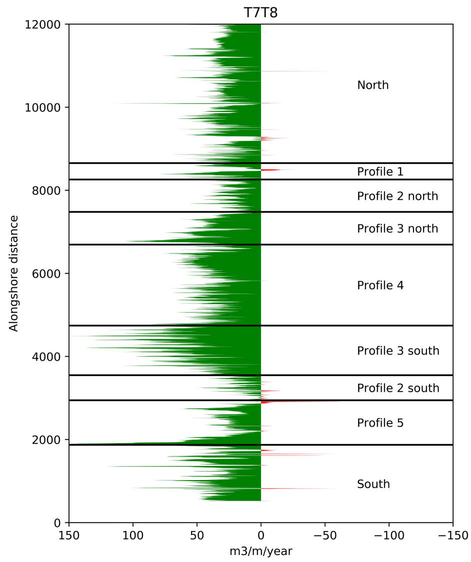


Figure 4.12: Dune volume change in period T7-T8

The difference in accretion rates due to vegetation density and health can be seen clearly in the dune growth rates during this period. The southern profiles

These losses can be attributed to the geometry of the dune in the case of profile 1, and due to the wind direction.

T0-T8 (24-05-2015 - 19-03-2018

Over the entire period since construction, the dunes have grown with the exception of the panoramic dune in profile 1. The average growth rate in profile 3 north and 2 north varies with the maximum rate at in the south, and the minimum at the north. This pattern can also be seen in profile 4. in profile 3 south, the dune volume change is positive and of the same magnitude over the entire profile. Profile 2 south shows the inverse relation which is seen in profile 2 and 3 north.

Though the growth hasn't been uniformly positive, overall the design of the HD has been effective. Except for the panoramic dune in profile 1. This part of the HD has steadily lost sediment, as it is at a higher elevation. This causes it to experience higher wind velocities, and any incoming sediment has to overcome a relatively high elevation at a steeper slope. On top of that, the marram grass on this dune cannot grow properly under this conditions. Meaning that stabilization is at a minimum on this dune.

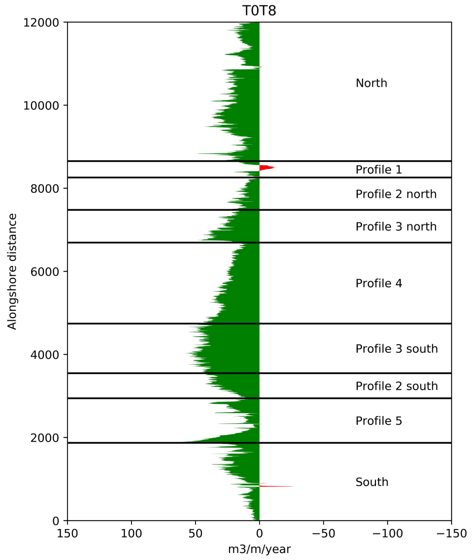


Figure 4.13: Dune volume change in period T0-T8

4.1.9. Conclusion

The dunes in the HD have had the highest rate of change right after construction. The aeolian transport rate tended to decrease as time went by, but the rates still had a high amount of variability. The main cause for this variability is the wind speed and direction in relation to the dune geometry and orientation. Though this is the main driving force in aeolian sediment transport, other factors had an effect on the dynamics of the HD too.

The most important parameter in aeolian sediment transport is the wind. Both the direction and the magnitude of it have the greatest influence on the development of coastal dunes. This isn't surprising, as it is the driving force in aeolian sediment transport, as explained in chapter 2.

Over time, the effects of sediment sorting on the beach has decreased the amount of sediment easily picked up by the wind. After construction, the sand on the beach and in the dunes was well sorted on a small scale, but with high variability on the longer scale. Over time, aeolian processes first take up the finer particles as they require lower velocity winds, and they travel faster over the domain. The supply of these smaller particles decline, and the large slower particles remain, decreasing the aeolian sediment transport rates in the process. The local wind speed and direction is affected by the geometry of the dunes. Furthermore, the definition of onshore, offshore and alongshore are all governed by both the wind direction and the shoreline (or dune) orientation. These effects are found in the performances of the different profile types. The northern versions of profile 2 and 3 have a less favourable orientation in relation to the dominant wind direction. This is proven by the findings of dune growth rates, which are significantly lower in the north compared to the south.

The beach volume and slope has already been determined to be an important factor in aeolian transport in the HD area [Wittebrood, 2017]. Under the influence of the waves and tide, the beach has steadily declined in volume, and the slope of the beach has steepened and become gentler. With the end result being an steepening of the beach slope over the entire domain. Both these phenomena negatively influence aeolian sediment transport rates. Decreased beach volume decreases sediment availability, and an increased beach slope increases the resistance to aeolian sediment transport.

In the HD, the importance of healthy vegetation in sandy coastal protections is illustrated perfectly. Healthy vegetation is vital for high accretion rates in the dunes of the HD. In the south where the marram grass was planted properly, accretion rates are The vegetation in the north has been improperly placed, leading to a reduced robustness of the vegetation. Though other factors mentioned above have played an important role in the difference in development of the northern and southern areas, the health of vegetation isn't a subordinate of these factors.

Groundwater doesn't have a lot of influence in the development in the dunes of the HD. The measured groundwater table is too low for the groundwater to inhibit aeolian sediment transport by increasing the resistance of the grains to movement.

4.2. Model study

In this section the calibrated model is used to simulate the scenarios as defined in 3.3.1. For each defined profile of the HD, a base measurement is made in which the calibrated model is run for 50 years. After that, the model is run in which nourishments are applied, as defined in chapter 3. These two scenarios are the base scenarios which are used as a reference to which the other results are compared. The base cases are also compared to each other, to determine the effectiveness of nourishments. Sea level rise and differing wind climates are modeled in situations with and without nourishments. The results are presented in order of the position of the profiles, starting at profile 1 in the North of the domain, and ending at profile 2 south, and the southern end of the HD. See figure 4.14 for reference.

Per model run, six graphs are generated, showing the dune volume, beach volume, beach width, and grensvolume (border volume). The vegetated area is defined as the surface area of the cells which contain any amount of vegetation. The vegetation density is defined as the average density of the vegetated cell in the profile domain. The two base cases (normal conditions with nourishments, and normal conditions without nourishments) are the basis of the model study. The results from these scenarios are compared to each other, and the results from the sea level rise and wind climate change scenarios are compared to the base cases.

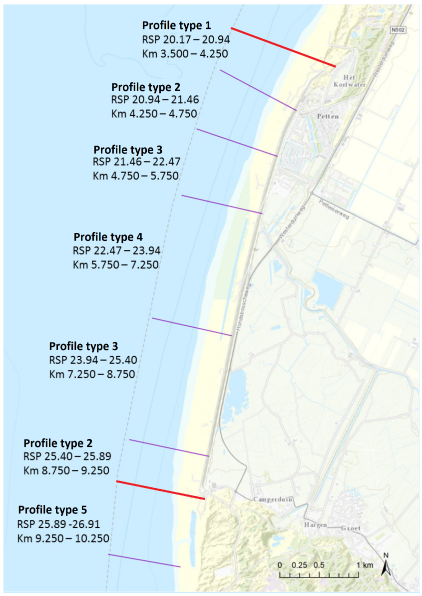


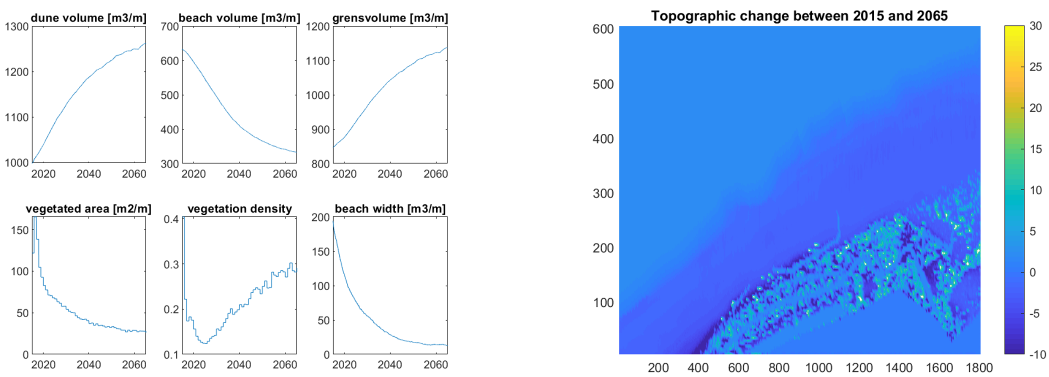
Figure 4.14: Profile areas in the HD

4.2.1. No nourishment

In this section, model runs of each profile are discussed in which the calibrated model is run for 50 years without changing any model parameters, and without the application of nourishments. The model starts in 2015, and continues to the year 2065. The observations and general trends are explained with knowledge from DuBeVeg, and related to the actual physics which have been discussed in chapter 2.

Profile 1

As can be seen in figure 4.15a, the dune volume in this profile grows, and the beach volume declines, with a tendency toward a stable equilibrium. The dune growth and beach decline can clearly be seen in the difference plot in figure 4.15b. The total amount of vegetated area decreases over time, while the average vegetation density grows after an initial decline. The grensvolume and beach width show similar behaviour to the dune and beach volume respectively.



(a) Temporal variation in dune and beach volume, and vegetation growth

(b) Topography change between 2015 and 2065

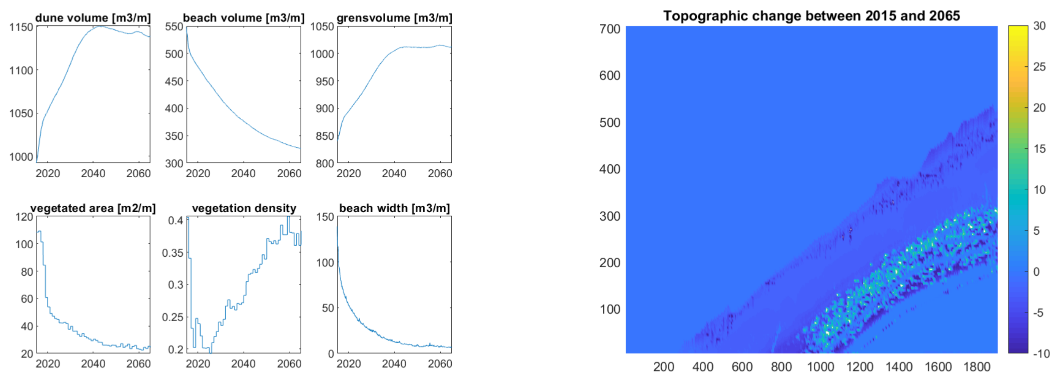
Figure 4.15: Base measurement without nourishments result for Profile 1

The volume increase in the dunes comes from the beach, but not all sediment lost on the beach has ended up in the dunes. As can be seen in table 4.11, the average beach erosion rate is -7 m^3/m/year, whereas the dune accretion rate is +5 m^3/m/year. The remaining 2 m^3/m/year coming from the beach is transported in cross shore direction to the deeper sea, by hydrodynamic processes, and a smaller portion is transported from the dunes toward the hinterland.

The initial dune growth rate is larger than the growth rate later on. This difference can be attributed to the availability of sediment, and the location of the sediment. As sediment is transported from the beach toward the dune, the elevation of the beach is lowered. Thereby increasing the area of the beach which is whetted by the spring-neap tidal cycle of the sea. Thereby limiting the sediment availability for aeolian sediment transport toward the dunes.

Profile 2 north

As can be seen in figure 4.16a, the dune growth and beach decline pattern of Profile 2 is similar to that of Profile 1. This can be seen spatially in figure 4.16b. The average beach erosion rate is -4 m^3/m/year, and the dune accretion rate is +3 m^3/m/year. The beach erodes due to aeolian and hydrodynamic processes, and the dune grows as a result of a net inflow of sediment. Though in this profile, the dune volume has reached a maximum in the year 2040. After that, the dune slowly erodes.



(a) Temporal variation in dune and beach volume, and vegetation growth

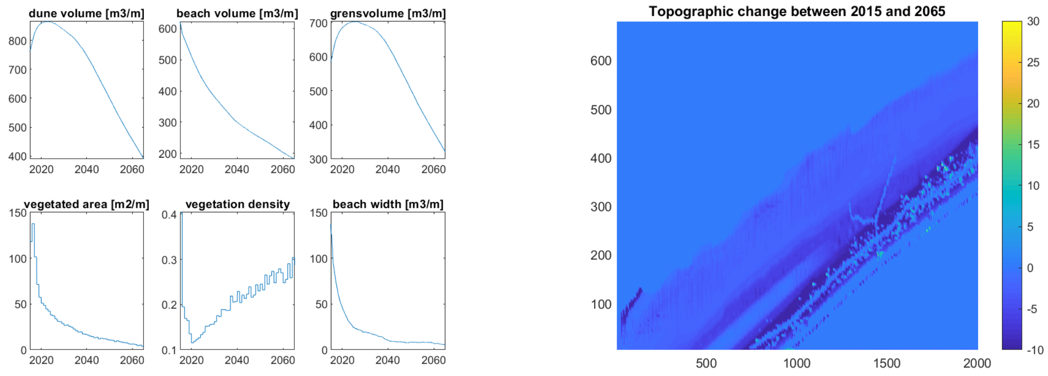
(b) Topography change between 2015 and 2065

Figure 4.16: Base measurement without nourishments result for Profile 2 north

Because no storms are simulated in DuBeVeg, and the imposed average water levels don't reach the elevation of the dunes, aeolian processes are the cause for this decline in volume. Just as in Profile 1, the sediment availability on the beach is lowered due to aeolian and hydrodynamic processes. Therefore, the aeolian sediment transport toward the dune goes down. Also, the vegetated area goes down to a very low value of 23 m^2/m. This low amount of vegetation isn't enough to stabilize the dune, and protect the dune from aeolian dune erosion. The combination of increased aeolian dune erosion, and decreased incoming sediment from the beach results in a net loss of sediment in the dunes.

Profile 3 north

In this profile, the dune and beach are both nearly eroded away after 50 years. The initial behaviour is similar to the previous two profiles, but erosion of the dune kicks in in the year 2025, and continues until the end of the simulation. With an average beach erosion rate of -9 m^3/m/year and an average dune erosion rate of -7 m^3/m/year. The vegetated area decreases faster compared to the simulations in the previous two profile areas, nearly reaching a value of 0 m^2/m at the end of the simulation.



(a) Temporal variation in dune and beach volume, and vegetation growth

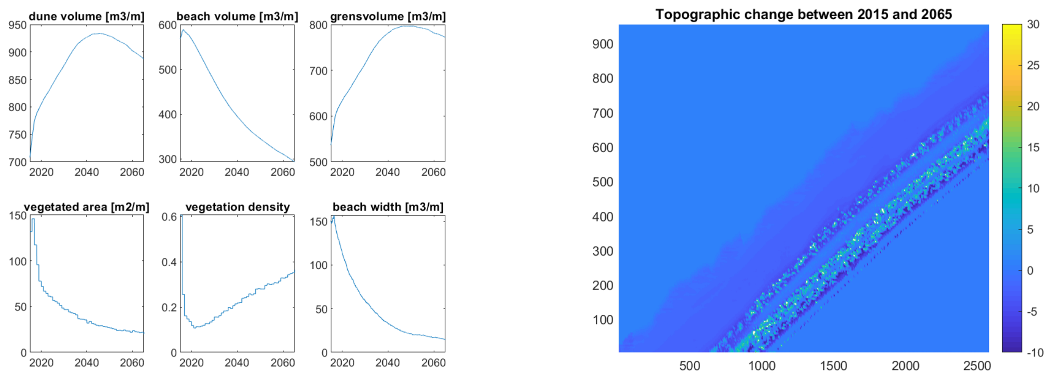
(b) Topography change between 2015 and 2065

Figure 4.17: Base measurement without nourishments result for Profile 3 north

The erosion of the dune is explained by the same mechanism as is present in Profile 2 north. The combination of lower sediment availability on the beach, and the very low amount of vegetated area on the dune result in a net outflow of sediment in the dune as a consequence of aeolian forcing. The difference between Profile 2 north and Profile 3 north is that the decrease of vegetated surface area in Profile 3 North is faster, and reaches a lower value. Also, the beach erosion rate is 2.25 times higher than that of Profile 2 North.

Profile 4

As can be seen in figure 4.18a, the dune growth an beach erosion rate in this profile is very similar to that of Profile 2 north. The vegetated surface area decreases, and the average vegetation density increases after an initial dip. The dune accretes, and reaches its maximum value in the year 2046, after 31 years of simulated time. The average beach erosion rate is -6 m^3/m/year, and the dune accretion rate is +4 m^3/m/year. The sum of these two accretion/accretion rate is non-zero. This is the consequence of hydrodynamic erosion of the beach, and sediment loss from the dune to the hinterland.



(a) Temporal variation in dune and beach volume, and vegetation growth

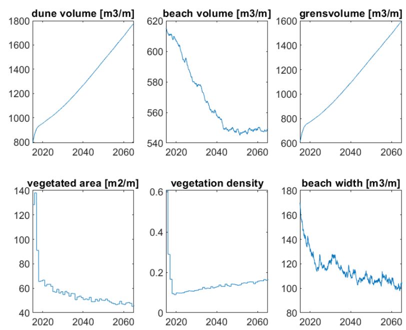
(b) Topography change between 2015 and 2065

Figure 4.18: Base measurement without nourishments result for Profile 4

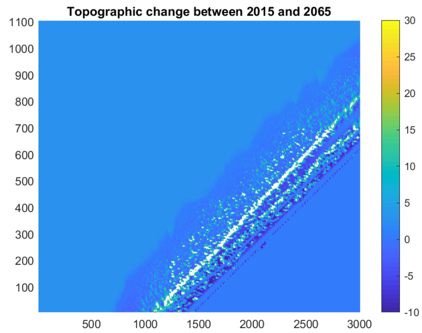
Just as in the other profiles where the dune starts to erode after a while, the dune erosion is due to aeolian processes in combination with a low amount of vegetated surface area and vegetation density. The sediment availability is lowered due to the eroding beach, resulting in a higher sediment income in the dune.

Profile 3 south

As can be seen in figure 4.19a, the dune volume continuously grows, with the maximum rate in the first 2 years of the simulation. The beach volume declines, and reaches an equilibrium after 30 years of simulation time. The vegetated surface area increases in the first 2 years, after which it quickly decreases, and then slowly decreases in surface area. The average beach erosion rate is -2 m^3/m/year, and the dune accretion rate is +20 m^3/m/year.



(a) Temporal variation in dune and beach volume, and vegetation growth



(b) Topography change between 2015 and 2065

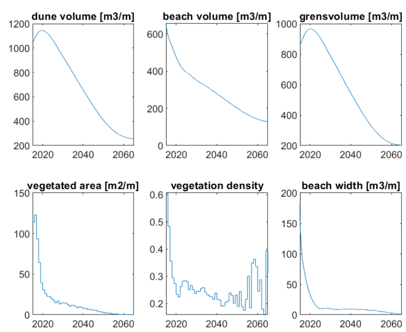
Figure 4.19: Base measurement without nourishments result for Profile 3 south

The low rate of beach erosion and high rate of dune accretion indicates that the hydrodynamic processes actually supply sediment to the beach. Aeolian processes pick up this sediment faster than it is supplied, resulting in an eroding beach.

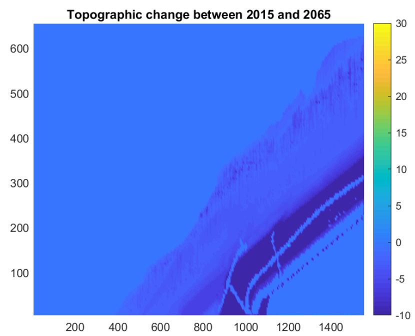
The change in dune accretion rate after 2 years is due to loss of sediment from the dune to the hinterland. this can be seen from the fall of vegetated surface area, which coincides with the decrease in dune accretion rate. The dune still continues to grow though, as the beach volume only decreases by a small amount. Still leaving enough sediment on the beach available for aeolian sediment transport toward the dunes.

Profile 2 south

As can be seen in figure 4.20a, the dune volume grows to a maximum in the year 2026, and then decreases to a very low value. The beach volume decreases rapidly at lower rates as time goes on. As can be seen in figure 4.20b, the dune and beach areas both show erosion. The end state of this profile actually shows that the dune profile has decreased dramatically in height. The average beach erosion rate is -11 m^3/m/year, and the dune erosion rate is -16 m^3/m/year.



(a) Temporal variation in dune and beach volume, and vegetation growth



(b) Topography change between 2015 and 2065

Figure 4.20: Base measurement without nourishments result for Profile 2 south

The aeolian dune erosion is caused by the low amount of incoming sediment from the beach, and the low amount of stabilization the low amount of vegetated area provides to the profile. Because the dunes are eroded so much after a while, the height of former dunes becomes so low that the average water levels start to reach these areas. Enhancing hydrodynamic erosion rates even more, until only the non erodible elements in the profile are left (foot and bicycle paths, and the sea dike. see figure 4.20b).

Conclusion no nourishments

Sediment availability, and vegetation generated dune stabilization are very important parameters for coastal dune growth. In average conditions, coastal dune growth is the balance of incoming and outgoing aeolian sediment transport. Sediment availability on the beach ensures that aeolian processes can provide a high sediment income for the dunes to grow. As can be seen in table 4.11, high beach erosion rates in Profiles 3 north, and 2 south show corresponding high dune erosion rates.

	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3S	Profile 2S
No nourishments beach	-7	-4	-9	-6	-2	-11
No nourishments dune	+5	+3	-7	+4	+20	-16

Table 4.11: Average beach and dune growth rates without beach nourishments

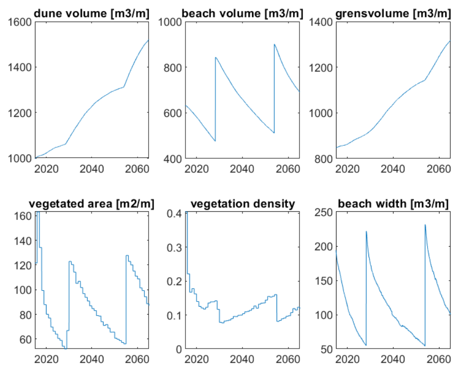
The same aeolian processes can cause the sediment in the dunes to move out of the dunes toward the hinterland. The presence of vegetation inhibits the outflow of sediment in the dunes by sheltering the sediment from the wind, lowering the local wind velocity at the dune surface. Resulting in lower forcing on the sediment in the dune, thereby lowering the outgoing sediment transport from the dune. Profiles 1, 2 north, and 4 show dune accretion even though the sediment availability declines over the simulated period. This is due to the healthy amount of vegetation on the dune. In these profiles, the dune accretion rate is lower in magnitude than the beach erosion rate. Indicating that not all eroded beach volume ends up in the dune. An amount the beach sediment is transported away by hydrodynamic processes toward the sea, and some is transported out of the dunes toward the hinterland. Profile 3 south shows a higher dune accretion rate than beach erosion rate. This indicates that the beach is actually accretion, though at a lower rate than sediment is transported toward the dune. Therefore, sediment availability and the presence of enough vegetation largely governs dune growth dynamics in the HD.

4.2.2. Nourishment

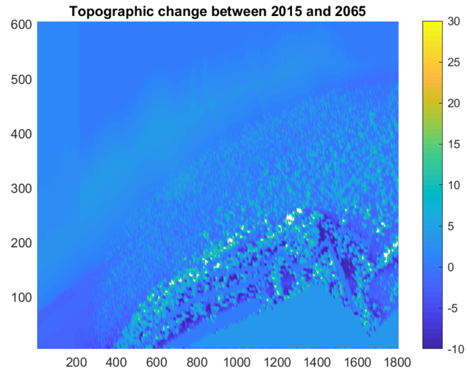
In this section, the results from the model runs with nourishments applied are discussed. The nourishment design, and application criteria have been discussed in chapter 3.3. The results are discussed per profile, and are compared to the results without nourishments. Please note that in the difference and topography plots, vertical lines can be seen. These lines are the results of the implementation of nourishments in DuBeVeg. In all simulations, these lines are found outside of the regarded profile domain, and under average water level, outside of the beach and dune areas. These lines show part of the nourishment design, and are unaffected in these areas due to the simplified nature of the hydrodynamic part of DuBeVeg in deeper areas of the sea.

Profile 1

As can be seen in figure 4.21a, two nourishments have been applied in Profile 1 as a response to average forcing, with the first one in 2028. Both nourishments have been triggered by the minimum beach width criterion of 50 meters. The nourishments have a large effect on all measured parameters shown in the figure. The beach volume and beach width are directly influenced by the nourishments, because this is the location where the added sediments is placed. The dune volume and grensvolume grow faster, because more sediments are available for aeolian transport. The vegetation also responds to the placement of beach nourishments.



(a) Temporal variation in dune and beach volume, and vegetation growth



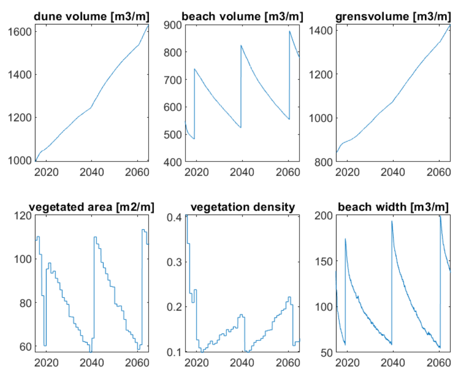
(b) Topography difference between 2015 and 2065

Figure 4.21: Zero-measurement results for profile 1

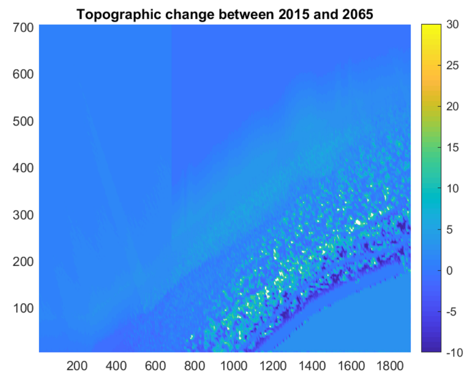
After each nourishment event, the vegetated area becomes larger as more area is at an elevated level, and sedimentation rates in these areas are at an optimum rate for the vegetation to expand into. The average vegetation density though, goes down after each nourishment. This is because the newly vegetated areas (embryonic dune areas) have a low vegetation density. Thus bringing the average vegetation density down. The average dune accretion rate over 50 years has increased by 10 m^3/m/year, and the beach accretion rate has increased with 11 m^3/m/year (see table 4.12 and 4.13).

Profile 2 north

The applied nourishments have a large positive effect on the dune, beach and vegetation development in this profile, similar to the effect it has on Profile 1 In this profile, three nourishments have been applied, with the first one being carried out in 2019 (as can be seen in figure 4.22a). All the nourishments have been carried out to ensure the minimal beach width of 50 meters. The average dune growth rate over 50 years is 13 m^3/m/year, which is roughly 10 m^3/m/year higher than in the case of this profile without nourishments. The beach growth rate is now positive at 5 m^3/m/year, roughly 9 m^3/m/year higher than this profile without nourishments (see table 4.12 and 4.13).



(a) Temporal variation in dune and beach volume, and vegetation growth



(b) Topography difference between 2015 and 2065

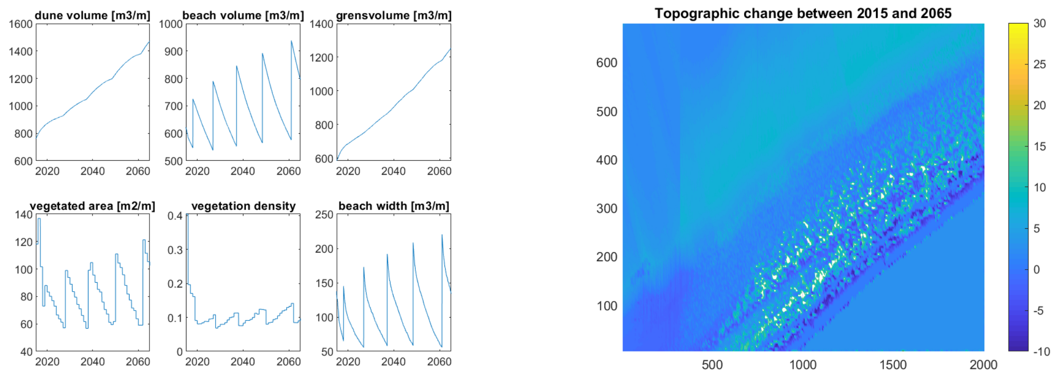
Figure 4.22: Zero-measurement results for profile 2 north

The vegetation, just as in profile 1, reaches a slightly higher maximum density after each subsequent nourishment. Though the difference in these maximum values is lower, as the interval between the nourishments is smaller. Therefore the vegetation has less time to grow between resets, resulting in lower vegetation density growth.

As can be seen in figure 4.22b, the beach profile shows accumulations of sediment on the beach area on the topographic change map. These accumulations resemble small embryonic dunes, and are a consequence of the last applied nourishment.

Profile 3 north

In this profile, a total of five nourishments have been carried out in the simulation, with the first one in 2018. Again, all the nourishments have been carried out to maintain the minimal beach width of 50 meters, as the grensvolume hasn't been under crossed at all. The average dune growth rate over 50 years is 22 m^3/m/year higher, and the beach accretion rate is 12 m^3/m/year higher than in the case without nourishments. Resulting in accretion rates of +14 m^3/m/year and +3 m^3/m/year respectively (see table 4.13).



(a) Temporal variation in dune and beach volume, and vegetation growth

(b) Topography difference between 2015 and 2065

Figure 4.23: Zero-measurement results for profile 3 north

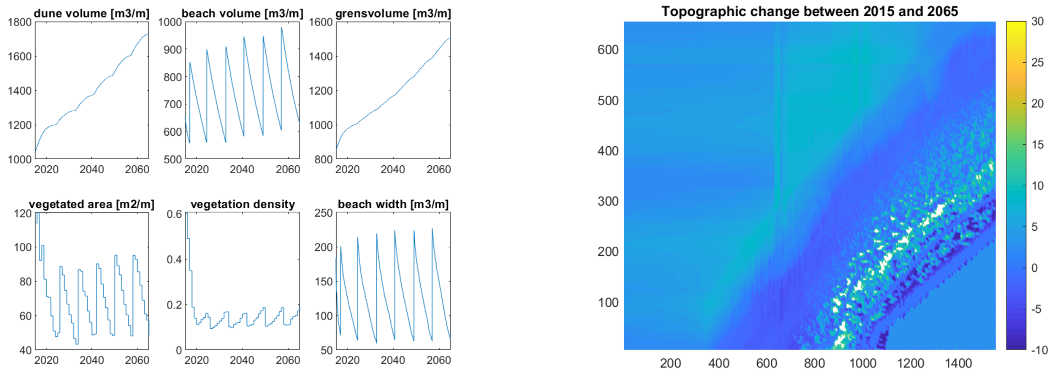
The base case of Profile 3 north showed a eroding dune profile, while in the case of nourishments, the dune continually grows. The application of nourishments have completely changed the dune growth pattern of this profile. Because the return period of beach nourishments is very short (compared to Profile 1 & 2 north), the vegetation doesn't have a lot of time to grow in between nourishments. This can be seen in the average vegetation density in this profile, which only slowly increases in average density.

Profile 4 and Profile 3 south

In these profiles, no nourishments have been necessary based on the criteria stated in the contract with the contractor. Though the beach width does get below 50 meters, this isn't a criterion for these profiles as they are located in the nature reserve zone. As discussed in chapter 3.3, there is no minimum required beach width to comply with to ensure the function of this area in the HD. Therefore, only in the case that the minimum required dune volume is going to be undercut, a beach nourishment is applied. This minimum requirement isn't reached under the average conditions simulated in the model runs, and therefore no nourishments have been applied under this criterion. Therefore, the results of these scenario's are the same as the results discussed in section 4.2.1 and 4.2.1.

Profile 2 south

In this profile, six nourishments have been carried out. Just as in the other profiles, all these nourishments have been triggered by the minimal beach width criterion. The first nourishment has been carried out in late 2017. This is earlier than in actuality, where the first nourishment in the HD in this profile has been carried out (march 2018, see chapter 1). The model therefore appears to overestimate beach erosion, but the qualitative behaviour corresponds to the findings of the data analysis. The average dune and beach growth rate over 50 years with nourishments are +29 m^3/m/year and +10 m^3/m/year higher than without nourishments respectively (see table 4.13).



(a) Temporal variation in dune and beach volume, and vegetation growth

(b) Topography difference between 2015 and 2065

Figure 4.24: Zero-measurement results for profile 2 south

The response of the beach, dune and vegetation parameters to the nourishments are similar to those found in the other profiles. Dune and beach volumes grow, vegetation surface area increases initially after which it slowly declines. Average vegetation density initially decreases as a consequence of newly low density vegetated areas, after which the average density goes up, as the cells with low vegetation density don't contain any vegetation anymore.

Conclusion nourishments

Beach nourishments have a large influence on aeolian sediment transport in the HD. The nourishments directly increase the sediment content of the beach, thereby ensuring sediment availability for aeolian transport toward the dunes. Next to providing sediment for aeolian sediment transport, the nourishment accommodates area for vegetation to expand into. Thereby stabilizing the surface, and increasing the overall health of the vegetation. As can be seen in table 4.12 and 4.13, Profile 4 and Profile 3 south don't show any difference in dune and beach growth rates. This is because no nourishments have been needed during the simulated period.

Beach	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3S	Profile 2S
No nourishment	-6 (0)	-4 (0)	-9 (0)	-6 (0)	-2 (0)	-11 (0)
Nourishment	+1 (2)	+5 (3)	+3 (5)	-6 (0)	-2 (0)	-1 (6)
Difference	+7 (2)	+9 (3)	+12 (5)	0 (0)	0 (0)	+10 (6)

Table 4.12: Comparison between beach growth rates with and without nourishments in m^3/m/year, with the amount of applied nourishments between the brackets.

Beach accretion rates are positive for all profiles where the beach has been nourished (see table 4.12). Though the average beach accretion rate in the case of nourishments is a bit trivial, as it largely depends on when the latest nourishment has taken place. As can be seen in the plots above for the profiles with nourishments, the minimum and maximum beach volume values increase over time. Thereby ensuring sediment availability, which can be seen in the average accretion rates of the dunes (see table 4.13).

Dune	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3S	Profile 2S
No nourishment	5 (0)	+3 (0)	-7 (0)	+4 (0)	+20 (0)	-16 (0)
Nourishment	+10 (2)	+13 (3)	+14 (5)	+4 (0)	+20 (0)	+14 (6)
Difference	+5 (2)	+10 (3)	+22 (5)	0 (0)	0 (0)	+29 (6)

Table 4.13: Comparison between dune growth rates with and without nourishments in m^3/m/year, with the amount of applied nourishments between the brackets.

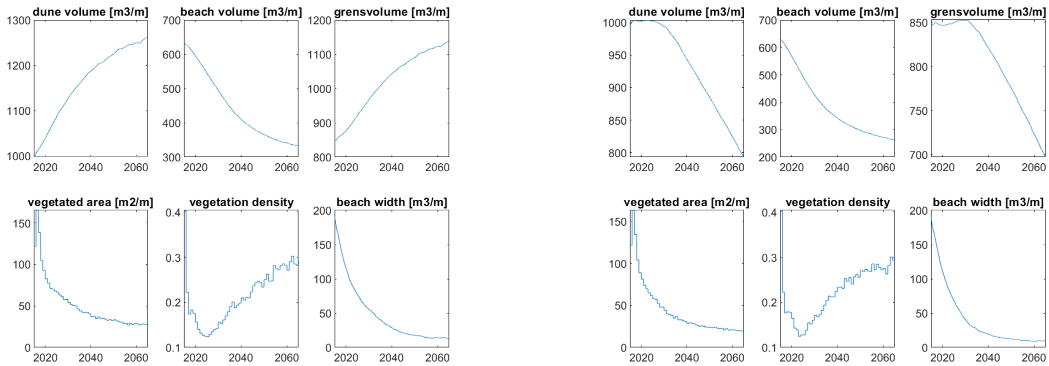
As can be seen in table 4.13, Profile 2 south shows the highest increase in dune growth rate, and the highest amount of applied nourishments. This is because in the case without nourishments, this profile has the highest beach erosion rate. Nourishments directly counteract the beach erosion, ensuring sediment available for aeolian transport toward the dunes. The difference in sediment availability hence explains the high difference in dune accretion rates.

4.2.3. Sea level rise

In this section, the results from the sea level rise simulations as discussed in section 3.3 are presented. The volume changes in the beach and dune, and general behaviour of the profiles are compared to the base cases with and without nourishments respectively. The general trends and observations are discussed, and any deviating results will be discussed more in depth.

Sea level rise - No nourishments

Sea level rise increases the erosion rate of the beach in the HD. Though the magnitude of this effect differs greatly for every regarded profile area in the domain. The largest effect of sea level rise has been observed in Profile 1 in the case of high sea level rise (see figure 4.25). The profile changed from an accreting dune area into an eroding dune area.



(a) Temporal variation in dune and beach volume, and vegetation growth without sea level rise

(b) Temporal variation in dune and beach volume, and vegetation growth with high sea level rise

Figure 4.25: Comparison between no sea level rise, and high sea level rise in Profile 1

Table 4.14 shows the difference in dune accretion rate between the base case and the different sea level rise scenario's Sea level rise has a relatively large influence on dune growth rates in Profile 1, 3 south, and 2 south. In the case of Profile 1, the accretion dune of the base case has changed into an eroding dune in all three sea level rise scenarios (see figure 4.25, and Appendix H for the numbers). Profile 2 north, and Profile 4 show a smaller eroding effect of sea level rise, and Profile 3 north even shows an accreting effect on the dune growth rate in the case of high sea level rise.

Dune	Profile 1	Profile 2 N	Profile 3 N	Profile 4	Profile 3 S	Profile 2 S
SLR low	-7.15	-0.19	-0.01	-0.16	-0.28	-0.34
SLR mid	-8.20	-0.44	-0.11	-0.28	-1.29	-2.62
SLR high	-9.38	-0.49	+0.28	-0.72	-2.92	-4.14

Table 4.14: Average dune growth rate differences compared to the base case without nourishments [m^3/m/year]

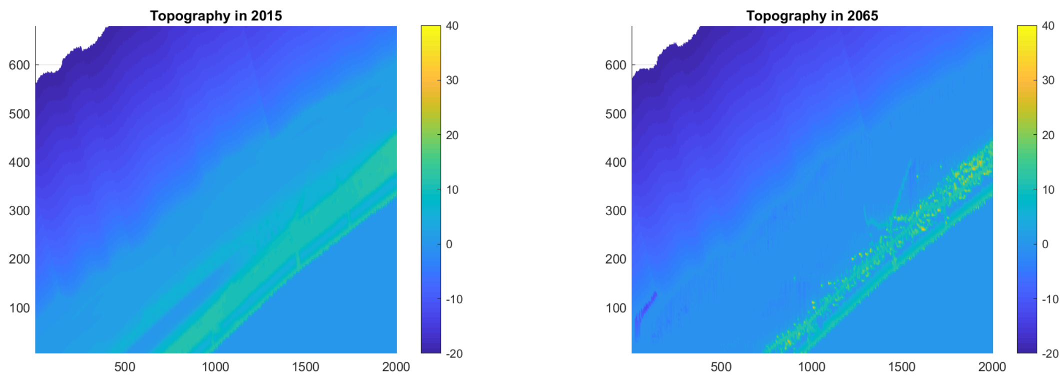
The decrease in accretion rate is caused by the lower sediment availability caused by sea level rise. When looking at the results of the beach erosion profiles in table 4.15, it seems that the erosion rates actually go up. This isn't actually the case, and this can be explained with the definition used as the beach profile. The definition of the beach rises with the average sea level rise. So in 50 years time, the definition of the beach zone has migrated upward, and now includes part of the original dune area. This effect can cause a seemingly less eroding, or even accreting beach profiles as a result of sea level rise.

As can be seen in table 4.15, the profiles with the largest decrease in dune accretion rates also have the highest increase in beach erosion rates.

Beach	Profile 1	Profile 2 N	Profile 3 N	Profile 4	Profile 3 S	Profile 2 S
SLR low	-0.31	+0.08	+0.12	+0.02	+0.23	+0.03
SLR mid	-0.35	+0.21	+0.21	+0.21	-0.05	-0.30
SLR high	-0.48	+0.23	+0.51	+0.37	-0.34	-0.72

Table 4.15: Average beach growth rate differences compared to the base case without nourishments [m^3/m/year]

The accreting dune in Profile 3 north can be attributed to the topography deviating from a natural system after a long period of simulation. In figure 4.26, the initial topography and the end result of the simulation of Profile 3 north with high sea level rise is shown. The starting conditions show a sloping beach toward the dune, with a smooth dune front with very little steep edges. The end result shows a flat area in front of the dune, and a steep dune front with some high peaks. In reality this situation wouldn't occur. A single storm would erode part of the dune. The eroded volume is transported toward lower lying areas, adding volume there, adding sediment to the beach. DuBeVeg cannot simulate these situations well, as the beach erosion modeling is accurately applicable to beach and dune profiles close to an equilibrium, or natural state (see model improvements in chapter 3). The situations in this profile, and for a part in the other profiles in this section, deviate too much from a natural state to accurately describe the dynamics of dune development accurately.



(a) Initial topography of Profile 3 north in 2015

(b) Topography of Profile 3 north in 2065 after forcing with high sea level rise

Figure 4.26: Begin and end topography of Profile 3 north with high sea level rise.

Another cause of this deviation is how the beach reset alorithm works. the beach reset only affects the area between average low water and the highest water level during a spring neap tidal cycle, migrating with sea level rise. In the case of the flat beach in this profile, the beach reset modeled more accretion than erosion on the beach. Increasing the sediment availability, and thereby increasing aeolian transport toward the dunes.

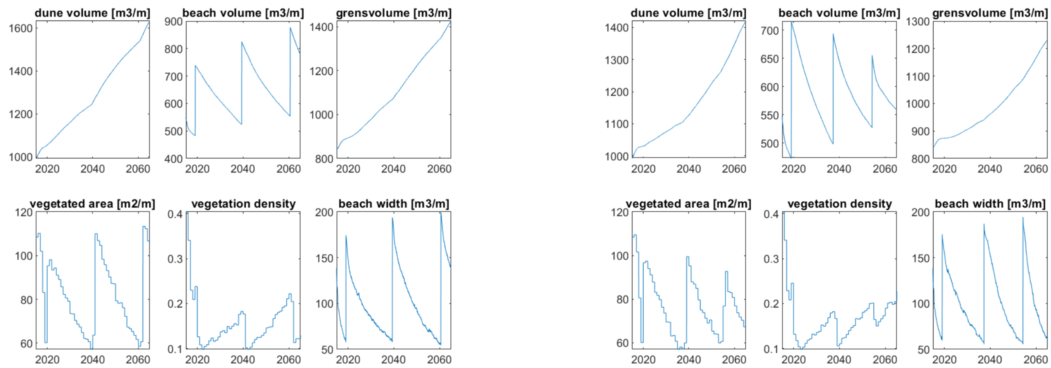
Sea level rise - Nourishments

Sea level rise has a large effect on dune growth rates in situations where beach nourishments are applied. Similar to the case of sea level rise without nourishments, the erosion rates of the beach go up. Thereby decreasing the sediment availability for aeolian sediment transport. As can be seen in table 4.16, the dune accretion rates go down as sea level rise is higher. Higher sea level rise results in faster eroding beaches, which results in nourishments needing to be supplied more often to maintain the minimal beach width of 50 meters. This higher needed frequency of nourishments can be seen in Profile 3 north and 2 south. Where the total number of applied nourishments is higher in the cases of higher sea level rise.

	Profile 1	Profile 2 N	Profile 3 N	Profile 4	Profile 3 S	Profile 2 S
SLR low	-1.34 (0)	-0.02 (0)	-1.30 (0)	-0.16 (0)	-0.28 (0)	-1.42 (+1)
SLR mid	-3.20 (0)	-2.71 (0)	-3.26 (0)	-0.28 (0)	-1.29 (0)	-3.27 (+5)
SLR high	-3.37 (0)	-4.25 (0)	-5.31 (+1)	-0.72 (0)	-2.92 (0)	-6.10 (+6)

Table 4.16: Average dune growth rates compared to the base case without nourishments [m^3/m/year], with the amount of extra nourishments applied in 50 years shown between brackets.

As can be seen in figure 4.27, the interval between nourishments is shorter in the case of high sea level rise compared to the case without sea level rise. Also, the beach volume in the base case has a positive trend, whereas the beach volume in the case with high sea level rise appears to have no trend upward or downward. This indicates that the erosion rates with high sea level rise are higher than in the base case.



(a) Temporal variation in dune and beach volume, and vegetation growth without sea level rise

(b) Temporal variation in dune and beach volume, and vegetation growth with high sea level rise

Figure 4.27: Comparison between temporal variations in dune and beach volume, and vegetation growth with and without sea level rise in the case of nourishments

Sea level rise - Conclusion

Sea level rise increases the reach of hydrodynamic processes. In the case of the HD, these processes erode the beach, resulting in less sediment available on the beach for aeolian transport toward the dunes. Because the sea level gradually increases, the influence of this elevated sea level becomes larger over time. In the case without nourishments, the beach also erodes at a high rate without sea level rise. Therefore, the effects of sea level rise in some profiles is not very pronounced. Since most of the beach has been eroded before sea level rise starts to have large effect on the beach.

In the case where nourishments are applied however, the stronger erosion strength due to sea level rise is very noticeable. Dune accretion rates go down, and the time interval between nourishments becomes smaller. In the case of Profile 3 north and 2 south, this effect is large enough to increase the total number of nourishments. (See table 4.16).

4.2.4. Wind velocity

The results from the wind climate simulations as discussed in section 3.3 are presented in this section. Volume changes in the beach and dune, and the overall behaviour of the profiles are compared to the base cases with and without nourishments. The general trends and observations are discussed, and any deviating results will be discussed in more detail.

Wind velocity - no nourishments

Because wind is the driving force in aeolian sediment transport, changing its magnitude has a large effect on the dynamics of the HD. As can be seen in table 4.17, lower wind velocities have a positive influence on dune growth rates in the case of no nourishments in all profiles. Except for Profile 1, and Profile 3 south. Profile 3 south shows higher dune accretion rates when wind speeds are increased, and Profile 1 shows lower accretion rates for both higher and lower wind velocities.

Dune	Profile 1	Profile 2 N	Profile 3 N	Profile 4	Profile 3 S	Profile 2 S
Wind low	-1.62	+5.65	+6.80	+5.88	-2.86	+4.46
Wind high	-7.23	-5.73	-2.75	-3.45	+2.74	-0.11

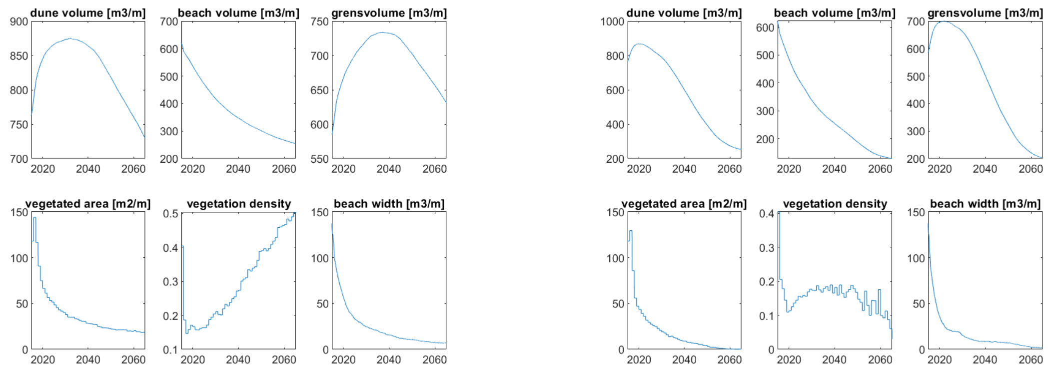
Table 4.17: Average dune growth rates compared to the base case without nourishments in the case of differing wind velocities [m^3/m/year]

High wind velocities transport sediment from the beach toward the dune at a faster rate. This can be seen in table 4.18, where the change in beach erosion rates are lower than in the base case. In the case of low wind velocity, beach erosion rates go down, as sediment from the beach is transported more slowly toward the dunes. The exception is Profile 1. In this profile, both lower and higher wind speeds result in faster beach erosion rates. This can be attributed to hydrodynamic beach erosion. Because the beach in this profile is very wide, the sediment has to be transported a large distance over the beach toward the dunes. In the case of Profile 1 with low wind speed, this doesn't happen fast enough, and the hydrodynamic processes can erode more sediment, since it is closer to the shore.

Beach	Profile 1	Profile 2 N	Profile 3 N	Profile 4	Profile 3 S	Profile 2 S
Wind low	-0.80	+0.13	+1.43	+0.40	+0.85	+1.51
Wind high	-1.57	-0.74	-1.07	-1.12	-0.65	-0.07

Table 4.18: Average beach growth rates compared to the base case without nourishments in the case of differing wind velocities [m^3/m/year]

Generally, lower wind velocities result in lower aeolian sediment transport rates. Therefore, lower dune accretion rates would be expected in the case of lower wind velocities. But, normal climatic conditions have resulted in accretion rates which the vegetation hasn't been able to keep up with. Therefore, the stabilizing effect of vegetation hasn't been able to fully develop. The lower wind velocities allow this vegetation to develop to a larger area, and higher average density (see figure 4.28). This stabilizes the dune, and prevents sand from being blown out of the dune area toward the hinterland. Resulting in higher accretion rates.

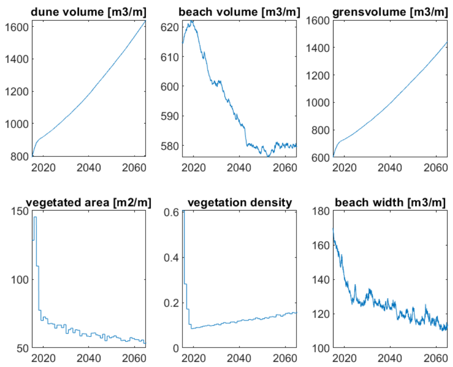


(a) Temporal variation in dune and beach volume, and vegetation growth with low velocity wind

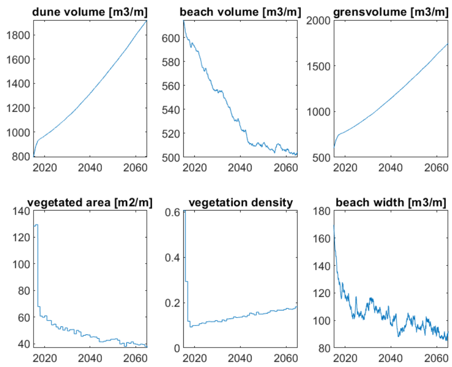
(b) Temporal variation in dune and beach volume, and vegetation growth with high velocity wind

Figure 4.28: Results

In Profile 3 south, this stabilizing effect of the vegetation on the dune doesn't occur. In this profile, the accretion rate of the dunes with high, low and normal wind velocities are too high for vegetation to thrive. Therefore, the stabilizing effect of vegetation doesn't occur in any of these cases. The state of the vegetation doesn't differ much between these cases, and therefore high wind velocities result in higher dune accretion rates.



(a) Temporal variation in dune and beach volume, and vegetation growth with low velocity wind



(b) Temporal variation in dune and beach volume, and vegetation growth with high velocity wind

Figure 4.29: Results

Wind velocity - nourishments

As can be seen in table 4.19, in the case of nourishments, dune accretion rates are generally higher in the case of high wind velocities. Though as can be seen in Profile 1, both higher and lower wind velocities can result in lower dune accretion rates. And as can be seen in Profile 2 north, both higher and lower wind velocities can result in higher dune accretion rates in the same profile. Please note that Profile 4 and Profile 3 south no nourishments have been applied during the simulation. Therefore, these two profiles are excluded in this analysis.

	Profile 1	Profile 2 N	Profile 3 N	Profile 4	Profile 3 S	Profile 2 S
Wind low	-0.14 (0)	+3.09 (-1)	-0.44 (-1)	+5.88 (0)	-2.86 (0)	-2.43 (-1)
Wind high	-0.10 (+1)	+0.57 (+1)	+2.92 (+1)	-3.45 (0)	+2.74 (0)	+4.36 (+2)

Table 4.19: Average dune growth rates compared to the base case with nourishments in the case of differing wind velocities [m^3/m/year]

In Profile 1, the dune accretion rates in the case of lower and higher wind velocities are very small. In the case of higher wind velocities, the higher potential aeolian sediment transport rate and the lower vegetation density due to this transport rate largely cancel each other out. In the same profile with lower wind speed, the stabilizing effect of higher vegetation density and the lower aeolian sediment transport rate from the beach toward the dune also largely cancel each other out. Both resulting in similar dune accretion rates, but with different mechanics reaching this result.

In Profile 2 north, both higher and lower wind velocities result in higher dune accretion rates. In the case of lower wind velocities, the stabilizing effect of the vegetation is responsible for this accretion rate increase. Sediment loss from the dune to the hinterland is minimized, and in the simulation period, only two nourishments have been applied (one less than the case with normal climatic conditions). With higher wind velocities, the higher aeolian transport rate results in higher accretion rates. Note that in this case, four nourishments have been applied with only a minor increase in accretion rate. This shows that a lot of sediment of the dune is lost to the hinterland, as the dune isn't stabilized enough by the vegetation to prevent this.

Wind velocity - Conclusion

Wind velocity has a large influence on aeolian sediment transport, as it is the driving force behind this type of sediment transport. High onshore directed wind speeds result in higher aeolian sediment transport rates, but it doesn't necessarily result in faster growing dunes. Dunes only grow faster under higher wind, when outgoing aeolian sediment transport is inhibited. In the case of the HD, this is primarily done by the sheltering effect of the vegetation. Vegetation like marram grass, has an optimum net sediment influx for which vegetation grows the fastest. Therefore, there is an optimum sediment influx for growing dunes.

Of course, sediment availability also plays a role. Nourishments provide a stable presence of sediments on the beach for aeolian transport. Because of this nourishment, the average increase in dune accretion rate is 13 m^3/m/year at lower wind speeds, and 22 m^3/m/year for higher wind speeds compared to the case without nourishments. See Appendix H for all values .

4.2.5. Conclusion

For the base scenario where no changes in forcing is made, differing results have been found. In some profiles the dune volume continuously increases, some profiles reach a stable equilibrium, and some start to erode after some time. The behaviour of the beach in the profiles is more uniform, the average sediment flux is negative (see table 4.20). The beaches tend to a very narrow beach width with very little sediment. The dunes in the model runs stay in place, because no storm events have been modeled. In the real world, a storm in a coastal dune area without beach would result in large losses of dune volume.

	Profile 1	Profile 2 N	Profile 3 N	Profile 4	Profile 3 S	Profile 2 S
SLR low	-7.15	-0.19	-0.01	-0.16	-0.28	-0.34
SLR mid	-8.20	-0.44	-0.11	-0.28	-1.29	-2.62
SLR high	-9.38	-0.49	+0.28	-0.72	-2.92	-4.14
Wind low	-1.62	+5.65	+6.80	+5.88	-2.86	+4.46
Wind high	-7.23	-5.73	-2.75	-3.45	+2.74	-0.11

Table 4.20: Average dune growth rates compared to the base case without nourishments [m^3/m/year]

The beach face nourishment applied in the simulations have a large effect on the dune growth rates. More sediment is available for transport toward the dunes, resulting in all dunes in all profiles continuously growing. All nourishments in the model have been triggered by the minimal beach width criterion, rather than the safety profile criterion. This can be attributed to the fact that the dune doesn't erode as a consequence of average hydrodynamic conditions. In reality, storms with varying intensities will cause erosion of the dune profile, and thus a nourishment which prevents under-crossing of this critical value is expected to be necessary in the future.

	Profile 1	Profile 2 N	Profile 3 N	Profile 4	Profile 3 S	Profile 2 S
SLR low	-0.91 (2)	-0.02 (3)	-1.30 (5)	-0.16 (0)	-0.28 (0)	-1.42 (07)
SLR mid	-2.60 (2)	-2.71 (3)	-3.26 (5)	-0.28 (0)	-1.29 (0)	-3.27 (11)
SLR high	-4.08 (2)	-4.25 (3)	-5.31 (6)	-0.72 (0)	-2.92 (0)	-6.10 (12)
Wind low	-0.14 (2)	+3.09 (2)	-0.44 (4)	+5.88 (0)	-2.86 (0)	-2.43 (5)
Wind high	-0.10 (3)	+0.57 (4)	+2.92 (6)	-3.45 (0)	+2.74 (0)	+4.36 (8)

Table 4.21: Average dune growth rates compared to the base case with nourishments [m^3/m/year]

The beach erodes faster in the case of higher water levels. Though in the case where no nourishments are applied to the beach, the profiles returned differing results. The dune accretion rates nearly all lowered, but not by much. This is because the state of the beach and dune started to deviate over time toward a less natural state, in which the beach erosion approach of the model isn't accurate anymore. Also, by the time sea level rise could start to have a real effect on erosion rates, most sediment has been eroded away already. Leaving little for the heightened sea level to act on.

Sea level rise has a very notable effect on dune growth rates when nourishments are applied. After each nourishment, new sediment is available for transport either by aeolian or hydrodynamic processes. This ensures the presence of a natural beach, in which the model approach to beach erosion is very suitable. In these scenarios, aeolian parameters stay the same, while beach erosion is enhanced by rising water levels. This effect can clearly be seen in the result, where higher sea level rise requires less and less time between nourishments. Therefore, it can be concluded that sea level rise influences aeolian sediment transport by influencing the sediment availability.

Wind velocity has a large effect on dune accretion rates in the HD. In some cases, higher wind velocities result in higher accretion rates, and in some cases lower wind velocities result in higher dune accretion rates. In the case where lower wind velocities are more favourable for dune growth, the vegetation grows to a larger surface area, and to a higher average density. Thereby stabilizing the dune, and inhibiting aeolian transport out of the dune area. The cases where higher wind results in higher accretion rates, the vegetation doesn't grow well in the base case and the low and high wind velocity cases. Therefore, the stabilizing effect of vegetation doesn't have any influence on the outcome. Here, higher velocity winds result in a lot of aeolian transport, and both the incoming and outgoing sediment transport is higher. Resulting in a higher net inflow of sediment.

In the case of a nourished beach, high wind velocities result in higher dune accretion rates. This is because the nourishments ensure a constant supply of sediment available for aeolian transport. But low wind velocity can also result in higher dune accretion rates. The cause for this is vegetation. In the case of profile 2 north, lower wind velocities have resulted in higher dune accretion rates, because the vegetated surface area, and the average density is relatively high. The stabilizing effect inhibits sediment outflow in the dune, resulting in higher net gains of sediment in the dune.

5 Discussion

In this thesis, the characteristics of aeolian sediment transport in the HD have been qualitatively and quantitatively researched. In this chapter, the method, used assumptions and the results of this thesis are critically assessed. First, the method and results of the data analysis is assessed on these qualities. After that, the method and results of the model study is assessed on these same qualities.

5.1. Data analysis

The data analysis has been carried out to identify which of the processes and parameters identified in the literature study have the greatest influence on dune development in the HD. The identification of the most relevant parameters and processes has helped in understanding the dynamics in the HD, and in choosing which model is most suitable for use in this thesis. The topographic data has been analyzed, and the beach and dune volumes have been determined for each profile in the domain. The changes in beach volume have been mapped, and the observations have been explained using data about relevant processes such as wind speed and direction, grain size distribution, the state of the vegetation, and sediment availability.

The topography has been divided into a beach area, and a dune area. This has been done because preceding research on this topic in the HD had concluded that the beach slope has a lot of influence on dune growth rate in the area. The results reaffirm this conclusion. Periods and locations when and where a steep beach is present have resulted in decreased dune growth rates. Because the beach slope is such an important parameter, it is important to know how the hydrodynamic processes in the area influence it. The presence of the gully near Profile 2 south for instance, has had a large impact on the dune growth rate in that area by steepening the beach, and reducing sediment availability.

Grain size distribution in the HD has a great influence on the development of the dunes. Because of the relatively coarseness of it, mobility of the grains is inhibited. The high spatial variability of the grain sizes as a result of the construction of the site, indicate that this area is man made. Though the temporal change in the grain size distribution shows that even an artificial system such as the HD wants to return to a more natural state. The variability of the grain sizes on the surface tend to a distribution found in more natural systems.

The development of vegetation and dune development go hand in hand. Dune growth is helped by healthy vegetation, and healthy vegetation is helped by a steady amount of incoming sediment, which contains nutrients. Therefore, a healthy looking dune, with green developing marram grass, is a good indicator for a steadily growing dune. Of course, when sedimentation is going too fast, marram grass can end up being buried. When high sedimentation rates keep going for too long, the vegetation cannot keep up anymore, and the grass dies out.

Accurate data on the development of vegetation in areas such as the HD is therefore very useful to be able to describe the development of the dunes accurately. For the HD, data regarding this subject is sparse in the sense that there aren't data sets which quantify the total area and density of vegetation on the dunes. Though qualitative data is abundant, both written and in memory of colleagues at the water board.

Because the focus of this thesis has been on aeolian sediment transport, the effects of hydrodynamic processes haven't been extensively analyzed. The effects of these processes have had more influence on aeolian processes than was expected beforehand. The gully which migrates from the south of the HD toward the north has had a great influence on sediment availability. This gully in fact, is the reason for the nourishment being brought forward in the planning, as described in chapter 1. For future research in the field of aeolian sediment transport, the effects hydrodynamic processes might have on long term sediment availability must be taken into account.

5.2. Model study

The model study has been conducted to provide insight in the likely future development of the HD. At the start of this thesis, the intended approach was to couple the strong points of AeoLiS and DuBeVeg. But because both models are in development, there is a lot to gain in improving these models themselves. Therefore, the choice was made to proceed with only using DuBeVeg instead of a combination of the two.

The improvements made to DuBeVeg also bring limitations with it in terms of applicability. The mass balance is a definite improvement, and the dynamic equilibrium profile in the beach update as opposed to a static one in the original is as well. Though the definition of the equilibrium erosion profile can be improved. In the case of sea level rise, accretion of the beach is simulated in certain situations. It is known that sea level rise is likely to induces coastal erosion, thanks to higher waves reaching further up the beach. Therefore, the erosion profile defined by Vellinga as implicated in DuBeVeg isn't universally applicable, and is very sensitive to calibration. The calibration value and the applicability of this approach to beach erosion is highly influenced by beach steepness.

The implementation of non-erodible elements are an important addition to the functionality of DuBeVeg for the application on the HD. The old sea dike at the downwind border of the HD domain would otherwise be modelled as a dune, which would be a large model inaccuracy. Though the application of the non erodible elements method on the foot and bicycle paths, might have introduced inaccuracies in the model. In the cases where dunes eroded in the model, the pavements in the dunes remained at the same location and elevation. Whereas in reality, these areas would have eroded.

In the zero measurement, the topography is forced by hydrodynamic and aeolian processes. Because the main focus is on aeolian processes, this process is more accurately described than the hydrodynamic processes. Therefore, the hydrodynamic part of the model is less accurate, which shows over longer simulated periods. Because the model is focused on average conditions, storm conditions aren't taken into account. Over the simulated period of 50 years, more than several storms are expected to take place on the HD. Storms can be thought of as resetting events where the beach, and if the storm is strong enough, part of the dune is affected. The occurrence of these storms prevents very steep dune fronts with short beaches. As the eroded dune front collapses in a storm, adding sediment to the beach. Because this important process isn't taken into account, the generated results deviate from the actual dynamics which are present in the HD

The design of the nourishments in the simulations is rough, and improvements to the shape and placement can be made. Though it is based on the nourishment applied to the HD in Profile 2 south in march of 2018, and documents describing the planned nourishments in the HD. Therefore it is a good, but rough approximation of the future nourishments in the HD.

Because the profile areas are simulated separate from each other, the effects nourishments have on alongshore sediment transport isn't taken into account. This effect influences sediment availability in neighbouring profile areas for aeolian transport. The fact that this process isn't taken into account, introduces inaccuracies in the result. The effects of nourishments in the HD would be more accurately described in a model which does take the alongshore transport of sediments into account. Though the effects of alongshore transport only influence boundary conditions for aeolian transport in the HD. For the purposes of this thesis, the boundary conditions for aeolian sediment transport have been approximated with reasonable accuracy.

The modeling of sea level rise without nourishments has given some questionable results. Without a beach for the hydrodynamic erosion module of DuBeVeg to act on, the Vellinga erosion profile is not very accurate. The application of nourishments however, ensures there is at least a beach like area for the Vellinga erosion profile to act on. Resulting in more reliable results, as this is what the Vellinga profile has been developed for. Higher sea level rise has resulted in faster beach erosion, which requires more frequent nourishments to ensure the presence of a beach. This also ensures sediment availability,

The results from the higher and lower velocity winds show the importance of enough vegetation of a high enough density in coastal dune areas. The stabilization these plants provide to the dunes is critical for the longevity of the dunes in the HD.

6

Conclusions & recommendations

In this section, the conclusions of this theses are presented, based on the results obtained in chapter 4 After that, the recommendations based on the conclusions are presented, regarding research on the model, dune development and aeolian sediment transport. The main research question and sub-questions which will be answered are repeated below: Main question:

- How can the HD system best be maintained to ensure its function as a sea defense now and in the future?

Sub-questions:

- What are the main processes which govern the long term growth and decline of coastal dunes?
- What types of models for dune development are available, and what are the main differences and commonalities regarding their operation, input, output and performance?
- What is the added value of improving or coupling models, and if it's worth it, how can these models be improved or coupled to produce a model which accurately predicts the behavior of the HD?
- What processes with their associated parameters have the biggest influence on the behaviour of the HD?

6.1. Conclusions

In this section, the research questions are answered. Because the first and last sub-question are closely connected, as well as the second and third, the answers to these questions are grouped together in the sections below.

6.1.1. Governing processes and parameters in the HD

What are the main processes which govern the long term growth and decline of coastal dunes?
Coastal dune growth in general is governed by several different processes and parameters. Aeolian sediment transport can be described as a balance between wind forcing and resistance to this forcing. The wind is easily described with its velocity and direction, and the fact that the wind flow is always turbulent in natural conditions. Individual grains are moved by a wind induced friction force. The resisting force is influenced by grain size, density of the material and friction between grains on the bed. Dunes grow in areas where deposition of sediment in transport is likely, and a supply of sediment is present. Vegetation in dunes encourage sedimentation by decreasing the local wind velocity, thereby creating a location where the resistance to movement is larger than the wind forcing. The vegetation grows as a result of incoming sediment carrying nutrients with it. The optimum growth rate of the vegetation is dependent on the type of vegetation.
What processes with their associated parameters have the biggest influence on the behaviour of the HD?
In the HD, some factors play a larger role in the development of the dunes than others. Vegetation and

sediment availability are two very important parameters which govern coastal dune growth in the HD. A north-south difference is present in the quality of the planted vegetation, resulting in a gradient in the effectiveness of the sheltering effect provided by the vegetation. This effect can in fact be seen in the difference between the dune growth rates of the different profile types, being larger in the south, where the quality of the vegetation is higher, and smaller in the north, where the quality of the vegetation is lower.

Though the health of the vegetation isn't the only contributing factor to this alongshore variation of dune growth. The orientation of the coastline, and with it the dunes, in relation to the dominant wind direction is a very important factor. The average wind direction comes in at an oblique angle with the dunes in the HD. The domain of the HD isn't a completely straight line, with the northern profiles' orientation bending toward the east, resulting in the average wind direction having a more alongshore character compared to the relative wind direction in the northern profiles. As onshore wind is more favourable for dune growth as a result of aeolian sediment transport, this factor plays a large role in the north-south gradient in coastal dune growth.

Sediment availability to the dunes influences dune growth rates in the HD as well. The north-south gradient holds for all defined profile areas, except for the southern most one, profile 2 south. This profile area has a lower overall dune growth rate than its northern neighbour, profile 3 south. This is because of a lower sediment availability in this profile area. The sediment availability is much lower here because of coastal erosion due to wave attack, and the formation of a gully which erodes the coast, and therefore beach even more.

Grain size distribution in the HD is very inhomogeneous in both cross shore and alongshore direction, due to the HD being man made. The sediment has been mined from several different sources in the north sea, resulting in a seemingly random mosaic of different grain sizes. Though the supplied sediment is relatively coarse, as was part of the design. Due to 3 years of hydrodynamic and aeolian processes working on the HD, the surface grain size distribution now tends to a more natural situation, with finer grains in the dunes, and coarser grains remaining in the intertidal zone and on the beach. The alongshore variation of grain size is found to be most coarse in profile 4, the middle of the domain, and finer in the northern and southern profiles. Because of the coarseness of the grains in profile 4, the effects of a larger sediment supply of the accreting beach in this profile is negated. The grain sizes are in the northern and southern profiles are comparable to each other.

Moisture increases the resistance of incoherent grains to transportation. Therefore the effects of groundwater have been analyzed. However, the groundwater level in the HD is sufficiently low that this parameter hasn't got a large influence on the aeolian transport in the HD.

6.1.2. Modelling coastal dune growth

What types of models for dune development are available, and what are the main differences and commonalities regarding their operation, input, output and performance?

In the search for a model suitable for modeling the HD, three models have been analyzed and compared to each other. Namely: AeoLiS, Aeolus, and DuBeVeg. In DuBeVeg, vegetation location and effectiveness changes in time, with the potential of accurately modeling the interplay between vegetation and aeolian sediment transport. Therefore, this model is very useful for the modeling of vegetated dunes, like the ones found in the HD. AeoLiS also models the effects of vegetation, but the state of the vegetation doesn't change in time. Aeolus is more focused on the dynamics which play a role at the interface between the beach and dune area.

What is the added value of improving or coupling models, and if it's worth it, how can these models be improved or coupled to produce a model which accurately predicts the behavior of the HD?

DuBeVeg has been used, as it is the most promising with respect to modeling vegetated dunes. To improve the performance of this model, changes have been made in the functionality of the model. Non-erodible elements have been added to accommodate for the non-erodible sea dike at the landward border of the domain. Mass balance has been implemented in the model, with the possibility to impose a mass flux in the marine area, to simulate alongshore or cross shore gains or losses in sediment. This has been implemented with the use of the Vellinga erosion profile, though this method comes with its limitations.

The results from the model runs using the improved version of DuBeVeg has resulted in insight in the importance of high quality vegetation on coastal dunes. The growth of vegetation like marram grass goes hand in hand with a positive sediment influx, carrying nutrients. In the model runs, it is shown that simulations where the vegetated surface area goes below a certain value, the dune starts to erode, and keeps on eroding. In all simulations the beach has eroded, decreasing the sediment availability for aeolian sediment transport. Though this has an effect on the dune growth rate, it isn't as pronounced as the effect the vegetation has. A decrease in sediment availability has a gradual effect on dune growth rate, whereas the state of coastal vegetation acts more as a tipping point for dune growth rates. Once the state of the vegetation dips below a certain value, erosion kicks in, and dune volume is lost.

6.1.3. Main conclusion

How can the HD system best be maintained to ensure its functions as a sea defense now and in the future?

In relation to the safety the HD provides to the hinterland by flooding, dune volume must be maintained. As concluded from the data analysis, wind direction in relation to the dunes' orientation has a large effect on dune growth rates. However, the orientation of the wind cannot be controlled. As concluded from the answers to the sub-questions, the most important factors which govern coastal dune growth in the HD are sediment availability and sheltering against the wind by vegetation.

Sediment availability can be ensured by nourishing the beach or foreshore in such a way that ensures the presence of a steady supply of aeolian transportable sediments. Placement of sediment directly on the dunes is not advisable, as this would damage the other important parameter for a safe dune area: vegetation. This way of nourishing the HD would bury the marram grass, and introduce salt into the area as the sediment will most likely be dredged from the North Sea. Both the saltiness and burying of the vegetation is damaging to the vegetation.

Marram grass grows best when sedimentation rate of the dune is within a certain range. This is a property of this certain type of vegetation, and differs from plant species to plant species. Because climate change, such as differing aeolian transport rates due to changing wind climates, and changing sediment availability due to sea level rise, it is difficult to ensure this optimum sedimentation rate for the marram grass. Therefore, it is advantageous for the health and sustainability of a dune system to have a variety of different species of plants in the dune area. Each with a different optimum sedimentation rate for optimum growth, so the optimum sedimentation rate bandwidth can be expanded, resulting in a more robust sea defence.

In order for the HD to function as a nature reserve, the right abiotic conditions must be met for vegetation to thrive. The presence of healthy vegetation attracts fauna to the area, resulting in a healthy nature reserve. This is in fact already the case, as many types of vegetation have already established themselves in the HD. In particular between the most landward dune row and the old sea dike. To ensure that this function can still be fulfilled in the future, the abiotic conditions must be maintained. In the case of sea level rise, the vegetation must be protected against the rising salt water, and with changing wind climate, ensure the right sedimentation rate toward the dune by placing well designed nourishments.

The function of the HD as a recreation area is ensured by the presence of a wide beach, and vegetation. The presence of a wide beach provides space for people to enjoy a day at the beach, and this can be ensured by placing well designed nourishments. To counteract the heightened erosion rate as a result of sea level rise, the nourishment can be designed with coarser grains. This solution can also be used in the case of more frequent higher wind velocities, as larger grains are less easily transported by aeolian processes. If the wind climate changes to a state with lower wind velocities, larger grain sizes aren't needed to protect the recreational function of the HD against the differing wind climate.

6.2. Recommendations

The recommendations are divided into two categories. Recommendations regarding the improvement of the model, and recommendations regarding future research into aeolian sediment transport, both in and outside of the HD.

6.2.1. Aeolian and coastal dune research recommendations

Vegetation monitoring
As proven with the model runs in DuBeVeg, vegetated area and density play a large role in the development of coastal dunes. Though data regarding this parameter is not readily, or at all, available. Quantitative data on vegetation, both in square meters and in percentages of density, can be very useful in understanding the dynamics of coastal dune growth. Both in the HD and in other areas. This can be done with NIR (Near infrared) photography, supplemented with observations in the field. NIR photographs can be analyzed using, for instance, NDVI (Normalized Difference Vegetation Index) analysis. The supplementation with observations in the field is necessary, as NIR photography can only determine surface vegetation. Biomass under the surface plays a large role in the stability of dunes, and in the case of excessive sedimentation of the dune, marram grass can become buried. Resulting in inaccurate data when only NIR photography is used. These measurements can also be used to calibrate models which model vegetation growth, such as DuBeVeg.

6.2.2. Application of different vegetation types

Vegetation is very important to the growth of coastal dunes, and each plant species responds different to different incoming sedimentation rates. Dune growth speed can be controlled in a limited way by placing nourishments with different designs, but wind is still uncontrollable. Therefore, future dune accretion rates are uncertain. With a greater bandwidth of favourable dune growth rates for healthy vegetation, a more robust dune system can be designed with higher growth rates.

Research on the effects of buildings on aeolian sediment transport
Buildings, or any type of structure on the beach influences wind speed and patterns locally. This can have a negative effect on dune growth, when the structure is placed close to, or on in the dune.

Settlement the constructed dune
A mega nourishment such as the HD settles over time as a result of its construction. The nourished sand compacts over time, resulting in a decreased sediment volume which can be wrongfully attributed to aeolian losses in the dunes and beach, or cross-shore or alongshore hydrodynamic losses in the intertidal zone and the beach

Sand drift hollows
Sand drift hollows are non vegetated areas in dunes are a sort of bypass for aeolian sediment transport toward the land behind the first dune row. The application of these hollows is to accrete the hinterland, which improves the safety against flooding, as well as influencing the natural dynamics of the dune area. These sand drift hollows are placed by local water authorities, though the influence of aeolian parameters isn't exactly known. Research on this topic can provide local water authorities with a guideline for efficient designs for sand drift holes, which allows for a certain amount of aeolian transport toward the hinterland.

6.2.3. Model recommendations

In this section, recommendations on the improvement of DuBeVeg are introduced and briefly discussed.

Elevation dependent erosion probability
In the model runs in DuBeVeg, the panoramic dune in profile 1 persistently accreted. But in reality, the panoramic dune eroded nearly continuously. This is explained by the logarithmic profile of the wind, meaning higher wind velocities are present in dunes with higher elevations.

Slope dependent erosion and deposition probabilities
An uphill slope decreases aeolian sediment transport rate by forcing the transport direction against the force of gravity. Because this effect isn't taken into account in the current iteration of DuBeVeg, sedimentation of the panoramic dune is experienced. By decreasing the erosion probabilities of slabs on an uphill slope in the imposed wind direction, this effect can be implemented in DuBeVeg. By increasing the deposition probability of a slab in transport which encounters a cell with a higher elevation, the same effect can be reached. Though the local wind velocity can be higher at such a location. Research is needed to find out what process has the most influence in such a situation.

Vellinga erosion

The implementation of the Vellinga erosion profile has limitations. In the current state, the applicability of this approach in DuBeVeg on very gentle slopes returns accretion of the beach in situations where sea level rise is present.

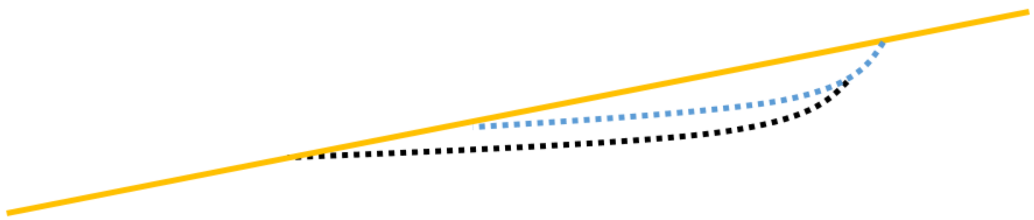


Figure 6.1: Vellinga erosion problem, blue showing first erosion event, black showing the second erosion event.

Interface hydrodynamic - aeolian dynamics

In DuBeVeg, Aeolian sediment transport is modeled accurately. But the hydrodynamics, present in any coastal system, isn't modeled accurately. This causes a problem, as the hydrodynamics in a coastal system governs the sediment supply for aeolian transport to a large extent. Therefore, the interface between the hydrodynamically active part, and aeolian active part of a coastal system must be modeled more accurately to improve the general applicability of DuBeVeg on coastal systems.

Combined use of models

DuBeVeg & AeoLiS To increase the accuracy of predictions on coastal development, a combination of DuBeVeg and AeoLiS seems to be an obvious approach. Though coupling two models is more easily said than done. A simple connection between the two models is the use of AeoLiS for the calibration of DuBeVeg. First, only the beach is modeled using AeoLiS. The maximum potential sediment transport can then be converted to probabilities of erosion and sedimentation with the use of equation 2.8, as described in section 2.5.2.

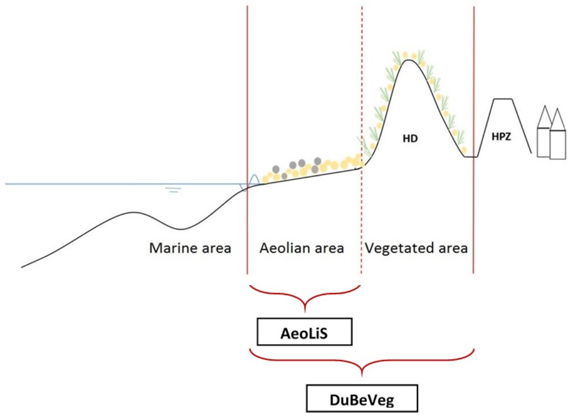


Figure 6.2: Model schematization using AeoLiS as a calibration tool for DuBeVeg

A second, more laborious method of combining the models, is using AeoLiS for the marine and beach parts, and using DuBeVeg only for the development of the dunes (see figure 6.3). The processes AeoLiS models are more focused toward aeolian sediment transport over the beach, and DuBeVeg incorporates factors which seem more important to dune development. Therefore AeoLiS can be used to model the beach and marine boundary condition, and DuBeVeg can be used to model the dune area. This way the strong points of each model is used, likely improving the performance of such a numerical model.

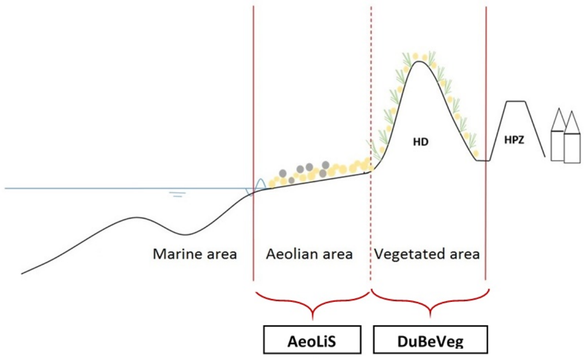


Figure 6.3: Model schematization using AeoLiS for the beach and intertidal zone, and DuBeVeg for the modeling of the dunes.

Convert DuBeVeg python

To be able to couple DuBeVeg with models such as AeoLiS, a conversion of the scripts from Matlab to Python can be very useful. Though cross-platform computing is possible, the conversion from a program such as Matlab, which requires a licence to run, to python, which is open-source, prevents programming difficulties. Improvements of DuBeVeg in Python can also go faster, as open source material is more easily shared between users, as everyone has access to open source material.

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A

Previous work

In previous work carried out by M. Wittebrood, the morphological development in the HD has been analyzed in the period between May 2015 and December 2016. The average dune growth during this period in the HD is 28 m3/m/year, which is in the same order of magnitude as the design expectations (35 m3/m/year). The spatial variability of the dune growth during this period is significant, as the volume change in profile type 1-North was lowest (14 m3/m/year), and the growth in profile 2-south (45 m3/m/year) and profile 3-south (48 m3/m/year) were highest.

The temporal variability was also pronounced. Not all dune geometries show a clear trend, but the average the HD system does. Average dune growth was highest during the first period after construction, and continuously slowed down in the period after that. This is due to a high availability of fine sand particles, as there hasn't passed enough time for a certain amount of beach armoring and sediment sorting to occur. The amount of available fine sediment decreases in time, as does the spatial averaged dune volume changes.

The volume of wind blown sand came from the beach and inter-tidal zone, where volumetric losses were measured. Not all sediment losses from these areas ended up in the dunes, as measurements show an increase in beach volume and accretion in the inter-tidal zone just north and south of the HD area. These changes had been attributed to spatio-temporal variations in sediment availability, and the local geometry of the beach and dunes. Five important parameters governing these processes had been derived, which are:

1. Orientation of the geometry in relation to the dominant wind direction
2. Beach width
3. Beach slope
4. Median grain size
5. Dune geometry

The first four parameters govern the sediment availability for aeolian transport, whereas the fifth parameter governs the ability of the sediment to reach the top of the regarded dune.

So it appears that the equilibrium state of the dunes in the HD hasn't yet been attained during the period of this research. As a consequence, it is expected that the dunes will continue to grow, be it with a lower speed than during the measured periods.

B

Definition of profiles

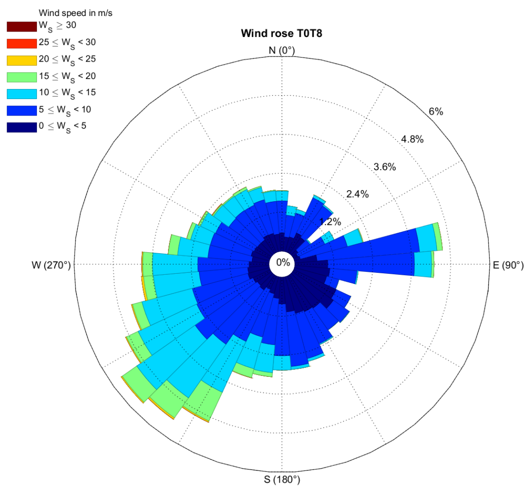
	RSP
Profile 1	2017-2094
Profile 2 north	2094-2146
Profile 3 north	2146-2247
Profile 4	2247-2394
Profile 3 south	2394-2540
Profile 2 south	2540-2589
Profile 5	2589-2691

Table B.1: Definition of profiles based on RSP (Rijksstrandpalen).

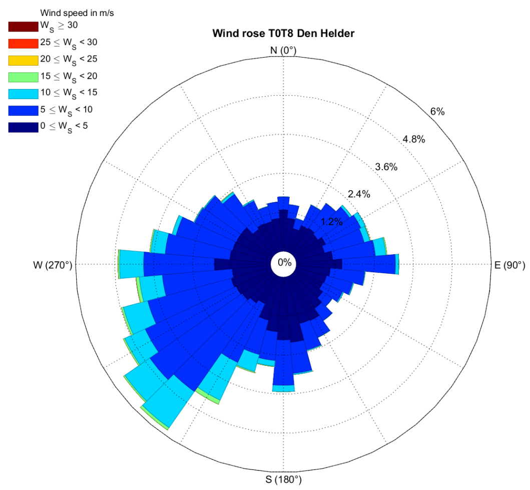
C
Climatic data

C.1. Wind

There is no weather station directly at the HD. The two nearest weather stations are ’De Kooy’ in Den Helder (20 km northeast of Petten), and at IJmuiden (30 km south of Camperduin). Though the weather station at IJmuiden is farther away from the project area, it is situated at the same coastline as the HD. Whereas weather station ’De Kooy’ is situated more inland. The effect of the land surface on the wind can be seen in the wind roses of both weather stations. The dominant wind direction is very similar in both stations, but the wind velocity is significantly higher in IJmuiden (see figure C.1).



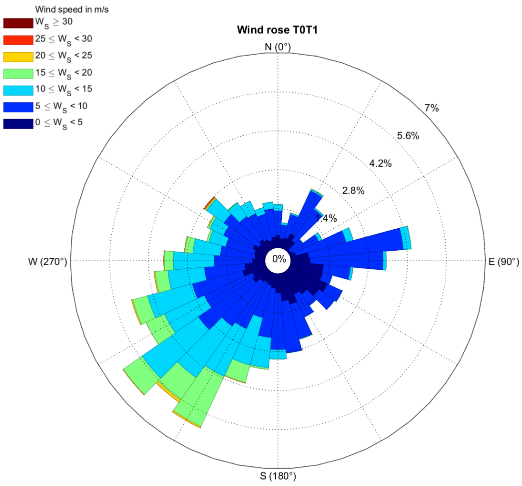
(a) IJmuiden (more representative for the HD area).



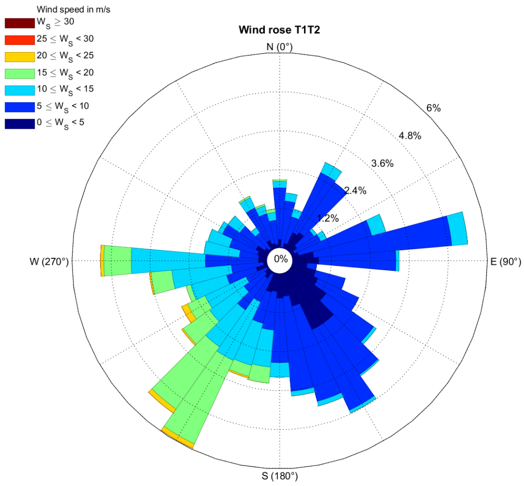
(b) De Kooy (Den Helder) (less representative for the HD area).

Figure C.1: Wind roses of weather stations nearby the HD (2015-2018) KNMI [2018a].

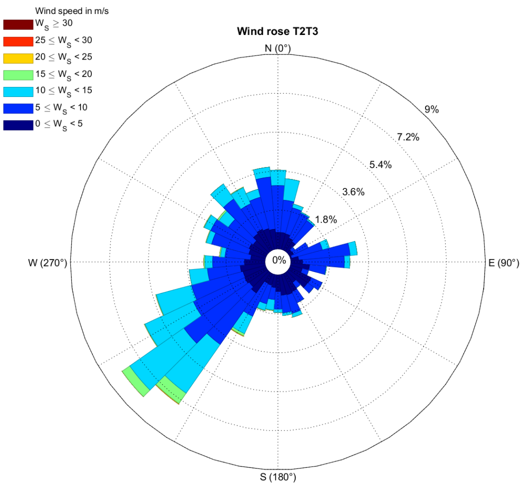
Because the area over which the wind blows has a large effect on the wind characteristics, and the alongshore coastline characteristics between IJmuiden and the HD is relatively uniform Therefore the wind data measured at IJmuiden is more suitable for use in the analysis and modeling of the HD area.



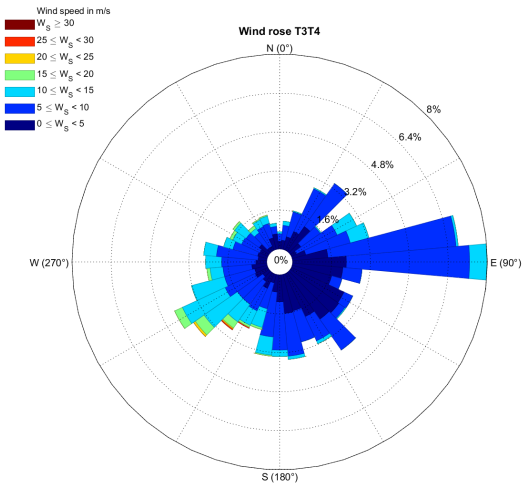
(a) Wind in period T0-T1



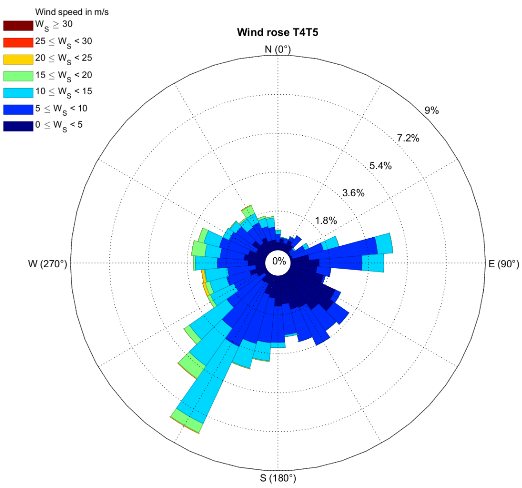
(b) Wind in period T1-T2



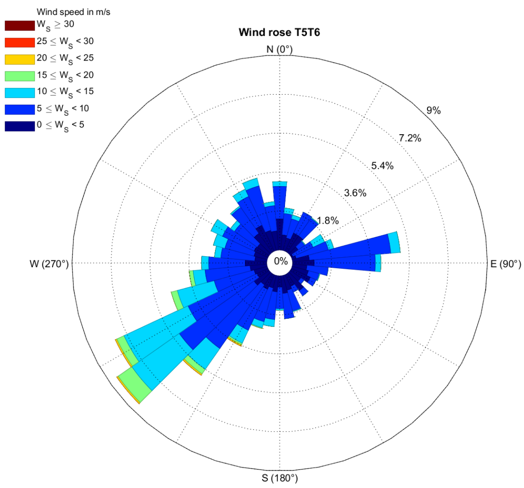
(c) Wind in period T2-T3



(d) Wind in period T3-T4

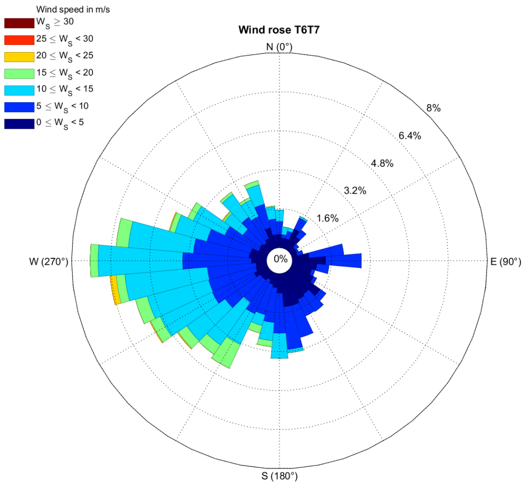


(e) Wind in period T4-T5

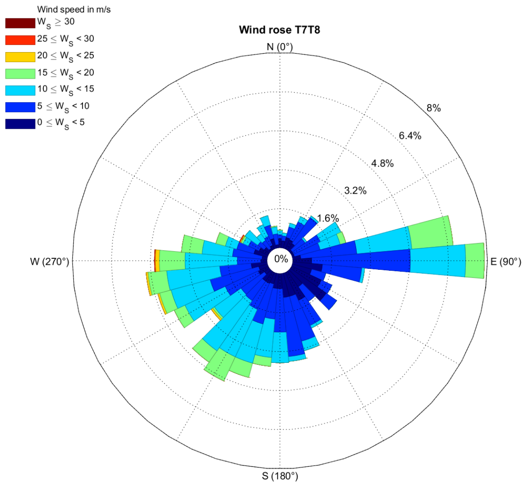


(f) Wind in period T5-T6

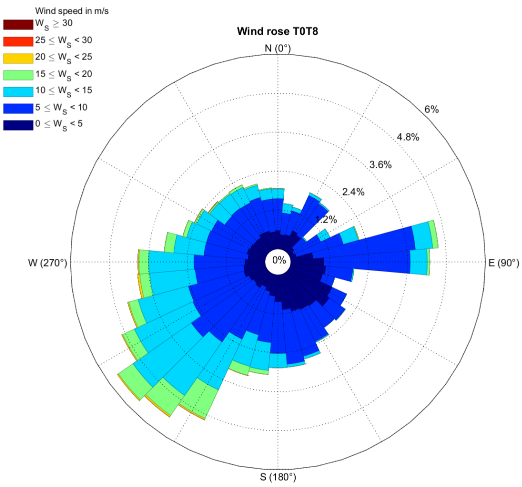
Figure C.2: Wind roses during time periods T0-T6



(a) Wind in period T6-T7.



(b) Wind in period T7-T8.



(c) Wind in period T0-T8.

Figure C.3: Wind roses during time periods T6-T8, and T0-T8.

C.2. Tide

The tide at the HD area is measured at a station in Petten-Zuid. The tide is influenced by astronomical effects and local topographic effects. The tide comes in from the south, and moves toward the north. But the wavelength of the tidal signal is so long compared to the length of the HD system, that the spatial variation in its values is negligibly small. Therefore, the direction of the tide isn't discussed in this section.

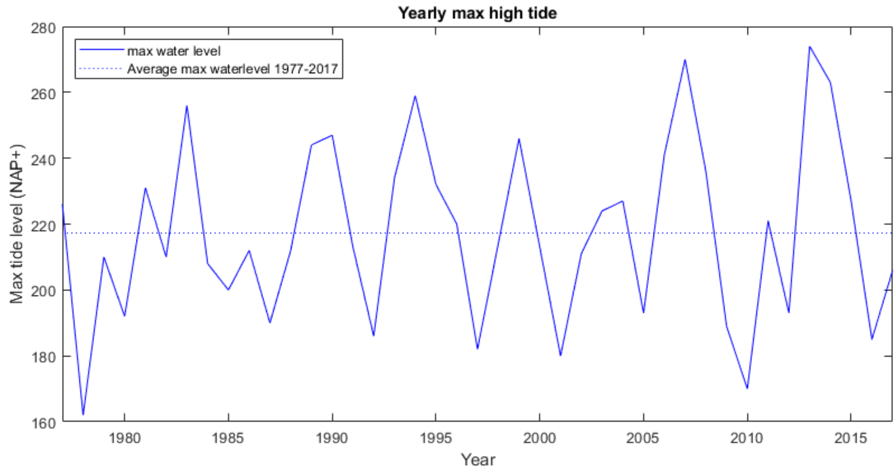


Figure C.4: Max high water level as measured at the Petten Zuid station (1977-2017).

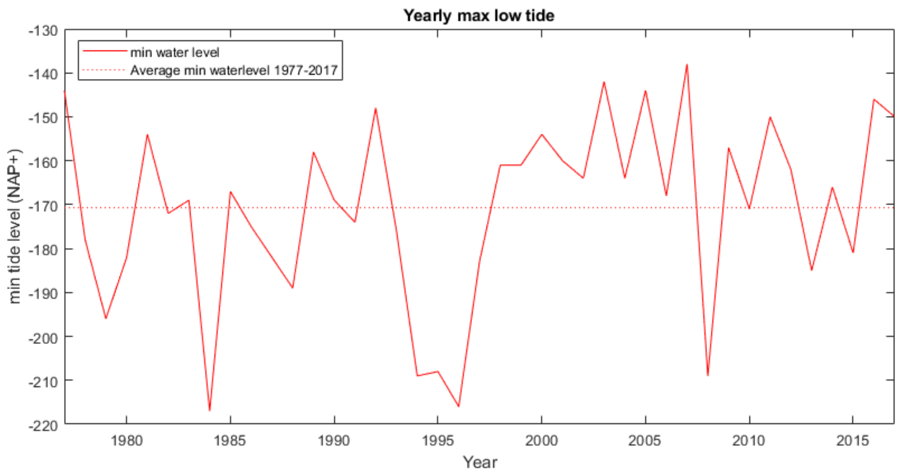


Figure C.5: Max low water level as measured at the Petten Zuid station (1977-2017).

Getijgebied 2011.0 Kenmerkende waarden

Noordzeekust
Petten Zuid

Standen in cm t.o.v. NAP

	Slotgemiddelden			Waarden maansverloop	
Getijtype cq grootheid	**HW-stand**	**LW-stand**	**tijverschil**	**HW**	**LW**
Gem. springtij	97	-83	180	3:02	12:23
Gem. tij	84	-76	160	3:06	11:45
Gem. doodtij	64	-66	130	3:14	11:17
Gem. duur rijzing				3:46	
Gem. duur daling				8:39	
Gem. waterstand		2			

Gemiddelde over- en onderschrijdingsfrequenties		
Frequentie	**Overschrijding hoogwaterstanden**	**Onderschrijding laagwaterstanden**
1x per 10.000 jaar	470	
1x per 5.000 jaar	450	
1x per 4.000 jaar	450	
1x per 2.000 jaar	430	
1x per 1.000 jaar	410	
1x per 500 jaar	390	
1x per 200 jaar	370	
1x per 100 jaar	345	
1x per 50 jaar	330	
1x per 20 jaar	300	
1x per 10 jaar	280	-210
1x per 5 jaar	260	-200
1x per 2 jaar	235	-180
1x per jaar	215	-170
2x per jaar	200	-165
5x per jaar	175	-145
LAT		-119

Hoogst bekende waarde 269 cm 9 nov 2007 Periode 1978-2010
Laagst bekende waarde -220 cm 12 mrt 1996 Periode 1978-2010

Bijzonderheden:
- 1863 Aanvang waarnemingen
- 15 jul 1977 Peilschrijver geplaatst
- 14 apr 1988 DNM geplaatst

20 RWS Ongeclassificeerd

Figure C.6: Characteristic values of the tide in Petten Zuid (in Dutch) RWS [2013].

C.3. Waves

Wave height and direction measured at an offshore wave buoy in the north sea. Available data up to 1-11-2017.

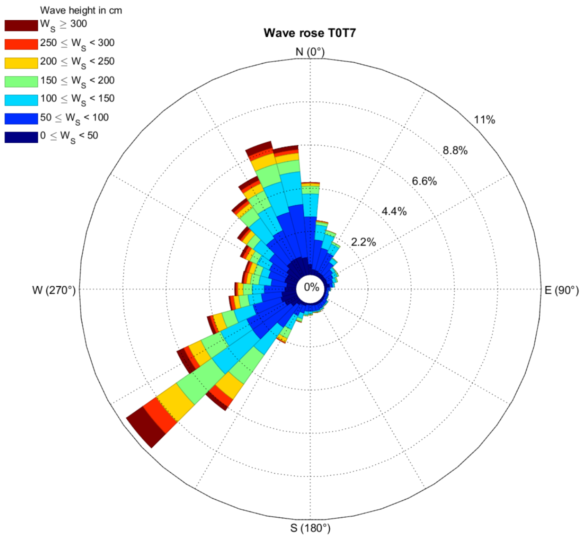
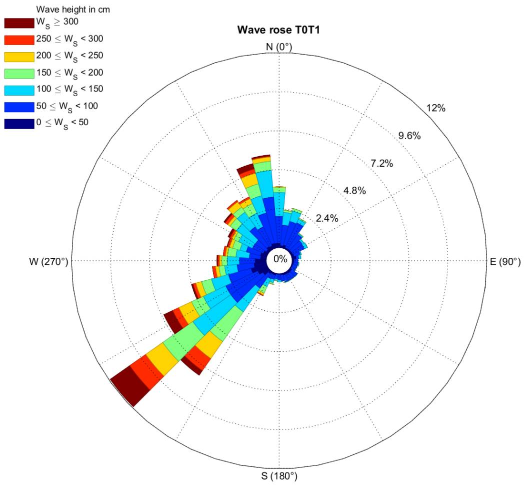
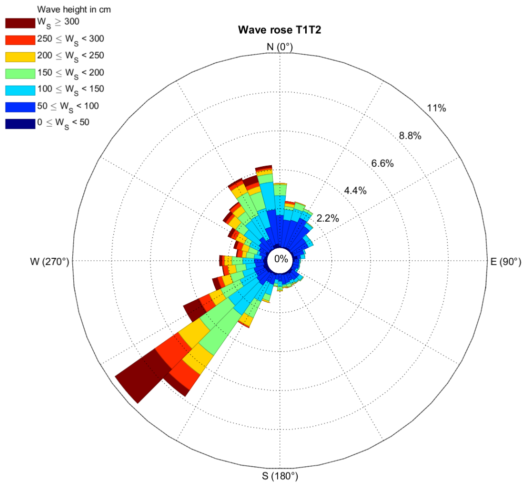


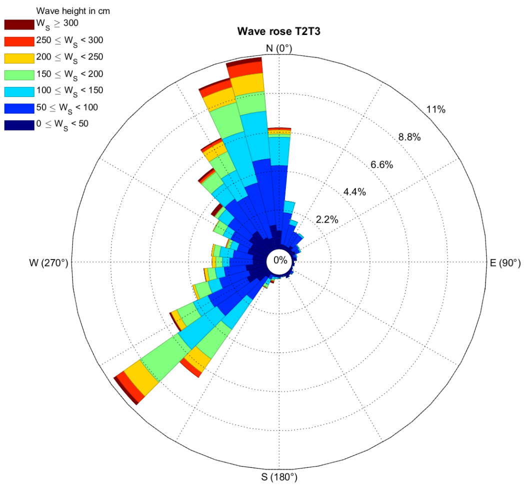
Figure C.7: Wave height and direction in the HD area, measured at the offshore wave buoy (T0-T7).



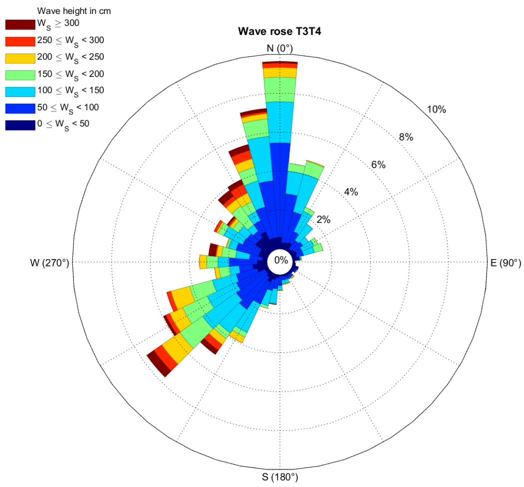
(a) Waves in period T0-T1



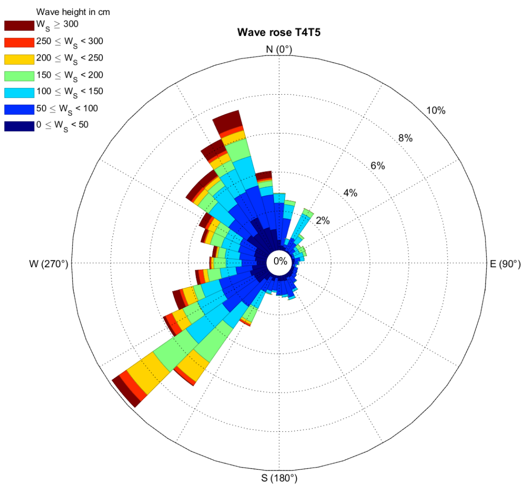
(b) Waves in period T1-T2



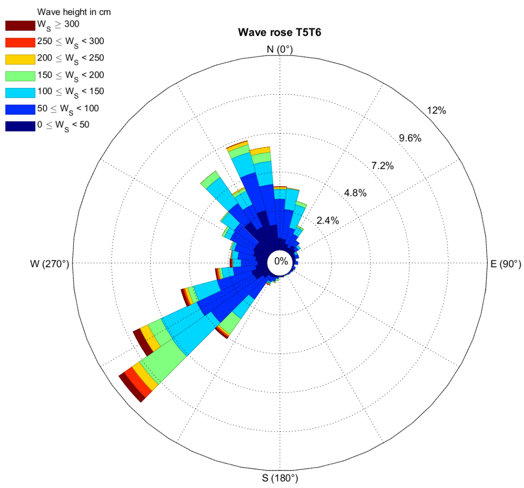
(c) Waves in period T2-T3



(d) Waves in period T3-T4

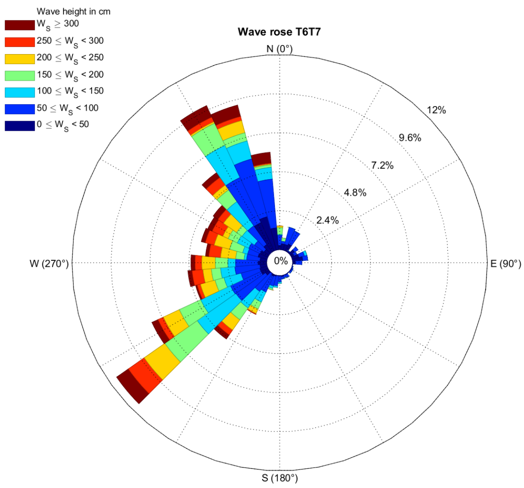


(e) Waves in period T4-T5

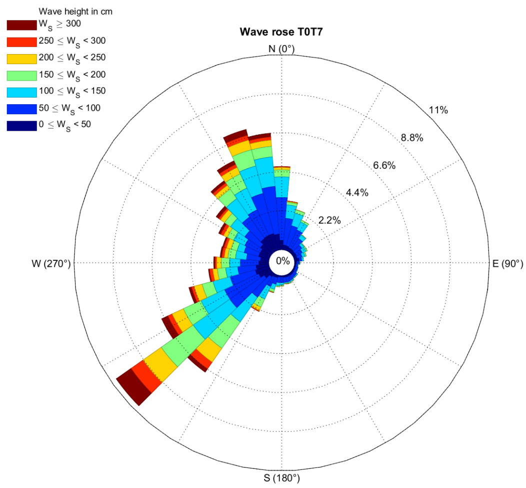


(f) Waves in period T5-T6

Figure C.8: Wave roses during time periods T0-T6



(a) Waves in period T6-T7.



(b) Waves in period T0-T7.

Figure C.9: Wave roses during time periods T6-T7, and T0-T7.

D

Spatial data

D.1. Grain size

2015

After construction of the HD, grain size measurements have been carried out. The results of these measurements show a variation in the initial sediment characteristics in the along shore direction. The samples have been taken in 125 m intervals in alongshore direction. The red line in figure D.1 shows the average grain size diameter in the HD, and the purple lines show the average d50 of each sub-domain. (note. the sub domains have been chosen by the contractor to differentiate between areas with higher and lower quality sand Brandeburg [2015]).

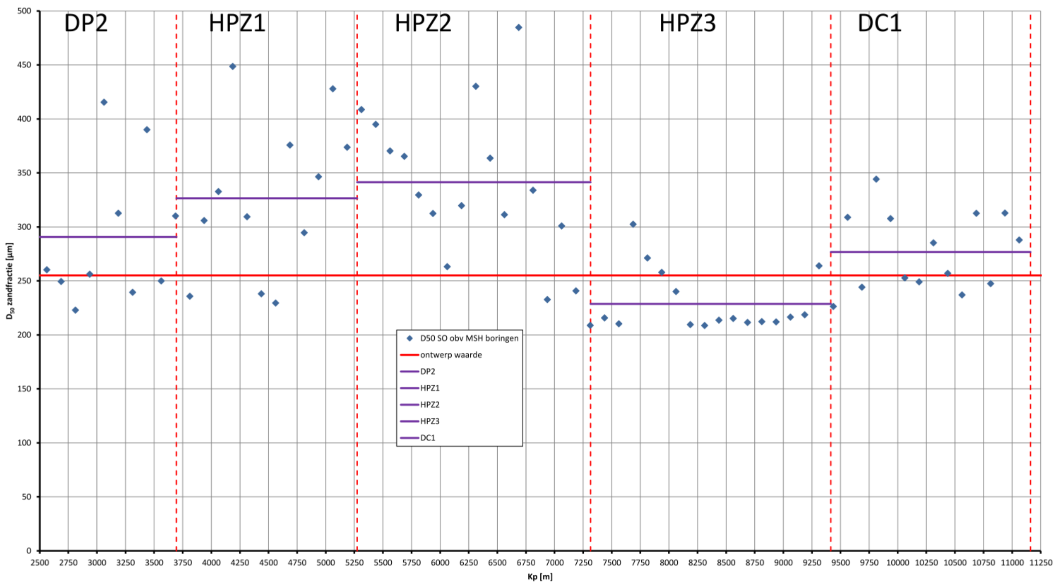


Figure D.1: Measured grain sizes in the HD Brandeburg [2015].

The alongshore variations in grain size is caused by a varying dredge location for sand mining. The location was changed due to, among other things, the presence of explosives in the original locations Brandeburg [2015].

The d_{10} & d_{90} of the samples show that the supplied sand is relatively uniform. The d_{10} varies between

	Profile 2 south	Profile 4	Profile 3 north	Profile 2 north	Profile 1
Swash	278	320	274	274	274
Beach	229	341	327	327	327
Dune foot	229	341	327	327	327
Dune seaside	259	357	358	358	358
Dune land side	-	357	-	-	-

Table D.1: Average d_{50} of each measured profile determined by Boskalis and Van Oord after completion of the HD (2015).

2018

Samples of sand have been collected on 14 may 2018 in the transects shown in figure D.2. In each transect samples have been collected in the inter tidal zone, on the beach, at the dune foot, and in the dune. In the middle transect, a wet dune valley is present. In this transect, a sample is collected in the dunes on either side of the valley.

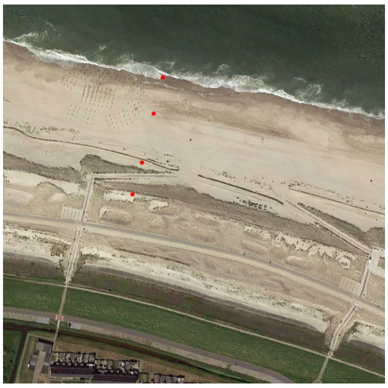
At every location, a total of four samples are collected. Two samples of the surface sediment, and two samples collected from a depth of 1 m. The samples are collected in twofold. In the case the measured grain size distribution differs significantly, additional measurements can be considered to try to explain this difference. These samples are compared to each other in order to determine whether or not these samples represent reliable data.

Figure D.2: Locations of samples for the sieve analysis of the sand in the Hondsbossche Dunes. North is to the right in this picture.

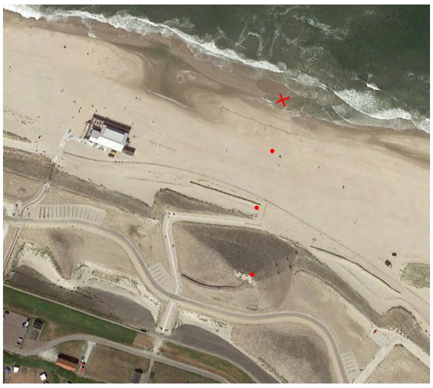
(a) Profile 2 south

(b) Profile 4

(c) Profile 3 north



(d) Profile 2 north



(e) Profile 1

Figure D.3: Locations of sample locations for each profile.

These samples have been analyzed at the VU in Amsterdam with the help of Dr. M.A. Prins. The results of the measurements are presented in the tables below.

	Profile 2 south	Profile 4	Profile 3 north	Profile 2 north	Profile 1
Swash	304.76	376.32*	574.04*	305.98	326.60
Beach	300.79	307.35	353.66	440.76	401.34
Dune foot	254.68	390.31	377.42	349.62	320.08
Dune seaside	238.06	357.18	417.23	331.85	428.56*
Dune land side	-	281.45	-	-	-

Table D.2: Measured d_{50} at each location on the surface.

	Profile 2 south	Profile 4	Profile 3 north	Profile 2 north	Profile 1
Swash	271.67	490.62	620.47*	385.97*	410.25*
Beach	344.28	388.20	487.71*	359.75	453.82
Dune foot	275.53	303.71	317.98	289.59	269.68*
Dune seaside	252.13	281.50	381.60	308.76	480.60
Dune land side	-	430.80*	-	-	-

Table D.3: Measured d_{50} at each location at 1m depth.

D.2. Vegetation cover

Aerial photographs are used to determine the vegetation cover. The photographs dates and resolution is shown in table D.4.

date	type	resolution [m]
24-05-2015	Aerial photograph	0.05
28-12-2015	Aerial photograph	0.05
21-03-2016	Aerial photograph	0.05
01-09-2016	Aerial photograph	0.05
05-12-2016	Aerial photograph	0.05
19-04-2017	Aerial photograph	0.05
11-08-2017	Aerial photograph	0.05
06-12-2017	Aerial photograph	0.05

Table D.4: Aerial photograph dates of the Hondsbossche Dunes.

For the analysis of vegetation cover another source of aerial pictures is used, containing NIR (near infrared) images. Also, after construction had finished, HHNK had measured the location of areas with vegetation, and areas without vegetation. These data sets are shown in table D.5

date	type	resolution [m]
24-05-2015	Polygon data	-
18-07-2016	Aerial IR photograph	0.25
22-06-2017	Aerial IR photograph	0.25

Table D.5: Vegetation data for the HD

D.3. Topography

Several measurements of the topography of the HD have been made since its construction. The interval between these measurements is roughly 4 months.

date	type	resolution [m]
24-05-2015	Topography	0.5
28-12-2015	Topography	0.5
21-03-2016	Topography	0.5
01-09-2016	Topography	0.5
05-12-2016	Topography	0.5
19-04-2017	Topography	0.5
11-08-2017	Topography	0.5
06-12-2017	Topography	0.5
19-03-2018	Topography	0.5

Table D.6: Dates of LiDAR measurements of the Hondsbossche Dunes.

D.3.1. Beach

	RSP	T0	T1	T2	T3	T4	T5	T6	T7	T8
Profile 1	20.17-20.94	628	600	596	604	598	589	598	620	610
Profile 2N	20.94-21.46	542	500	497	510	500	490	495	485	483
Profile 3N	21.46-22.47	614	577	587	585	579	558	556	539	545
Profile 4	22.47-23.94	569	585	595	601	604	598	597	583	586
Profile 3S	23.94-25.40	614	609	607	615	621	615	618	613	611
Profile 2S	25.40-25.89	647	626	598	604	603	564	567	533	526
HD	20.17-25.89	603	583	580	587	584	569	572	562	560

Table D.7: Beach volume for each measurement period in m3

	RSP	T0	T1	T2	T3	T4	T5	T6	T7	T8
Profile 1	20.17-20.94	194	137	130	136	118	127	124	123	125
Profile 2N	20.94-21.46	136	73	75	88	70	68	66	60	65
Profile 3N	21.46-22.47	136	98	92	89	85	73	67	53	65
Profile 4	22.47-23.94	147	119	117	121	119	113	113	97	114
Profile 3S	23.94-25.40	170	145	154	149	141	136	134	115	117
Profile 2S	25.40-25.89	184	141	115	121	114	85	85	53	76
HD	20.17-25.89	161	119	114	118	108	100	98	83	93

Table D.8: Beach width for each measurement period in meters

	RSP	T0	T1	T2	T3	T4	T5	T6	T7	T8
Profile 1	20.17-20.94	3,36	4,09	3,95	4,33	4,40	4,00	4,66	4,51	4,06
Profile 2N	20.94-21.46	3,51	2,91	3,36	3,59	3,76	3,46	4,16	3,84	4,33
Profile 3N	21.46-22.47	3,64	3,43	4,23	4,42	4,33	3,98	4,75	5,21	4,82
Profile 4	22.47-23.94	8,33	8,98	9,26	8,80	8,81	8,81	9,16	9,41	8,96
Profile 3S	23.94-25.40	3,33	2,88	2,67	3,04	2,96	2,69	3,15	3,16	3,53
Profile 2S	25.40-25.89	2,86	2,29	2,28	3,11	2,59	2,97	3,91	5,16	9,60
HD	20.17-25.89	4,17	4,10	4,29	4,55	4,48	4,32	4,96	5,22	5,88

Table D.9: Beach slope for each measurement period in degrees

	RSP	T0-T1	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6	T6-T7	T7-T8	T0-T8
Profile 1	20.17-20.94	-48	-16	19	-25	-24	28	67	-33	-6
Profile 2N	20.94-21.46	-71	-12	29	-38	-28	18	-31	-10	-21
Profile 3N	21.46-22.47	-62	42	-3	-23	-56	-6	-53	19	-24
Profile 4	22.47-23.94	25	44	14	11	-17	-4	-41	8	6
Profile 3S	23.94-25.40	-9	-8	17	23	-16	10	-16	-9	-1
Profile 2S	25.40-25.89	-36	-120	13	-4	-106	10	-106	-25	-43
HD	20.17-25.89	-33	-11	15	-9	-41	9	-30	-8	-15

Table D.10: Beach volume changes per time period in m3/m/year

	RSP	T0-T1	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6	T6-T7	T7-T8	T0-T8
Profile 1	20.17-20.94	-97	-29	14	-71	25	-11	-2	6	-25
Profile 2N	20.94-21.46	-105	5	31	-69	-6	-6	-18	16	-25
Profile 3N	21.46-22.47	-62	-27	-7	-15	-33	-19	-45	43	-25
Profile 4	22.47-23.94	-46	-10	10	-8	-17	-2	-50	62	-12
Profile 3S	23.94-25.40	-41	38	-11	-33	-14	-4	-61	7	-19
Profile 2S	25.40-25.89	-72	-112	13	-26	-79	-1	-99	81	-38
HD	20.17-25.89	-71	-23	8	-37	-21	-7	-46	36	-24

Table D.11: Beach width changes, average of each beach profile in m/year.

	RSP	T0-T1	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6	T6-T7	T7-T8	T0-T8
Profile 1	20.17-20.94	1,24	-0,63	0,86	0,25	-1,08	2,12	-0,47	-1,61	0,25
Profile 2N	20.94-21.46	-1,01	1,96	0,51	0,64	-0,80	2,23	-0,98	1,72	0,29
Profile 3N	21.46-22.47	-0,36	3,48	0,43	-0,34	-0,95	2,47	1,41	-1,36	0,42
Profile 4	22.47-23.94	1,09	1,22	-1,03	0,04	-0,01	1,11	0,80	-1,60	0,22
Profile 3S	23.94-25.40	-0,75	-0,92	0,82	-0,31	-0,75	1,49	0,02	1,33	0,07
Profile 2S	25.40-25.89	-0,95	-0,07	1,86	-2,00	1,03	3,00	3,90	15,73	2,39
HD	20.17-25.89	-0,12	0,84	0,57	-0,29	-0,43	2,07	0,78	2,37	0,61

Table D.12: Beach slope changes, average for each profile in degrees/year

D.3.2. Dune

	RSP	T0	T1	T2	T3	T4	T5	T6	T7	T8
Profile 1	20.17-20.94	980	984	985	988	995	983	988	1005	1002
Profile 2N	20.94-21.46	978	992	999	1003	1010	1013	1017	1020	1024
Profile 3N	21.46-22.47	747	774	782	788	795	803	806	812	821
Profile 4	22.47-23.94	716	728	730	739	748	761	770	784	797
Profile 3S	23.94-25.40	790	824	838	853	861	878	885	906	924
Profile 2S	25.40-25.89	1014	1048	1058	1069	1078	1089	1092	1102	1102
HD	20.17-25.89	871	892	899	907	915	921	926	938	945

Table D.13: Absolute dune volume at each time step m^3/m.

	RSP	T0-T1	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6	T6-T7	T7-T8	T0-T8
Profile 1 N	20.17-20.94	8	2	8	26	-32	14	53	-9	8
Profile 2 N	20.94-21.46	24	28	10	27	7	12	9	17	16
Profile 3 N	21.46-22.47	47	35	12	30	21	10	19	30	26
Profile 4	22.47-23.94	19	8	20	36	35	30	42	46	28
Profile 3 S	23.94-25.40	58	57	34	33	44	24	65	65	48
Profile 2 S	25.40-25.89	56	43	25	35	29	10	32	0	31
HD	20.17-25.89	35	29	18	31	17	17	37	25	26

Table D.14: Dune growth per time period in m^3/m/year

E

Bathymetry of the HD

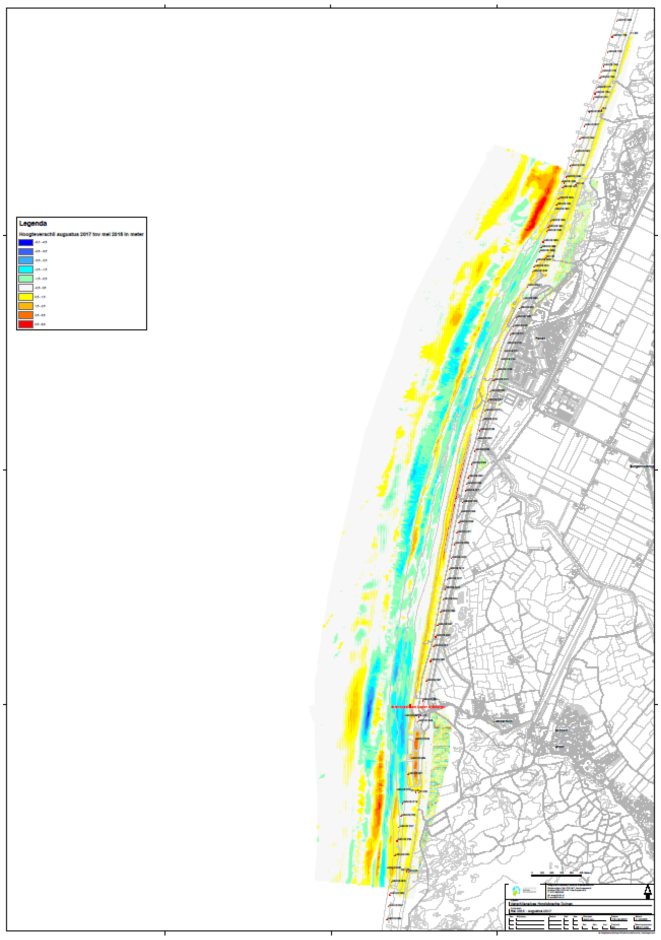


Figure E.1: Difference analysis of the bathymetry in the HD between may 2015 and august 2017. Red indicating sedimentation, blue indicating erosion.

Figure E.1 shows the topographic change of the HD below the water line. A gully is forming in front of the southern part of the HD in front of profile 2 south. This gully acts as a sediment sink, and is a natural feature of this part of the North sea coast. The gully originally extended along the entire stretch of the HD. It was filled with sediment during the construction of the HD, and now the natural processes are eroding this added volume of sand.

F

DuBeVeg set-up

DuBeVeg only accepts topographic data in the form height measurements in an equidistant matrix form. The distance between the measurements is set at 1 m, which couldn't be deviated from. After modification of the code, DuBeVeg now accepts topographic data with a variable equidistant grid size. The grid size depends on the available data (which also needs to be equidistant).

The available topographic data of the HD, is represented on an equidistant grid of size 20 m. To increase the resolution and accuracy of the model results, extra grid points can created by interpolating or replicating the measured data points a number of times. Replication of grid points results in an unrealistic starting situation, with jumps between the measured points. This effect is quickly smoothed out by erosion and deposition in the dunes.

F.1. Numerical parameters

The grid size is determined by dividing the original distance between the data points by the amount of added grid points. Increasing the amount of grid points can make it easier to interpret the model results, but the calculation time increases exponentially with the increase of resolution.

Equation F.1 is used to set up the numerical parameters of DuBeVeg. The same equation is used to calibrate the model using AeoLiS.

$$Q = h_s L \frac{P_e}{P_d} n \tag{F.1}$$

For the set up of DuBeVeg, equation F.1 is modified to equation F.2, by assuming Q and the erosion and deposition probabilities as constants. h_s has a base value of 0.1 m Keijsers et al. [2016], this value of modified to the values chosen for the hop length and the amount of iterations per year.

$$h_s = \frac{C}{Ln} \tag{F.2}$$

In which C is a constant substituted for Q and the erosion and deposition probabilities.

The yearly sediment transport capacity as calculated by AeoLiS is put into equation F.1. In the set up process the values for the slab height, jump length and iterations per year have been determined. This leaves the erosion and deposition probabilities as calibration parameters.

F.2. Equilibrium beach profile

DuBeVeg requires an equilibrium state for the beach as an input. The equilibrium state of the beach at the Hondsbossche Dunes is most likely not reached yet. Therefore, an approximation using the Bruun rule is applied. (See equation F.3).

$$h = A * y^{2/3} \tag{F.3}$$

Where h is the water depth, A is a parameter relating to the sediment scale, and y is the distance from the shoreline.

F.3. Forcing

Because of the nature of DuBeVeg, the magnitude of the wind forcing is incorporated in the deposition and erosion probabilities. But the direction isn't. The direction of the wind is implemented in DuBeVeg by rotating the topographic map, instead of rotating the forcing itself. For the direction of the wind, the weighted average of the wind in the period between T0 and T8 is used.

The water levels are taken from measurements at the water level measurement site at Petten Zuid. The maximum water level of each 2 week period is used as input (2 weeks is approximately equal to a spring-neap tidal cycle).

F.4. Calibration

The factors used for calibration are the following:

- p erosion
- p deposition
- p deposition vegetated
- jump length
- grid size
- slab height
- iterations per cycle
- potential aeolian sediment transport
- groundwater depth

Parameters such as grid size, jump length, and iterations per cycle are determined beforehand. The grid size is determined by the input, iterations per cycle is set at 52 iterations per year. This way, the model calculates aeolian sediment transport each week. The jump length is set at the same value as the grid size.

That still leaves a lot of parameters for calibration. The formula introduced in the main text is used for the calibration of some of these parameters.

$$Q = h_s L \frac{P_e}{P_d} n \tag{F.4}$$

this formula incorporates every parameter summed up above, except for the groundwater depth.

	Dune growth	Beach growth	Dune/beach growth
Profile 1	0.0228	-0.0156	-1.4660
Profile 2 north	0.0476	-0.1005	-0.4733
Profile 3 north	0.0998	-0.1018	-0.9808
Profile 4	0.1122	0.0340	3.2969
Profile 3 south	0.1700	-0.0027	-63.6614
Profile 2 south	0.0868	-0.1792	-0.4844

Table F.1: Fractional growth of the beach and dune area, and the ration between the beach and dune fractional growth

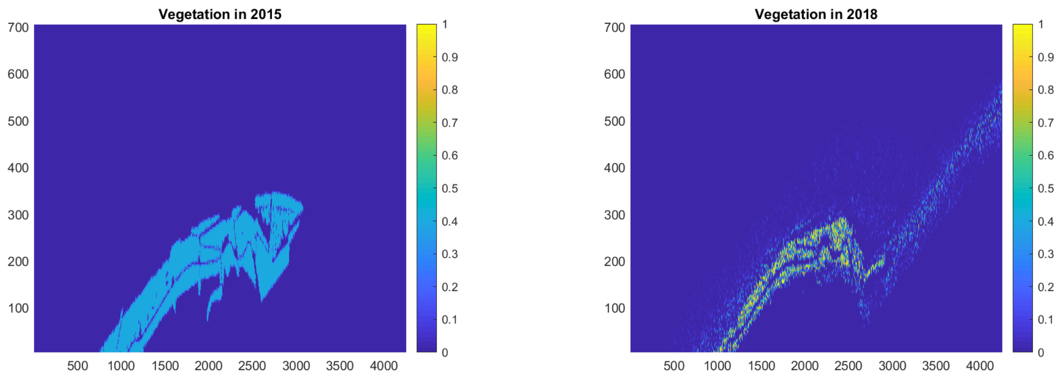
F.5. Calibration values

	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3S	Profile 2S
Iterations per cycle [-]	52	52	52	52	52	52
Slabheight [m]	0.1	0.1	0.1	0.1	0.1	0.1
Start density vegetation [-]	0.4	0.4	0.4	0.6	0.6	0.6
p_dep_vegetation [-]	-	0.6	0.6	0.6	0.6	0.6
p_dep_bare [-]	-	0.3	0.3	0.4	0.39	0.2
p_erosion [-]	-	0.2077	0.2308	0.1538	0.3750	0.1500
Vellinga	-	0.6	0.32	0.03	0.0265	0.9
Groundwater factor [-]	0.2	0.2	0.2	0.2	0.2	0.2

Table F.2: Calibration values for the different model runs in DuBeVeg

G

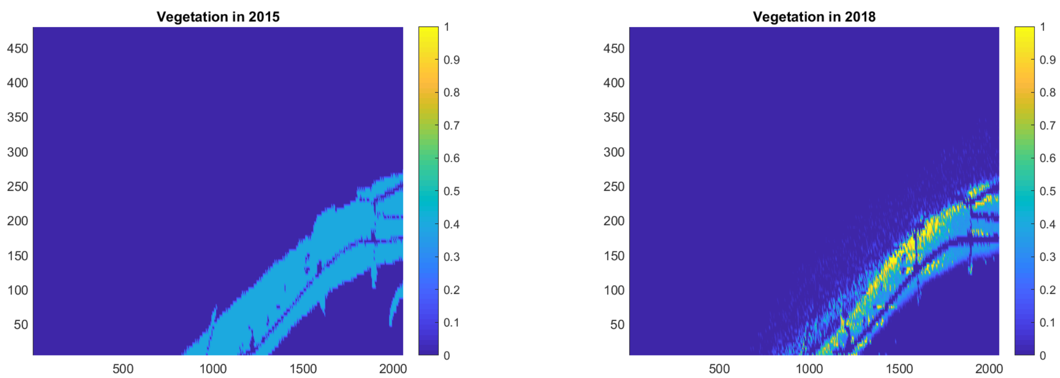
Validation



(a) Vegetation state at t=0 (2015)

(b) Vegetation state at t=3 (2018)

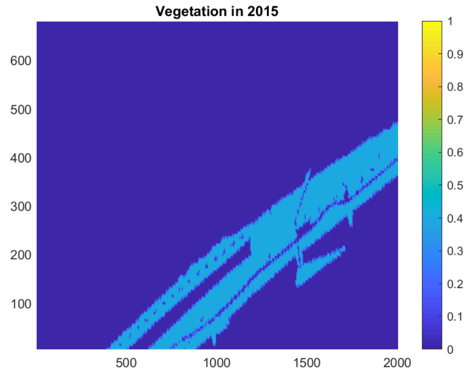
Figure G.1: Vegetation development in profile 1 in the years since construction.



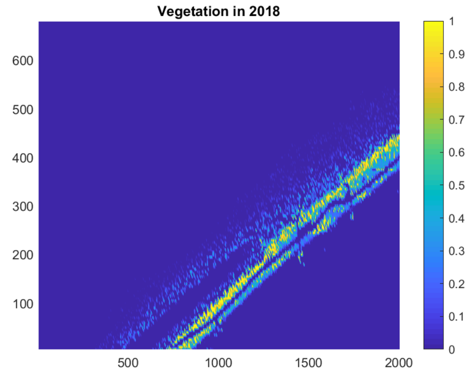
(a) Vegetation state at t=0 (2015)

(b) Vegetation state at t=3 (2018)

Figure G.2: Vegetation development in profile 2 north in the years since construction.

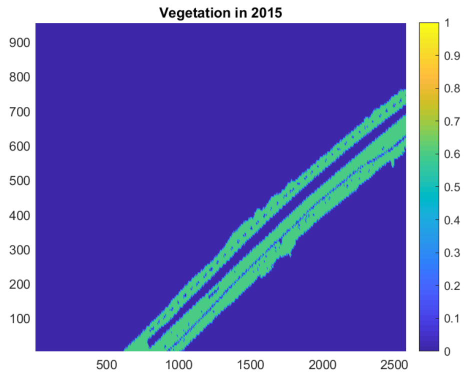


(a) Vegetation state at t=0 (2015)

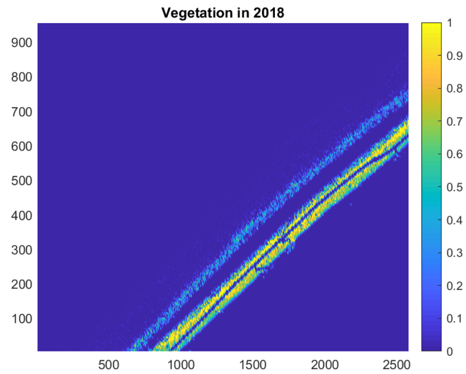


(b) Vegetation state at t=3 (2018)

Figure G.3: Vegetation development in profile 3 north in the years since construction.

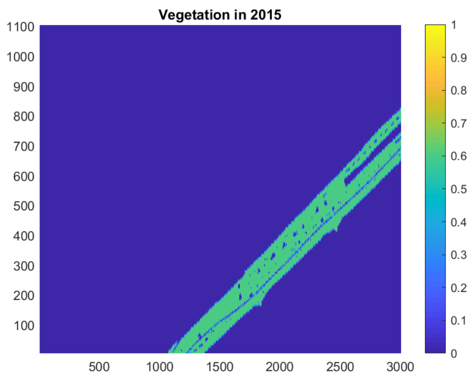


(a) Vegetation state at t=0 (2015)

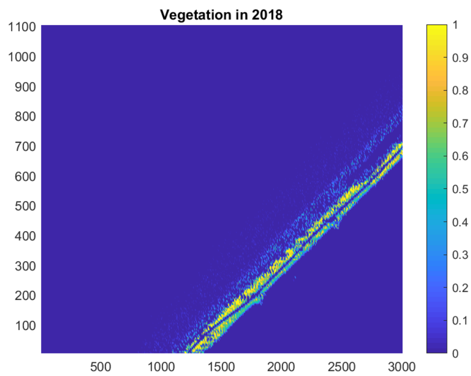


(b) Vegetation state at t=3 (2018)

Figure G.4: Vegetation development in profile 4 in the years since construction.

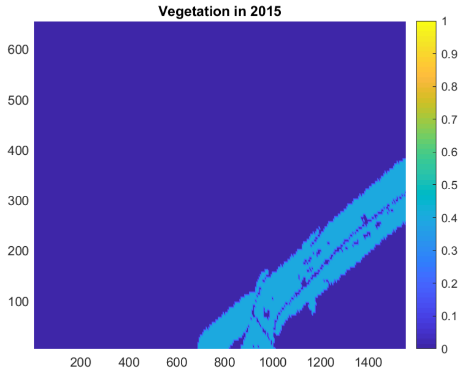


(a) Vegetation state at t=0 (2015)

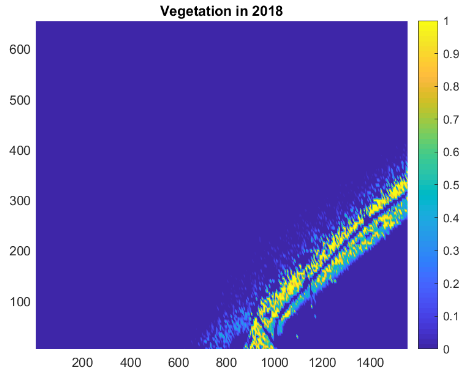


(b) Vegetation state at t=3 (2018)

Figure G.5: Vegetation development in profile 3 south in the years since construction.



(a) Vegetation state at t=0 (2015)



(b) Vegetation state at t=3 (2018)

Figure G.6: Vegetation development in profile 2 south in the years since construction.

H

DuBeVeg results

H.1. Dune growth rates

	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3Z	Profile 2Z	Average
No nourishment	+5	+3	-7	+4	+20	-16	+1
slr low	-2	+3	-7	+3	+20	-16	+0
slr mid	-3	+2	-8	+3	+19	-18	-1
slr high	-4	+2	-7	+3	+17	-20	-1
wind low	+4	+9	-1	+9	+17	-11	+4
wind high	-2	-3	-10	0	+23	-16	-1

Table H.1: Average dune growth rates between 2015-2065 in m3/m/year in simulations without nourishments

	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3Z	Profile 2Z	Average
Nourishments	+10 (2)	+13 (3)	+14 (5)	+4 (0)	+20 (0)	+14 (6)	+12
slr low	+10 (2)	+13 (3)	+13 (5)	+3 (0)	+20 (0)	+12 (7)	+12
slr mid	+8 (2)	+10 (3)	+11 (5)	+3 (0)	+19 (0)	+11 (11)	+10
slr high	+6 (2)	+9 (3)	+9 (6)	+3 (0)	+17 (0)	+8 (12)	+9
wind low	+10 (2)	+16 (2)	+14 (3)	+9 (0)	+17 (0)	+11 (5)	+13
wind high	+10 (3)	+13 (4)	+17 (6)	0 (0)	+23 (0)	+18 (8)	+14

Table H.2: Average dune growth rates between 2015-2065 in m^3/m/year in simulations with nourishments

	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3Z	Profile 2Z	Average
base	+5	+10	+22	0	0	+29	+18
slr low	+11	+10	+20	0	0	+28	+18
slr mid	+11	+8	+18	0	0	+29	+16
slr high	+10	+6	+16	0	0	+28	+15
wind low	+7	+7	+14	0	0	+23	+13
wind high	+12	+16	+27	0	0	+34	+22

Table H.3: Difference in average dune growth rates in the period between 2015-2065 in m3/m/year for the cases with and without nourishments. Positive values indicate higher accretion rates in the case with nourishments.

H.2. Beach growth rates

	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3Z	Profile 2Z	Average
No nourishment	-7	-4	-9	-6	-2	-11	-6
slr low	-7	-4	-9	-5	-1	-10	-6
slr mid	-7	-4	-9	-5	-2	-11	-6
slr high	-7	-4	-8	-5	-2	-11	-6
wind low	-7	-4	-7	-5	-1	-9	-6
wind high	-8	-5	-10	-7	-2	-11	-7

Table H.4: Average beach growth rates between 2015-2065 in m3/m/year in simulations without nourishments

	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3Z	Profile 2Z	Average
Nourishments	+1 (2)	+5 (3)	+3 (5)	-6 (0)	-2 (0)	-1 (6)	0
slr low	0 (2)	+3 (3)	+2 (5)	-5 (0)	-1 (0)	+2 (7)	0
slr mid	-1 (2)	+1 (3)	-1 (5)	-5 (0)	-2 (0)	+1 (11)	-1
slr high	-2 (2)	0 (3)	+1 (6)	-5 (0)	-2 (0)	+1 (12)	-1
wind low	+4 (2)	+1 (3)	+2 (3)	-5 (0)	-1 (0)	+5 (5)	-1
wind high	+6 (2)	+7 (3)	+4 (6)	-7 (0)	-2 (0)	+2 (8)	1

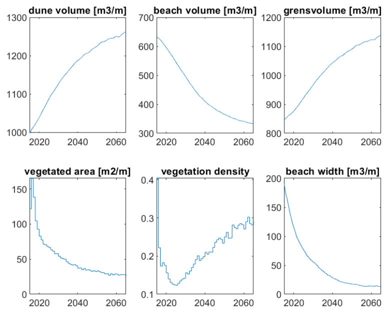
Table H.5: Average beach growth rates between 2015-2065 in m3/m/year in simulations with nourishments

	Profile 1	Profile 2N	Profile 3N	Profile 4	Profile 3Z	Profile 2Z	Average
base	+7	+9	+12	0	0	+10	+10
slr low	+7	+7	+11	0	0	+12	+9
slr mid	+6	+6	+8	0	0	+12	+8
slr high	+6	+4	+10	0	0	+12	+8
wind low	+11	+5	+9	0	0	+14	+10
wind high	+14	+12	+13	0	0	+13	+13

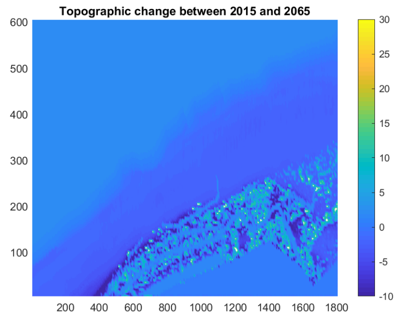
Table H.6: Difference in average baech growth rates in the period between 2015-2065 in m3/m/year for the cases with and without nourishments. Positive values indicate higher accretion rates in the case with nourishments.

H.3. Profile 1

H.3.1. No nourishment



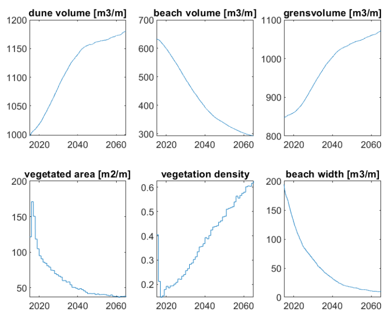
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



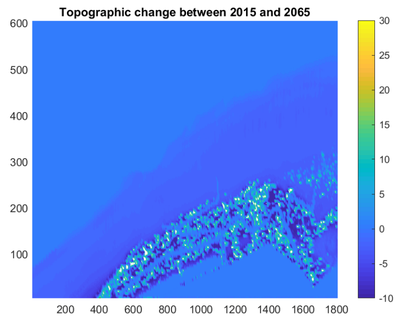
(b) Vegetation state at t=50 (2065)

Figure H.1: Zero-measurement results without nourishments for profile 1

Wind speed change

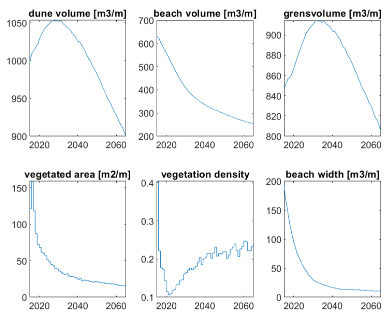


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

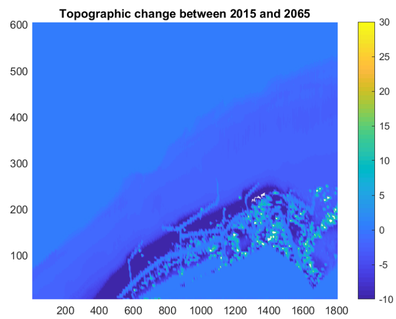


(b) Difference map (2015-2065)

Figure H.2: Low wind results without nourishments for profile 1



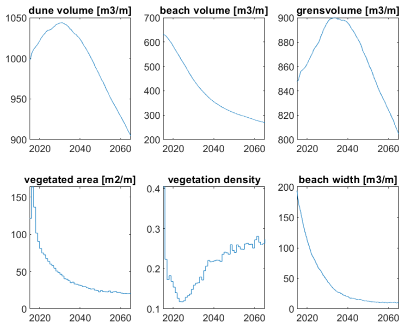
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



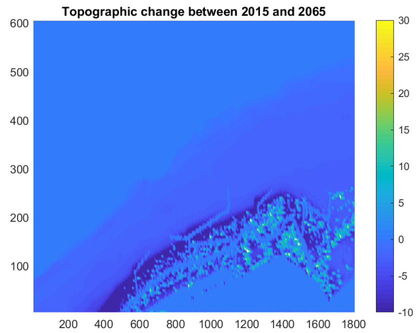
(b) Difference map (2015-2065)

Figure H.3: High wind results without nourishments for profile 1

Sea level rise

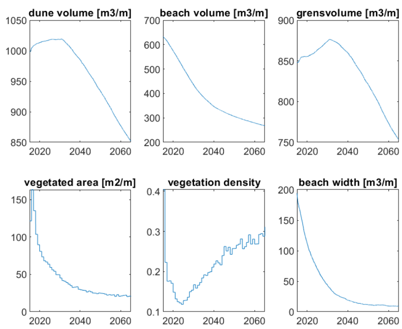


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

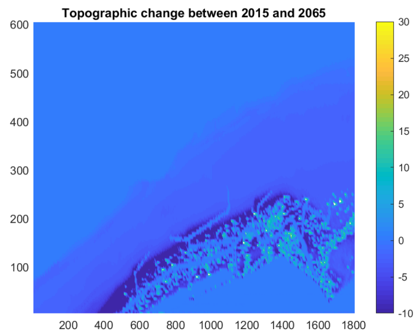


(b) Vegetation state at t=50 (2065)

Figure H.4: Low sea level rise results without nourishments for profile 1

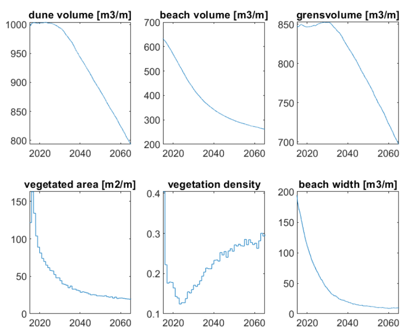


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

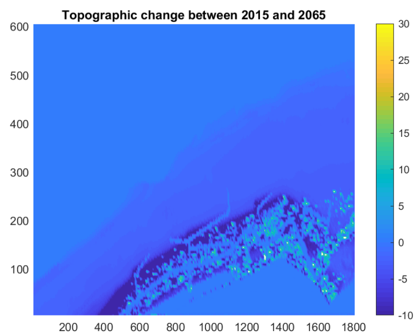


(b) Vegetation state at t=50 (2065)

Figure H.5: Medium sea level rise results without nourishments for profile 1



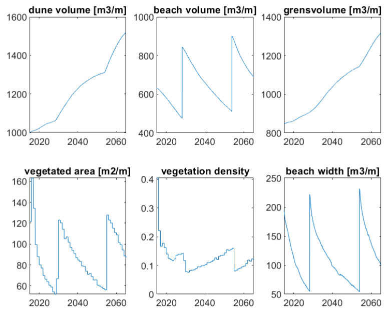
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



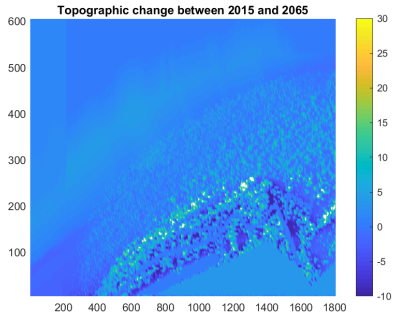
(b) Vegetation state at t=50 (2065)

Figure H.6: High sea level rise results without nourishments for profile 1

H.3.2. Nourishments



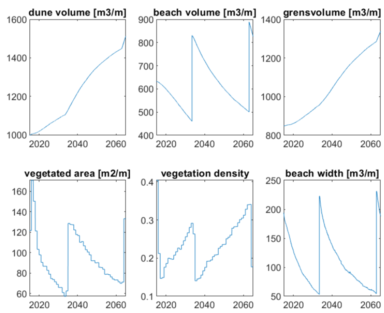
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



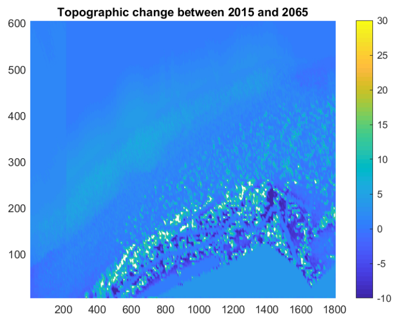
(b) Vegetation state at t=50 (2065)

Figure H.7: Zero-measurement results with nourishments for profile 1

Wind speed change

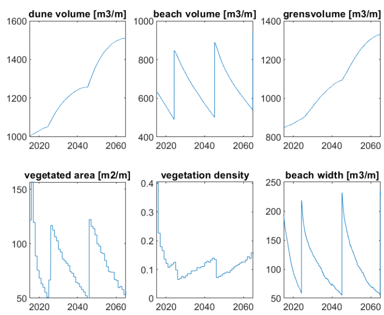


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

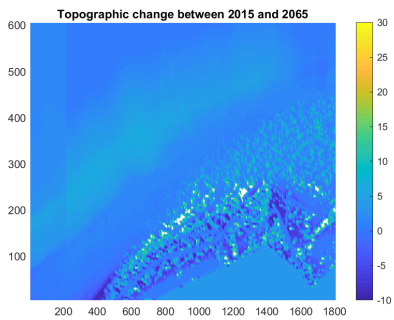


(b) Difference map (2015-2065)

Figure H.8: Low wind results with nourishments for profile 1



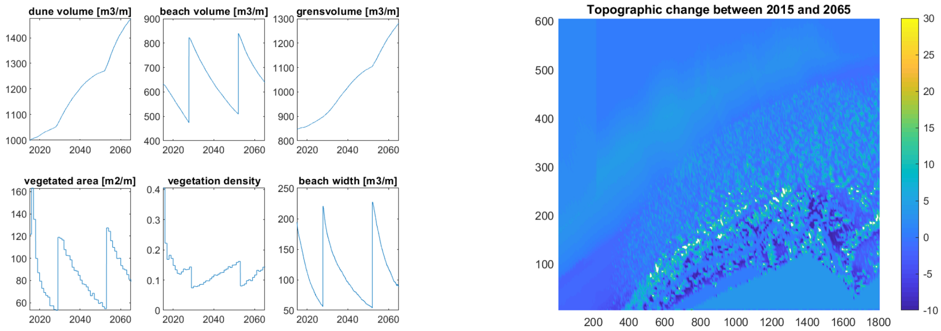
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



(b) Difference map (2015-2065)

Figure H.9: High wind results with nourishments for profile 1

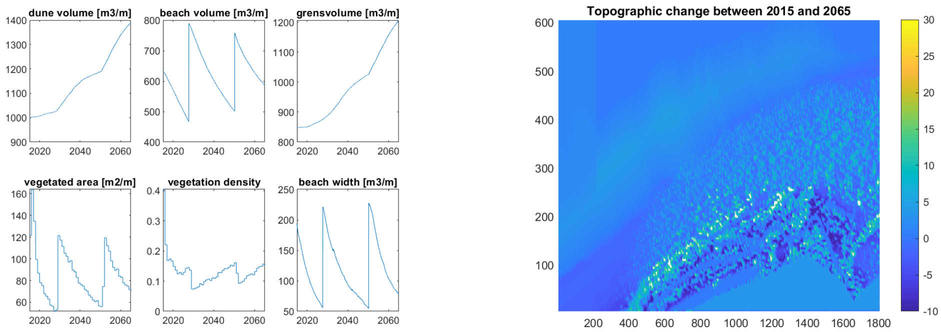
Sea level rise



(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

(b) Vegetation state at t=50 (2065)

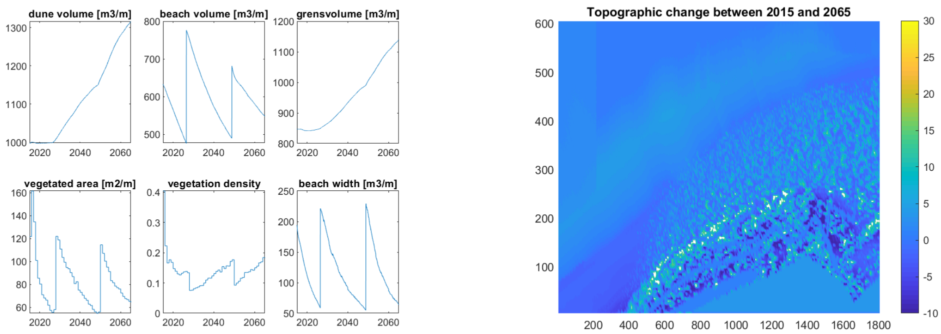
Figure H.10: Low sea level rise results with nourishments for profile 1



(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

(b) Vegetation state at t=50 (2065)

Figure H.11: Medium sea level rise results with nourishments for profile 1



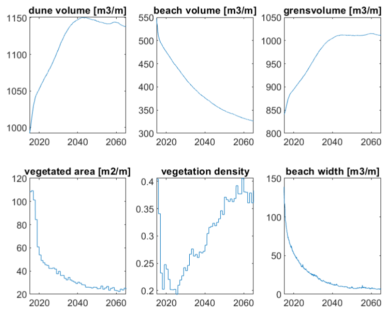
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

(b) Vegetation state at t=50 (2065)

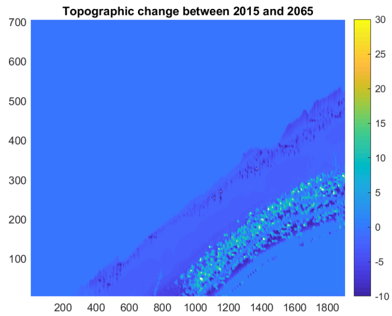
Figure H.12: High sea level rise results with nourishments for profile 1

H.4. Profile 2 north

H.4.1. No nourishment



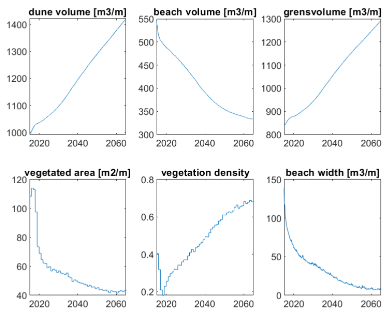
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



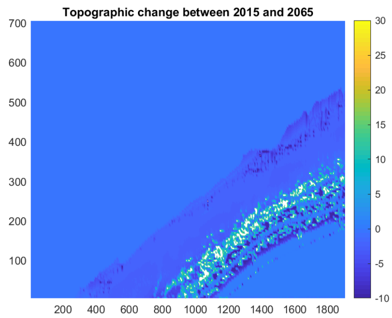
(b) Vegetation state at t=50 (2065)

Figure H.13: Zero-measurement results without nourishments for profile 2 north

Wind speed change

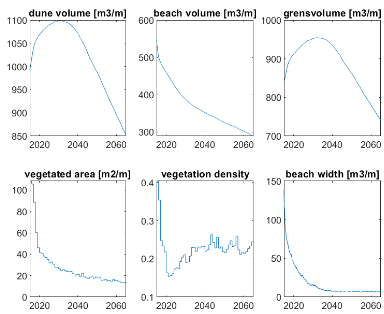


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

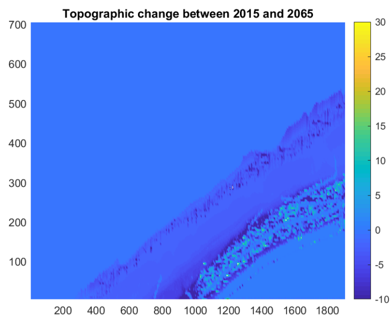


(b) Difference map (2015-2065)

Figure H.14: Low wind results without nourishments for profile 2 north



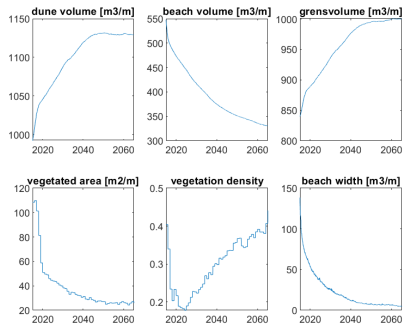
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



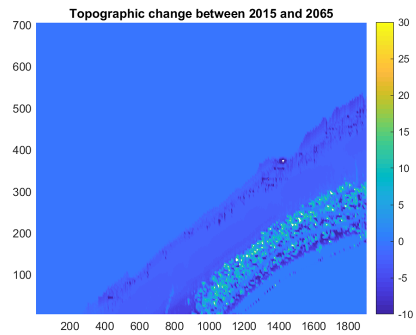
(b) Difference map (2015-2065)

Figure H.15: High wind results without nourishments for profile 2 north

Sea level rise

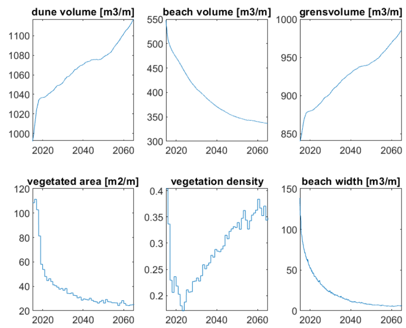


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

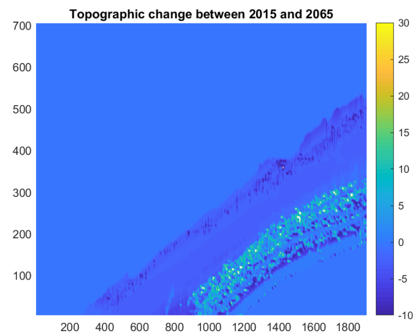


(b) Vegetation state at t=50 (2065)

Figure H.16: Low sea level rise results without nourishments for profile 2 north

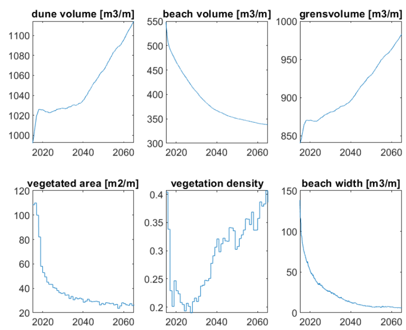


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

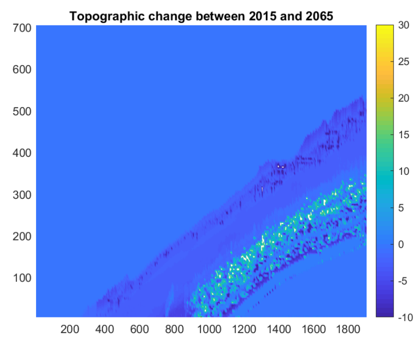


(b) Vegetation state at t=50 (2065)

Figure H.17: Medium sea level rise results without nourishments for profile 2 north



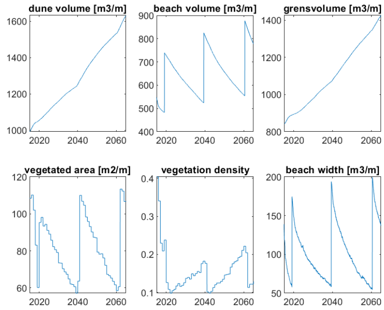
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



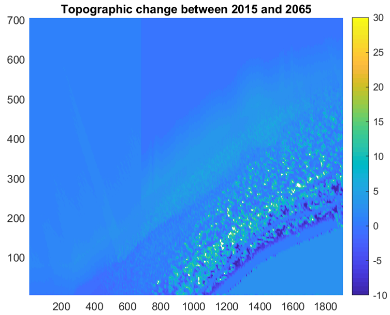
(b) Vegetation state at t=50 (2065)

Figure H.18: High sea level rise results without nourishments for profile 2 north

H.4.2. Nourishments



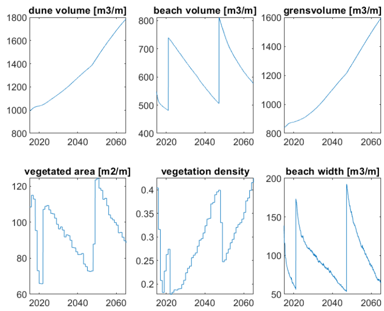
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



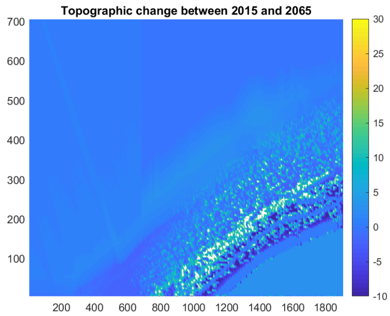
(b) Vegetation state at t=50 (2065)

Figure H.19: Zero-measurement results with nourishments for profile 2 north

Wind speed change

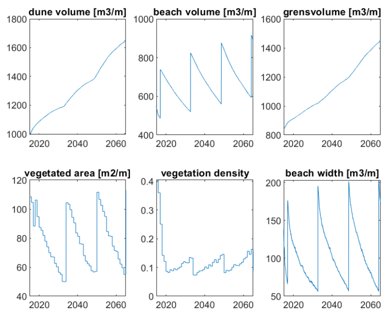


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

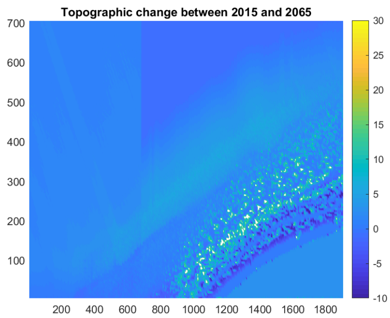


(b) Difference map (2015-2065)

Figure H.20: Low wind results with nourishments for profile 2 north



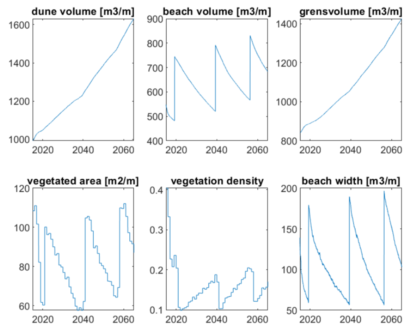
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

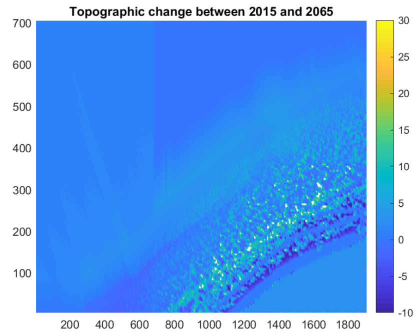


(b) Difference map (2015-2065)

Figure H.21: High wind results with nourishments for profile 2 north

Sea level rise

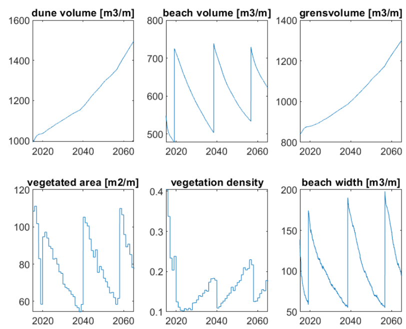


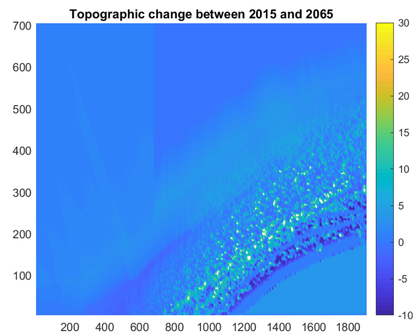


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

(b) Vegetation state at t=50 (2065)

Figure H.22: Low sea level rise results with nourishments for profile 2 north

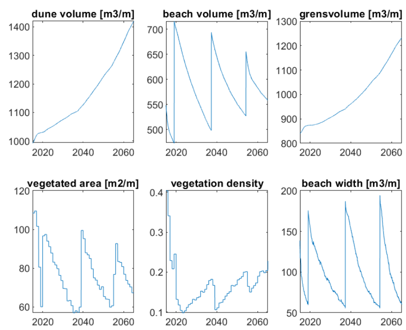


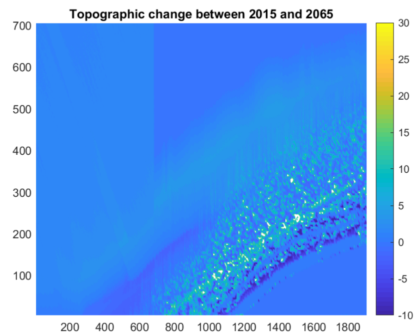


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

(b) Vegetation state at t=50 (2065)

Figure H.23: Medium sea level rise results with nourishments for profile 2 north





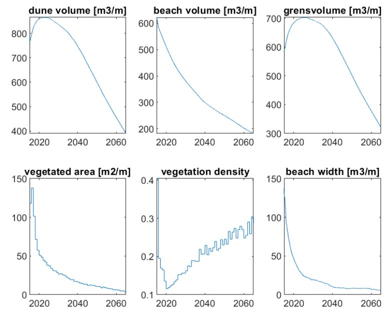
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

(b) Vegetation state at t=50 (2065)

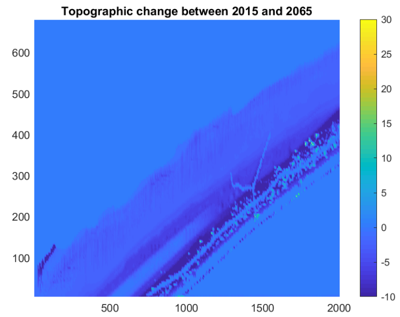
Figure H.24: High sea level rise results with nourishments for profile 2 north

H.5. profile 3 north

H.5.1. No nourishment



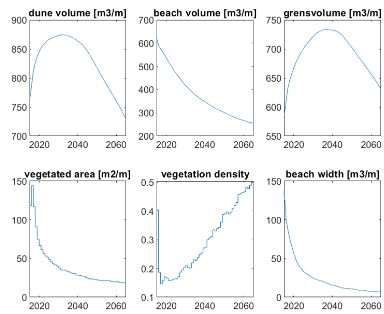
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



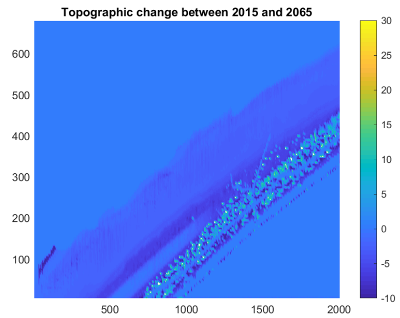
(b) Vegetation state at t=50 (2065)

Figure H.25: Zero-measurement results without nourishments for profile 3 north

Wind speed change

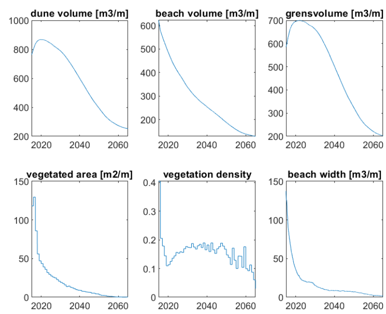


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

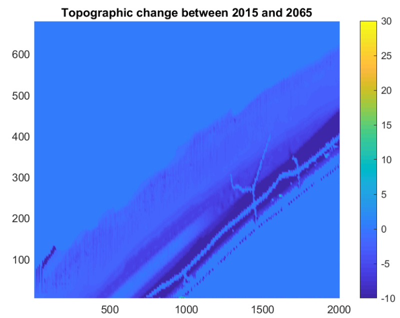


(b) Difference map (2015-2065)

Figure H.26: Low wind results without nourishments for profile 3 north



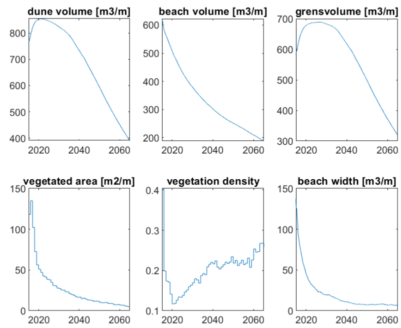
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



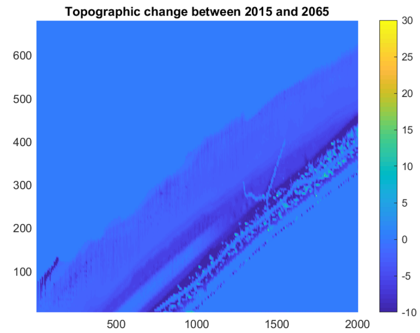
(b) Difference map (2015-2065)

Figure H.27: High wind results without nourishments for profile 3 north

Sea level rise

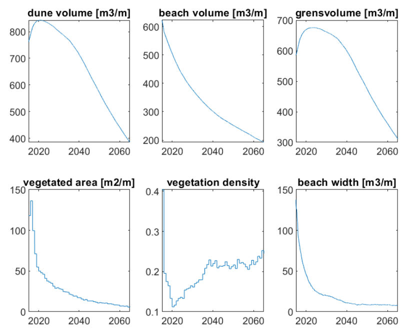


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

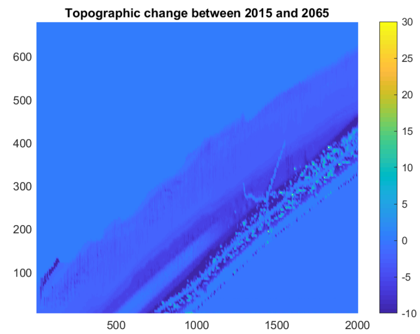


(b) Vegetation state at t=50 (2065)

Figure H.28: Low sea level rise results without nourishments for profile 3 north

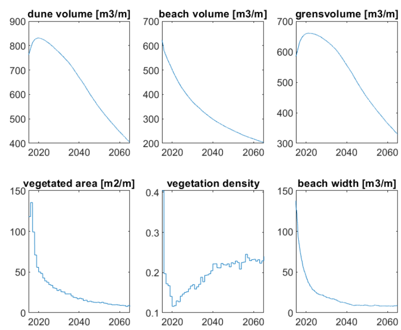


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

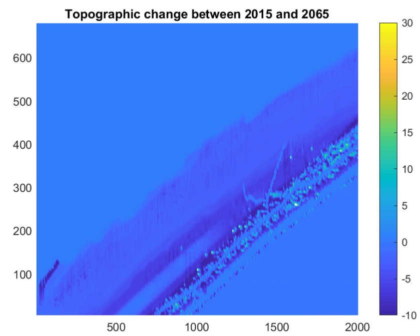


(b) Vegetation state at t=50 (2065)

Figure H.29: Medium sea level rise results without nourishments for profile 3 north



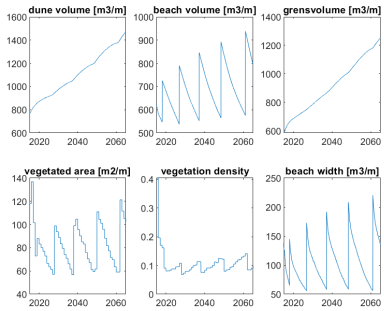
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



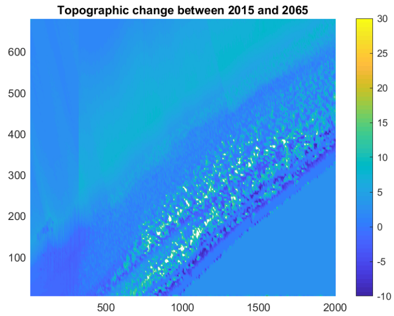
(b) Vegetation state at t=50 (2065)

Figure H.30: High sea level rise results without nourishments for profile 3 north

H.5.2. Nourishments



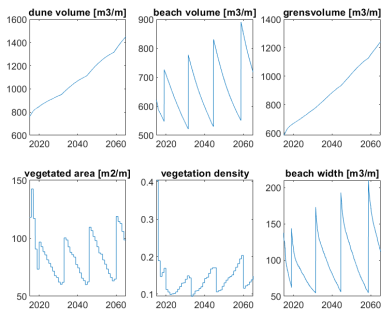
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



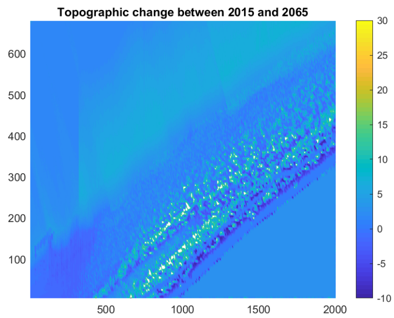
(b) Vegetation state at t=50 (2065)

Figure H.31: Zero-measurement results with nourishments for profile 3 north

Wind speed change

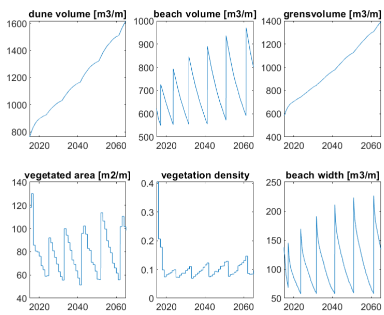


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

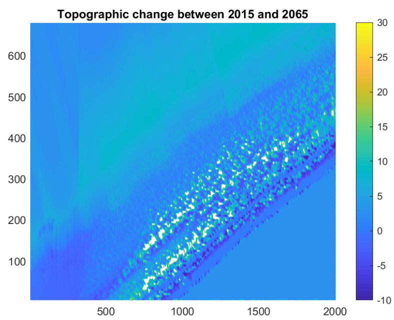


(b) Difference map (2015-2065)

Figure H.32: Low wind results with nourishments for profile 3 north



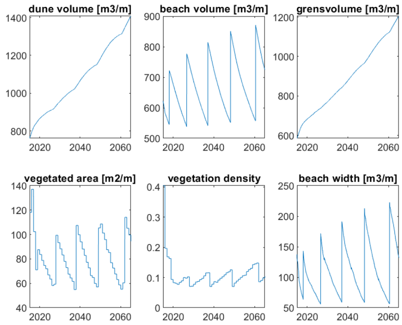
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



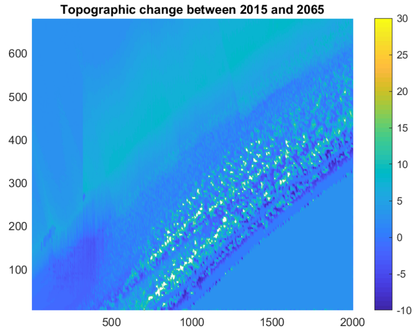
(b) Difference map (2015-2065)

Figure H.33: High wind results with nourishments for profile 3 north

Sea level rise

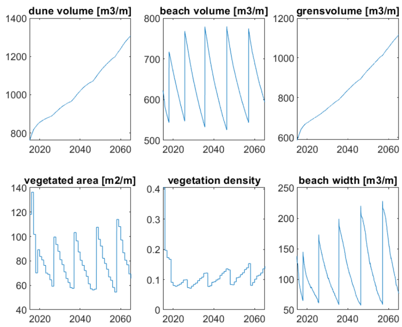


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

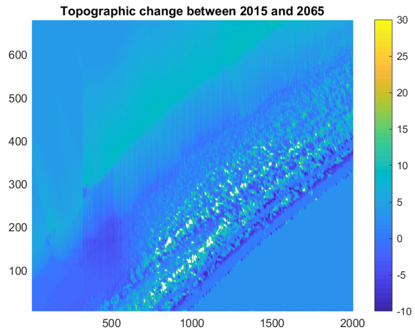


(b) Vegetation state at t=50 (2065)

Figure H.34: Low sea level rise results with nourishments for profile 3 north

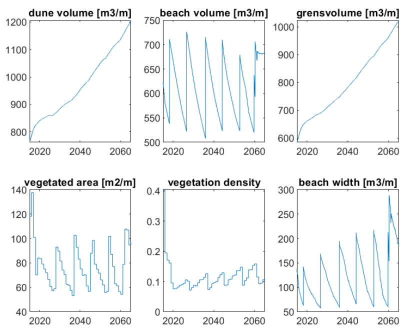


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

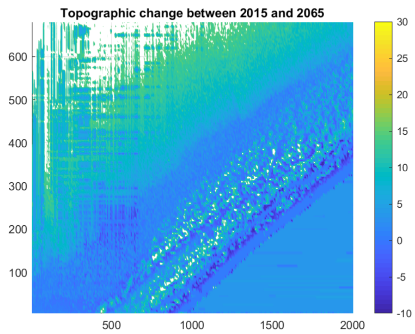


(b) Vegetation state at t=50 (2065)

Figure H.35: Medium sea level rise results with nourishments for profile 3 north



(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

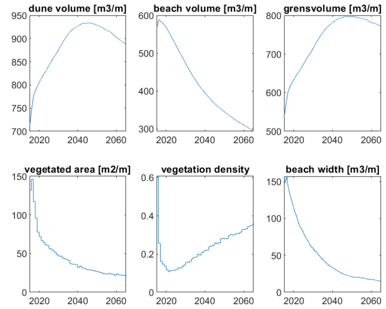


(b) Vegetation state at t=50 (2065)

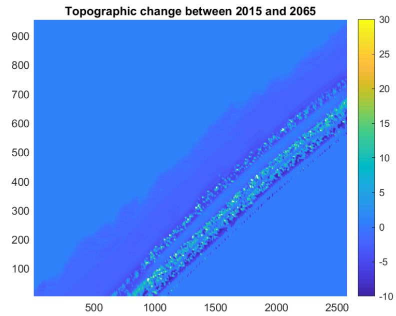
Figure H.36: High sea level rise results with nourishments for profile 3 north

H.6. profile 4

H.6.1. No nourishment



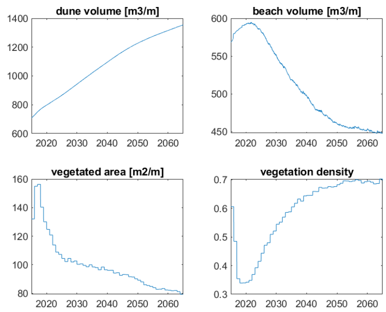
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



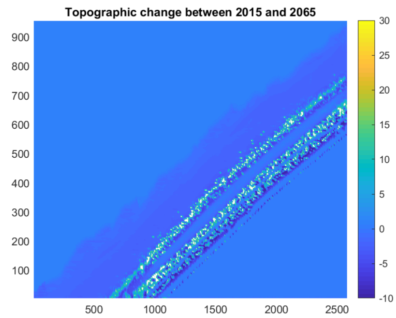
(b) Vegetation state at t=50 (2065)

Figure H.37: Zero-measurement results without nourishments for profile 4

Wind speed change

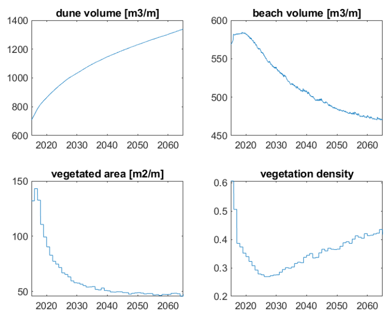


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

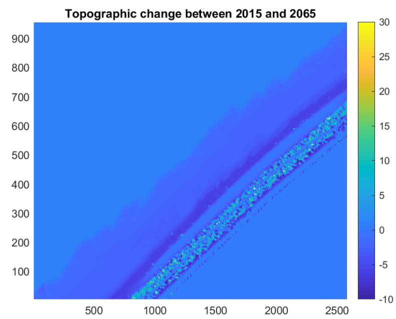


(b) Difference map (2015-2065)

Figure H.38: Low wind results without nourishments for profile 4



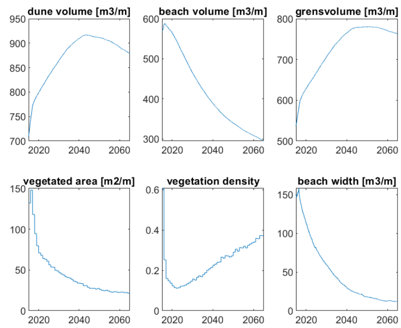
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



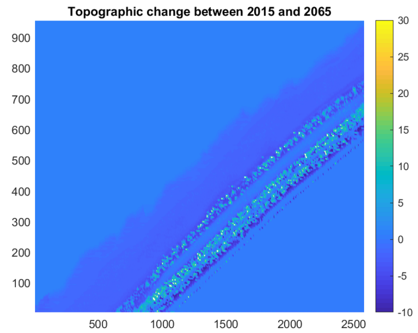
(b) Difference map (2015-2065)

Figure H.39: High wind results without nourishments for profile 4

Sea level rise

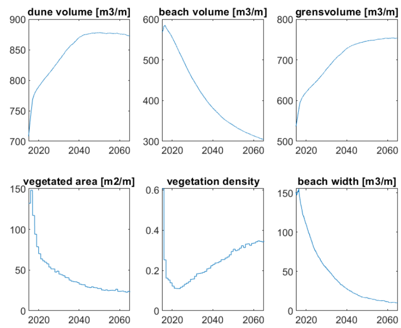


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

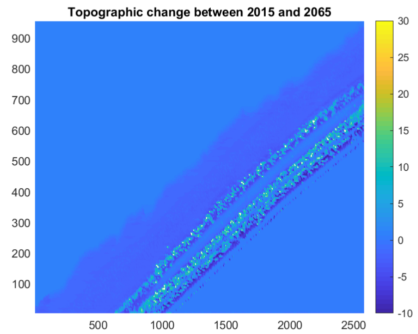


(b) Vegetation state at t=50 (2065)

Figure H.40: Low sea level rise results without nourishments for profile 4

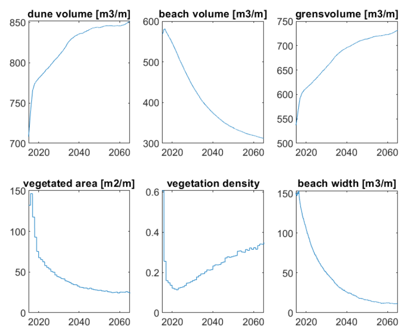


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

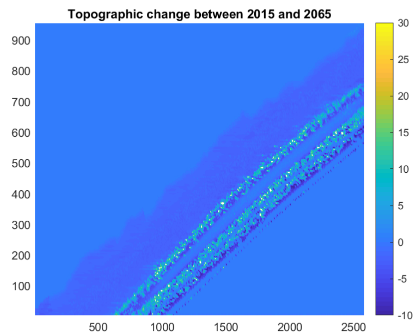


(b) Vegetation state at t=50 (2065)

Figure H.41: Medium sea level rise results without nourishments for profile 4



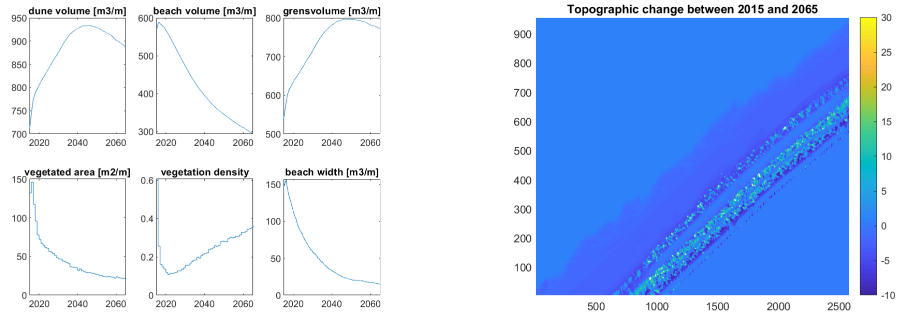
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



(b) Vegetation state at t=50 (2065)

Figure H.42: High sea level rise results without nourishments for profile 4

H.6.2. Nourishments

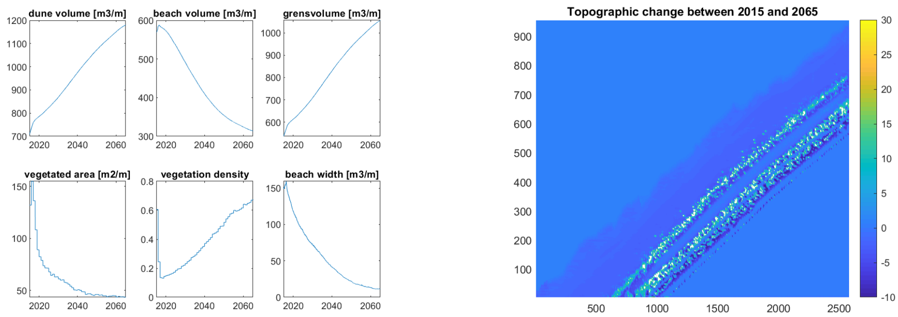


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

(b) Vegetation state at t=50 (2065)

Figure H.43: Zero-measurement results with nourishments for profile 4

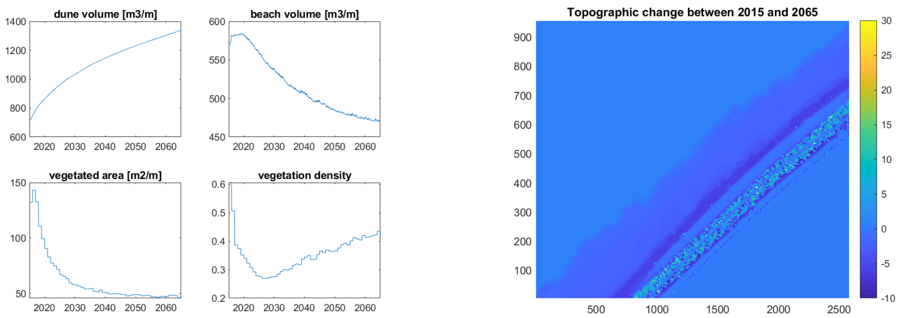
Wind speed change



(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

(b) Difference map (2015-2065)

Figure H.44: Low wind results with nourishments for profile 4

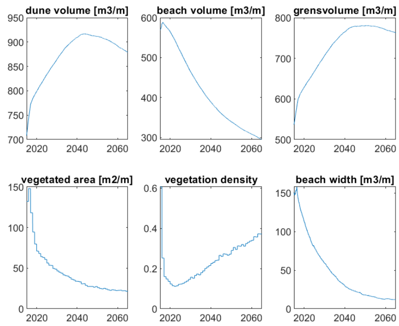


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

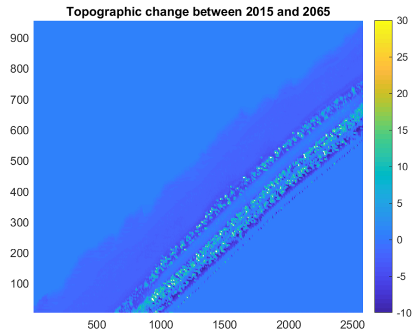
(b) Difference map (2015-2065)

Figure H.45: High wind results with nourishments for profile 4

Sea level rise

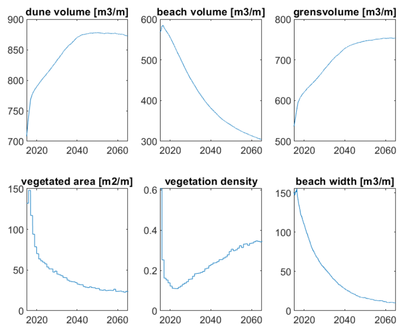


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

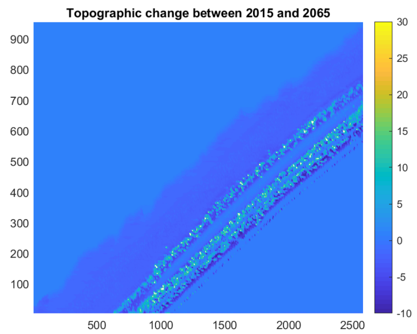


(b) Vegetation state at t=50 (2065)

Figure H.46: Low sea level rise results with nourishments for profile 4

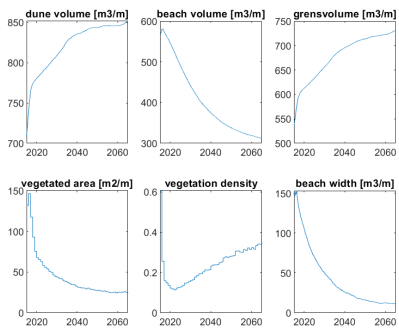


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

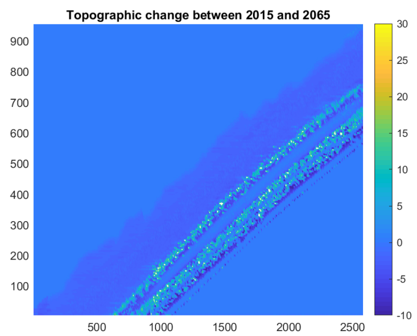


(b) Vegetation state at t=50 (2065)

Figure H.47: Medium sea level rise results with nourishments for profile 4



(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

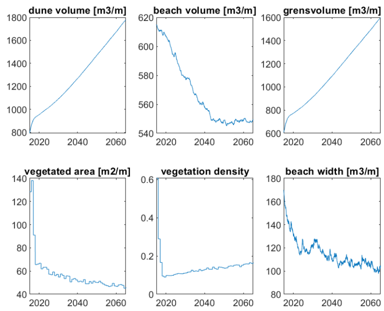


(b) Vegetation state at t=50 (2065)

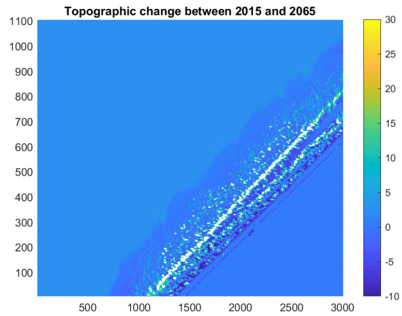
Figure H.48: High sea level rise results with nourishments for profile 4

H.7. profile 3 south

H.7.1. No nourishment



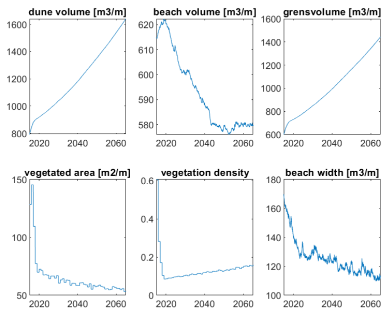
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



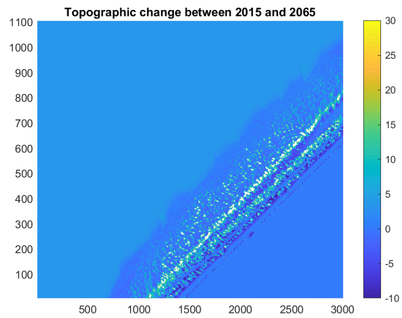
(b) Vegetation state at t=50 (2065)

Figure H.49: Zero-measurement results without nourishments for profile 3 south

Wind speed change

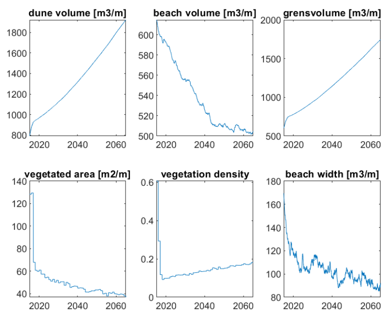


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

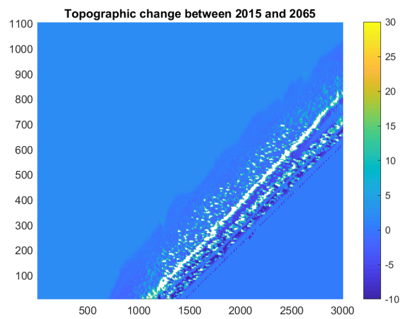


(b) Difference map (2015-2065)

Figure H.50: Low wind results without nourishments for profile 3 south



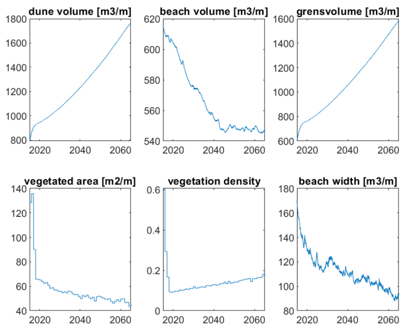
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



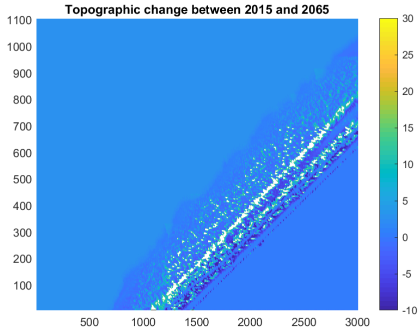
(b) Difference map (2015-2065)

Figure H.51: High wind results without nourishments for profile 3 south

Sea level rise

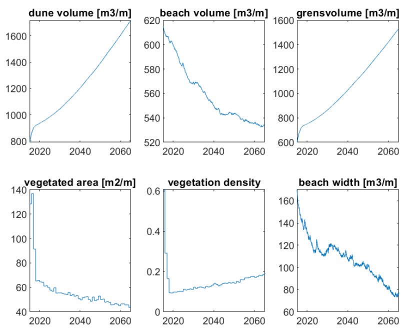


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

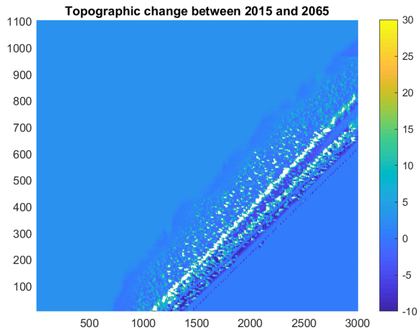


(b) Vegetation state at t=50 (2065)

Figure H.52: Low sea level rise results without nourishments for profile 3 south

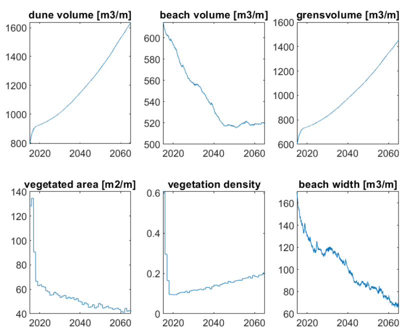


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

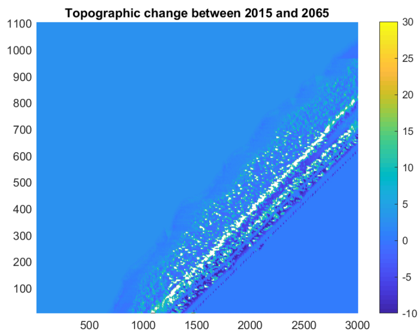


(b) Vegetation state at t=50 (2065)

Figure H.53: Medium sea level rise results without nourishments for profile 3 south



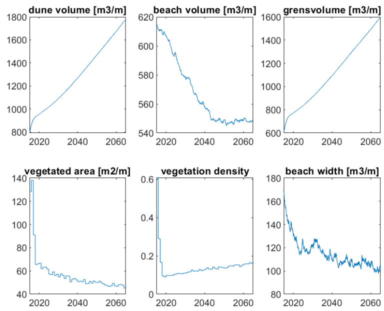
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



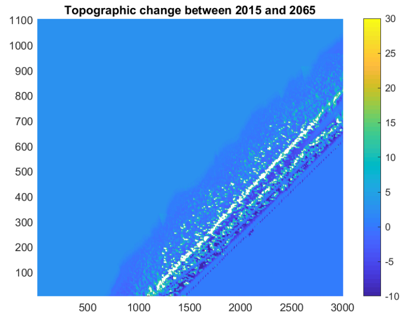
(b) Vegetation state at t=50 (2065)

Figure H.54: High sea level rise results without nourishments for profile 3 south

H.7.2. Nourishments



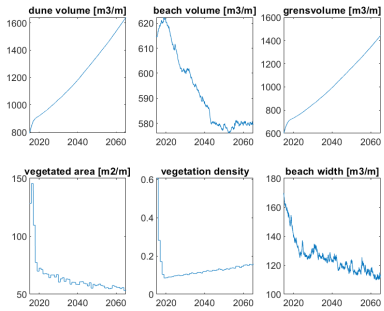
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



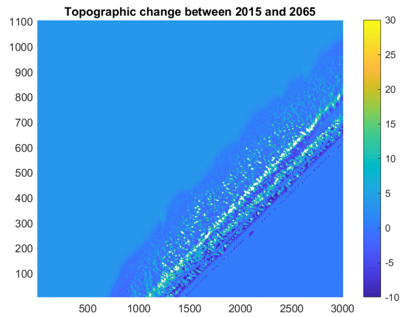
(b) Vegetation state at t=50 (2065)

Figure H.55: Zero-measurement results with nourishments for profile 3 south

Wind speed change

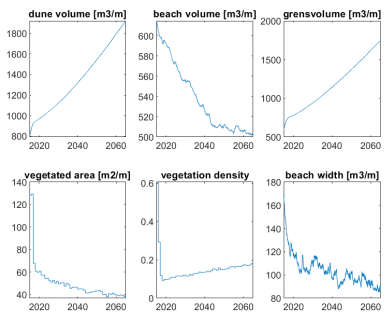


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

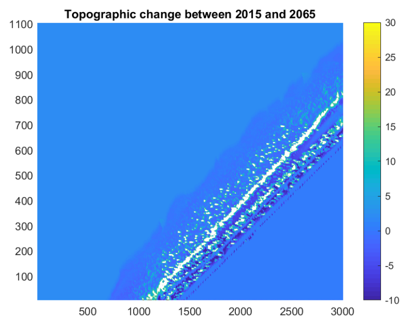


(b) Difference map (2015-2065)

Figure H.56: Low wind results with nourishments for profile 3 south



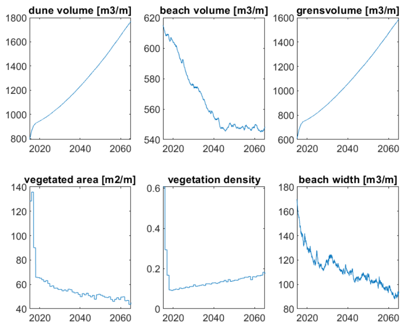
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



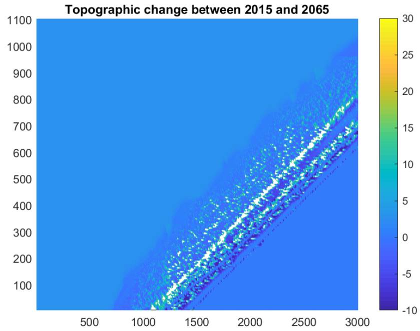
(b) Difference map (2015-2065)

Figure H.57: High wind results with nourishments for profile 3 south

Sea level rise

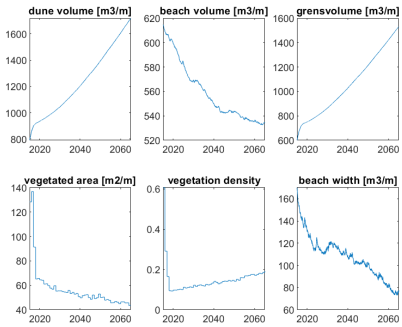


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

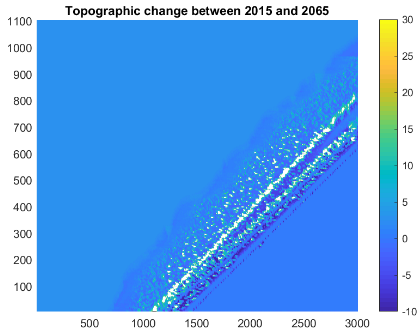


(b) Vegetation state at t=50 (2065)

Figure H.58: Low sea level rise results with nourishments for profile 3 south

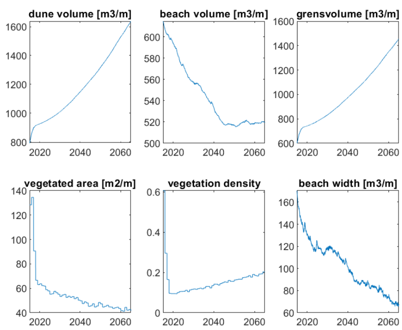


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

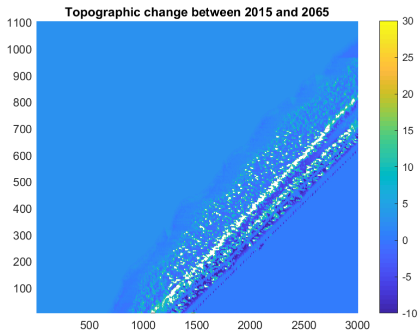


(b) Vegetation state at t=50 (2065)

Figure H.59: Medium sea level rise results with nourishments for profile 3 south



(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

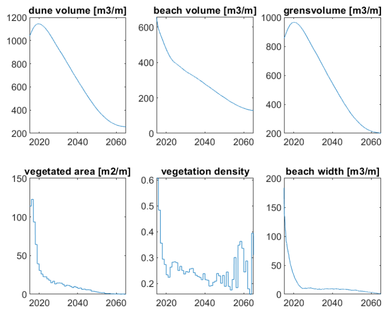


(b) Vegetation state at t=50 (2065)

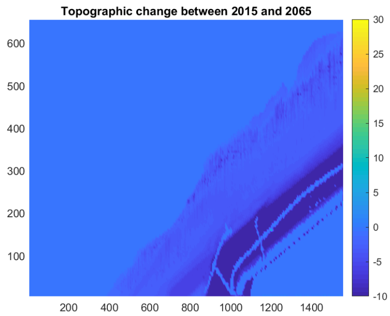
Figure H.60: High sea level rise results with nourishments for profile 3 south

H.8. profile 2 south

H.8.1. No nourishment



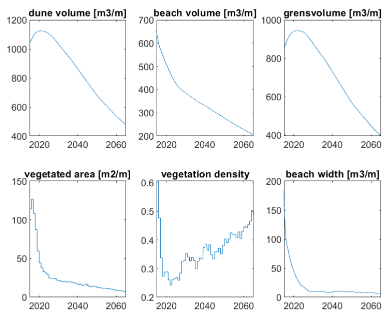
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



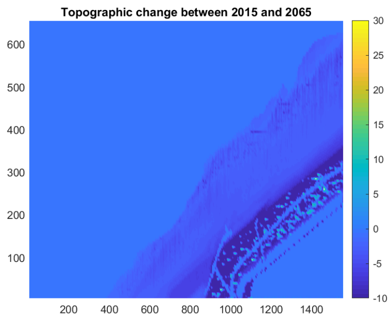
(b) Vegetation state at t=50 (2065)

Figure H.61: Zero-measurement results without nourishments for profile 2 south

Wind speed change

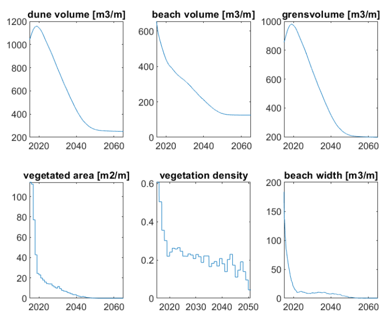


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

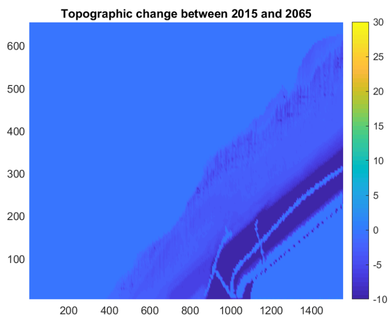


(b) Difference map (2015-2065)

Figure H.62: Low wind results without nourishments for profile 2 south



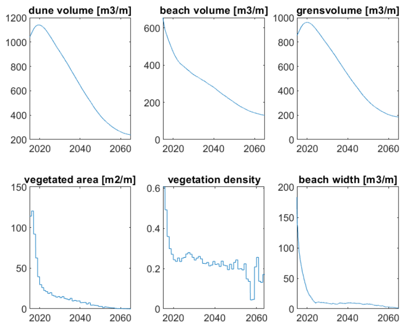
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



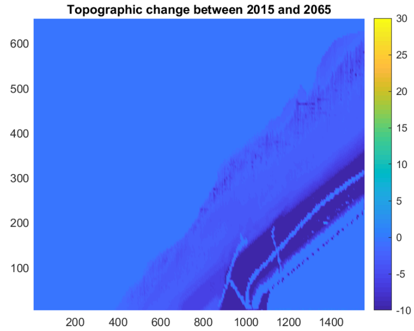
(b) Difference map (2015-2065)

Figure H.63: High wind results without nourishments for profile 2 south

Sea level rise

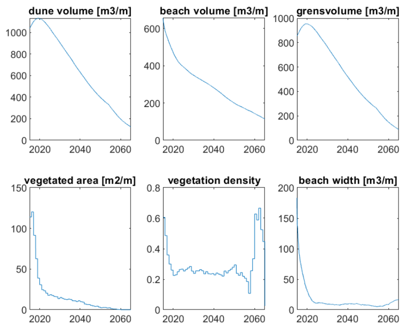


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

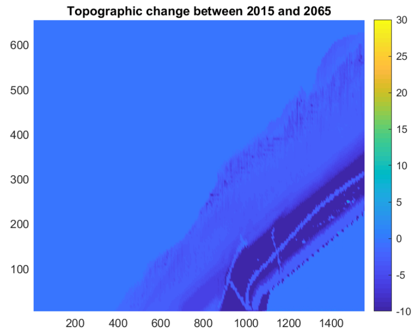


(b) Vegetation state at t=50 (2065)

Figure H.64: Low sea level rise results without nourishments for profile 2 south

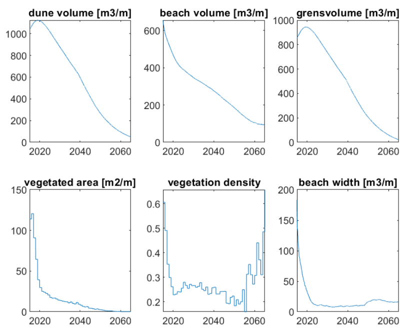


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

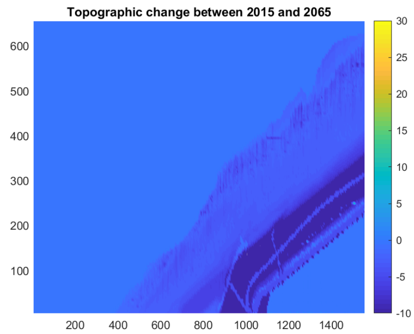


(b) Vegetation state at t=50 (2065)

Figure H.65: Medium sea level rise results without nourishments for profile 2 south



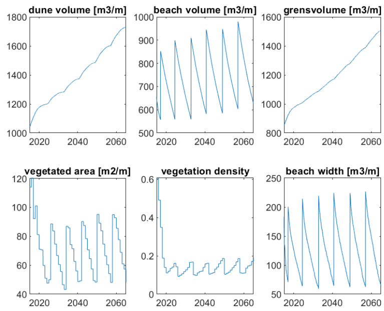
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



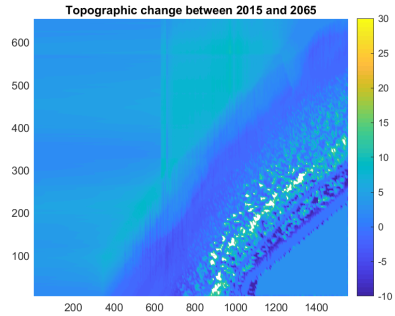
(b) Vegetation state at t=50 (2065)

Figure H.66: High sea level rise results without nourishments for profile 2 south

H.8.2. Nourishments



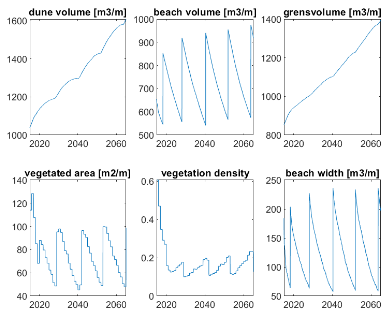
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



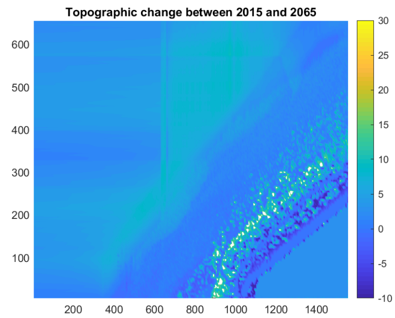
(b) Vegetation state at t=50 (2065)

Figure H.67: Zero-measurement results with nourishments for profile 2 south

Wind speed change

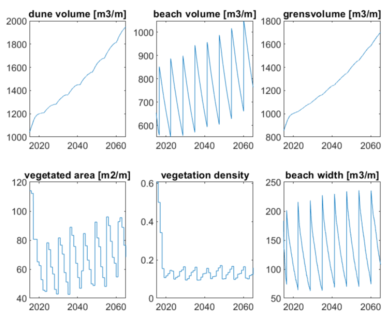


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

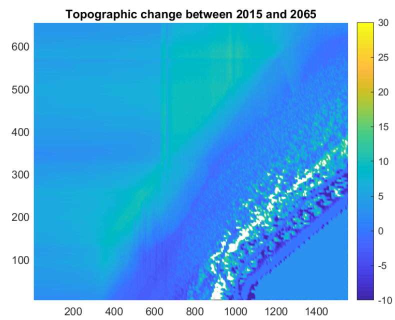


(b) Difference map (2015-2065)

Figure H.68: Low wind results with nourishments for profile 2 south



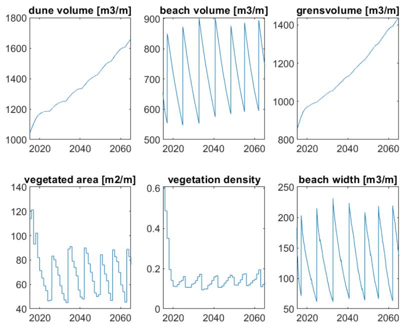
(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



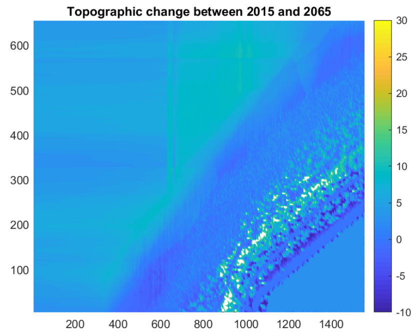
(b) Difference map (2015-2065)

Figure H.69: High wind results with nourishments for profile 2 south

Sea level rise

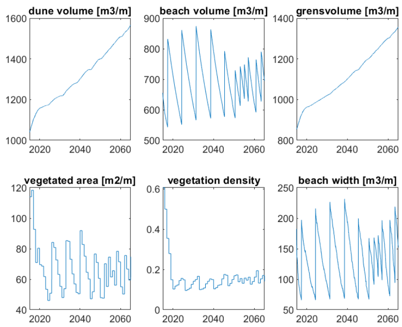


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

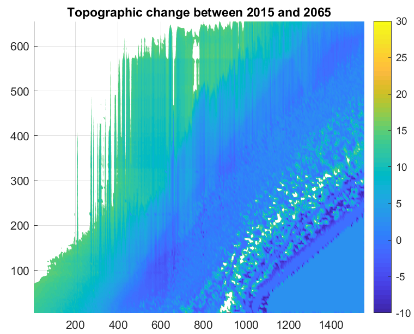


(b) Vegetation state at t=50 (2065)

Figure H.70: Low sea level rise results with nourishments for profile 2 south

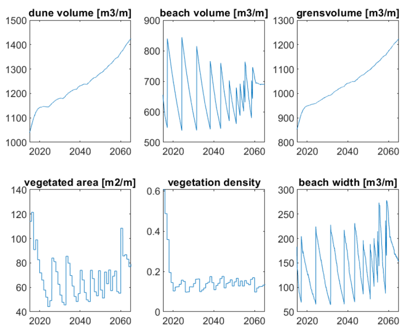


(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).

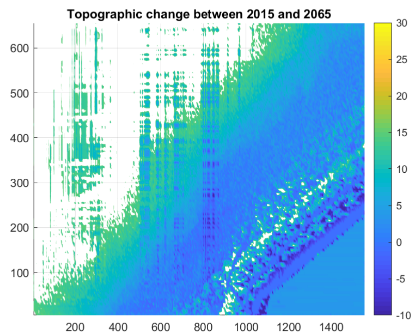


(b) Vegetation state at t=50 (2065)

Figure H.71: Medium sea level rise results with nourishments for profile 2 south



(a) Temporal variation in dune and beach volume, beach width, vegetation growth, and border volume (grensvolume).



(b) Vegetation state at t=50 (2065)

Figure H.72: High sea level rise results with nourishments for profile 2 south