AEOLIAN SEDIMENT TRANSPORT AT A MAN-MADE DUNE SYSTEM BUILDING WITH NATURE AT THE HONDSBOSSCHE DUNES

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This paper presents the influence of aeolian sediment transport on the initial morphological evolution of beach and dunes at the man-made dune system 'Hondsbossche Dunes' at the Dutch coast. In total 35 million m^3 dredged material was used for the construction of a beach, dune and foreshore system. This study focused on differences in morphological response within the five different realized dune profile types. A conceptual framework was developed, based on the assessment of (1) environmental forcing, (2) sediment supply from aeolian and marine sources and (3) dune types. These three components were quantified from an analysis of measured profile evolution and the application of an aeolian sediment transport model for the first 19 months since the project delivery date in May 2015. Morphological changes were most pronounced in the first seven months after construction. Dune growth of a profile type at this location is determined by a temporal and alongshore variability in local processes that determines the aeolian sediment supply towards the dunes and the dune geometry that determines the capacity of the profile type to capture the sediments. The model simulations managed to qualitatively reproduce alongshore variations in dune growth as a result of spatial variations in sediment availability, grain size, profile shape and interaction with vegetation. Overall, this study shows the relevance of both marine and aeolian processes in such man-made dynamic systems that are comparable to natural systems. Continuing the monitoring and modelling of this system will improve the quantitative knowledge for design optimization of the Building with Nature philosophy.

Keywords: aeolian transport, man-made coastal system, dune development, aeolian sediment transport model

A MAN-MADE DUNE SYSTEM

In 2014-2015 the coastal stretch, with a total length of six kilometers, in the Northwest part of the Netherlands; was strengthened by an artificially placed beach, dune and foreshore system, consisting of 35 million m^3 of sand, on the sea dike foreshore of the Hondsbossche & Pettermer sea defence (HPZ). The project location is given in Figure 1, which is part of the sandy coast of the North sea and connected to the low dunes of Petten in the North and the high dunes of Camperduin in the South.

The responsible water authorities Hoogheemraadschap Hollands Noorderkwartier (regional waterboard) and Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management) defined the design requirements for this coastal stretch together with their stakeholders. The new coastal area was constructed in a consortium of two marine contractors Boskalis and Van Oord who are also responsible for the maintenance in the first 20 years after construction.

The Building with Nature philosophy was used to design a new coastal system that serves multiple purposes. While protecting the hinterland against flooding during storm erosion events, it also creates opportunities for the development of new nature and recreation areas. Furthermore, the new Hondsbossche Dunes (HD) have the advantage of being a dynamic system which allows for adaptive management (through nourishments) if changes in future environmental forcing occur.

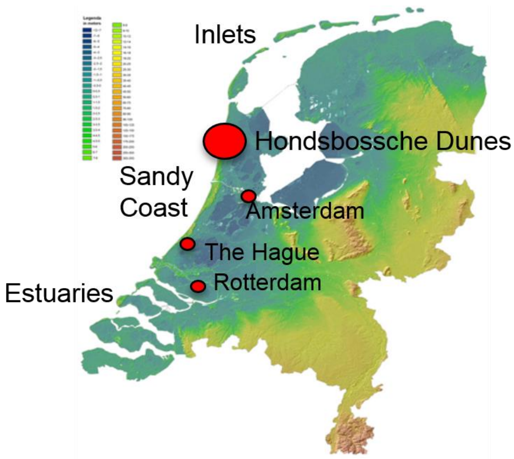

Figure 1. Location of the Hondsbossche Dunes on the North Sea coast of the Netherlands.

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A volume of 26 million m^3 was required for the reinforcement to comply with the legal Dutch safety standard. The remaining 9 million m^3 of sand was considered as expected losses due to foreseen erosion of the system in the coming 7 years. Locally, the nourished sand reached amounts of up to 5000 m3/m with a shoreline extension up to 330 m in front of the old sea dike, see Figure 2. The old sea dike is no longer an active part of the primary flood defense system, but remains in place as a cultural landmark. The new HD flood defense is a dynamic system where erosion and sedimentation of the beach and dune profile will take place as opposed to the old static sea dike (Wittebrood, 2017).

Figure 2. Left figure: Situation prior to construction in 2014, taken from Camperduin (South). The old sea dike is depicted as the primary flood defense system. Right figure: Situation immediately post construction in 2015. The Hondsbossche Dunes is constructed seawards of the old sea dike and has increased locally the coastal safety. Adapted from (Oudesluis, 2012).

Along the HD, five different types of morphological dune profiles were realized in an effort to stimulate a range of morphological dynamics of the system (Leenders and Smit, 2016). These profile types vary in dune width, height and the seaward slope of the dune front. As shown in Figure 3, profile type 1 is schematized as a high dune with a steep slope (1:1.7) of which the dune top has a height of +26.20 m NAP. Profile type 2, Figure 3 – right, is constructed as a low dune (+12.5 m NAP) with a milder slope (1:2.1). Profile type 3 is schematized in Figure 4 as a high dune (+10.4 m NAP) with a lower dune in front (+5.5 m NAP) and a mild slope (1:4). Profile type 4, Figure 4 – right, is schematized as two dune rows with a wet dune valley in between of which the seaward dune is low (+6 m NAP) and has a relatively mild slope (1:3). Profile type 5 is schematized in Figure 5 as a low dune (+5 m NAP) with a relatively steep dune front (1:2). This small dune row is the border between the beach and the lagoon, see also Figure 2 – right, which is constructed for recreational activities.

The alongshore locations of these five dune profile types are given in an aerial overview in Figure 6, it can be seen that profile type 2 and profile type 3 are located in the North and South of the domain. Also, the beach and dunes along the HD domain consists of varying grain size distribution and shell content alongshore.

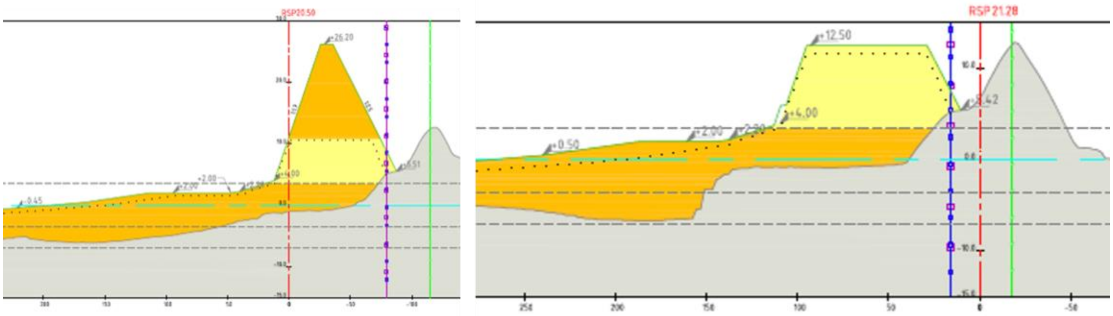

Figure 3. Schematization of dune profile type 1 (left) and 2 (right) in yellow and orange on top of the existing cross-profile in gray. Profile type 1 is schematized as a high dune with a steep slope and profile type 2 is a low dune with a milder slope. Adapted from: (Leenders and Smit, 2016).

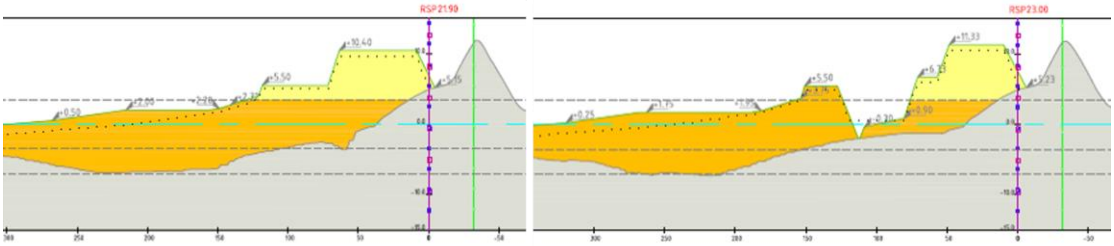

Figure 4. Schematization of dune profile type 3 (left) and 4 (right) in yellow and orange on top of the existing cross-profile in gray. Profile type 3 is schematized as a high dune with a lower dune in front and a mild slope. Profile type 4 is schematized as two dune rows with in between a wet valley, the seaward dune is low and has a relatively mild slope. Adapted from: (Leenders and Smit, 2016).

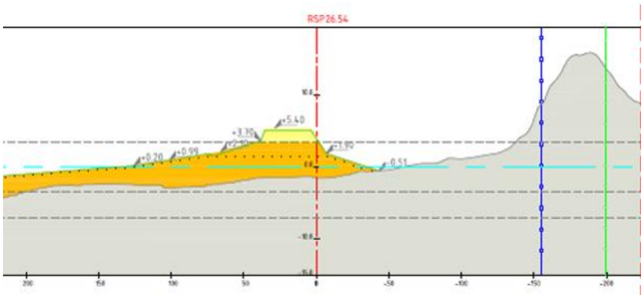

Figure 5. Schematization of dune profile type 5 in yellow and orange on top of the existing profile in gray. Profile type 5 is schematized as a low dune with a relatively steep dune front slope. Adapted from: (Leenders and Smit, 2016).

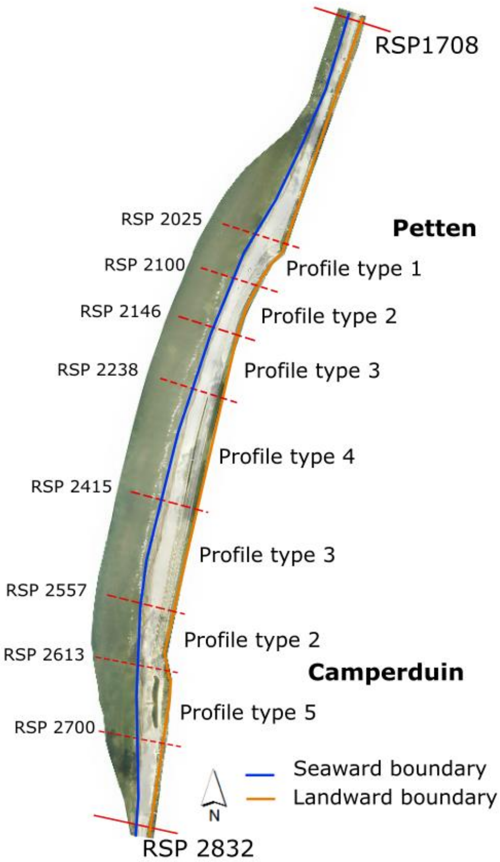

Figure 6. Aerial picture showing the domain of the Hondsbossche Dunes of in total six kilometers long between Petten (North) and Camperduin (South) and locally more than 300 meters wide. In blue the seaward boundary (left) and in orange (right) the landward boundary. The alongshore location of the five different dune profile types are indicated by red cross-sectional lines and RSP-coordinates (Dutch coastline reference system).

RESEARCH AIM

In this paper we aim to gain quantitative insight in the development of the man-made dune area as a whole as well as the development of the different dune profiles during the first 19 months after the project delivery in May 2015. Each of the different dune profiles were expected to develop differently under the occurring environmental forcing. The anticipated influence of aeolian sediment transport on dune development for this system was estimated based on rudimentary assumptions since specific quantitative knowledge on aeolian sediment transport processes in coastal areas remains limited (Hoonhout, 2017; Wittebrood, 2017).We have executed a quantitative data analysis and modelling study on understanding how and when aeolian and marine sediments are transported towards the dunes. The results contribute to an effective approach for future management and maintenance of the new system.

METHODOLOGY

We focused on differences in morphological response within the five different realized dune profile types. A conceptual framework was developed, based on the assessment of (1) environmental forcing, (2) sediment supply from aeolian and marine sources and (3) dune types, see Figure 7.

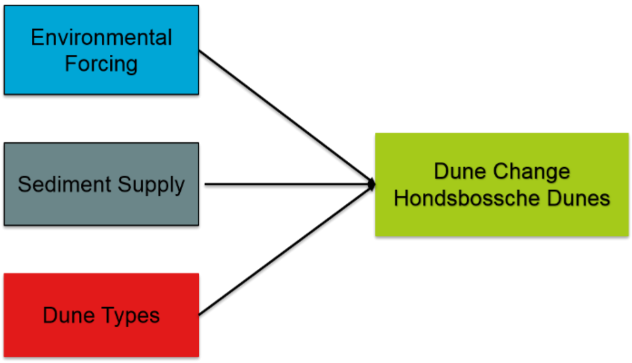

Figure 7. Conceptual framework of the dune change at the Hondsbossche Dunes. The system is influenced by three major aspects: Environmental forcing, Sediment Supply (aeolian and marine supply) and Dune Types (5 profile types).

These three components are quantified from an analysis of measured profile evolution along 135 transects and the application of the wind sediment transport model AeoLiS using a two-dimensional horizontal schematization (de Vries et. al., 2015; Hoonhout & de Vries, 2017), during the first 19 months after construction (May 2015 – Dec 2016).

LiDAR data

The profile evolution of the beach and dunes were measured five times in 19 months by Airborne LiDAR in May 2015, December 2015, March 2016, September 2016 and December 2016. The surveyed domain span at least the dry beach and dunes landward of the mean high water line (+0.8 m NAP). The surveyed domain was 11.2 km in alongshore direction, covering the area Northwards and Southwards of the HD, by at least 340 m in cross-shore direction, respectively. The measurements have a spatial resolution of 0.5 m and a vertical accuracy within an order of magnitude of a few centimeters.

The surveys were converted to 135 standardized cross-shore profiles which locations are identical to the 'JARKUS' cross-shore profiles used for the annual surveys executed by the Dutch Ministry of Infrastructure and Water Management. The cross-shore profiles were divided into four different zones to derive spatial and temporal volume changes of the beach and dunes The four zones were distinguished by horizontal boundaries in vertical direction. Figure 8 depicts the four zones that are defined:

1. Dunes: +3.5 m NAP (location dune foot)
2. Dry beach zone: +0.8 m NAP till +3.5 m NAP
3. Intertidal zone: -0.75 m NAP till +0. 8m NAP
4. Surf zone: -3.5 m NAP till -0.75 m NAP

The surf zone and the intertidal zone together provide information about the spatial and temporal variations in marine sediment supply along the HD system which is based on monthly single-beam monitoring for 11 cross-shore transects.

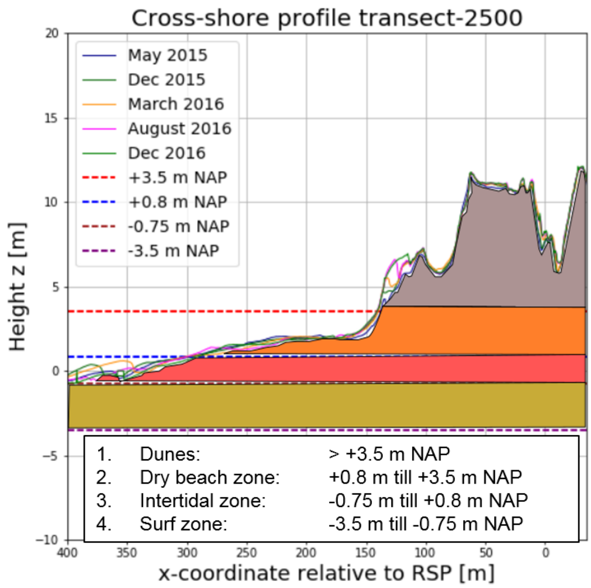

Figure 8. Definition of cross-profile zones used in this research. Four zones were distinguished: (1) Dunes, (2) Dry beach zone, (3) Intertidal zone and (4) Surf zone.

Aeolian sediment transport model

AeoLiS was used to model the effect of the local variation in topography and the measured variation in alongshore grain size distribution on the dune change at the Hondsbossche domain. For practical reasons, the Hondsbossche domain was divided into five subdomains S1-S5 based on the measured grain size distribution in these areas. Each subdomain was simulated separately by selecting the local topography and imposing the measured grain size distribution. Figure 9 shows a schematic overview of the location of the five subdomains and the measured median grain size. The dune profile types correspond not to one to one to these five subdomains, but are defined by RSP coordinates (Dutch coastline reference system) in Figure 6.

The local topography of the first LiDAR survey (May 2015) was imposed to the model which is interpolated to a 10 by 10 m grid and ran with an hourly time step over the total period till December 2016. Furthermore, measured environmental forcing with respect to tidal levels, wind and wave conditions were imposed to the model. Vegetation was implemented in the model landwards of the dune foot at +3.5 m NAP to capture and hold the sediments in the dune area. Therefore, a vegetation mask was implemented in which the threshold velocity for initiation of motion is increased by 50% and constant over time and in space. Due to the implementation of this vegetation mask a boundary is made between the beach zone and the dunes. Moreover, it forces the effect of vegetation on reduced aeolian sediment transport and deposition in the dune area. Figure 10 provides a flow chart of the model schematization.

The performance of the model is analyzed by comparing the measured and modelled erosion and deposition patterns. Besides, the model results are validated with the measured dune growth rates.

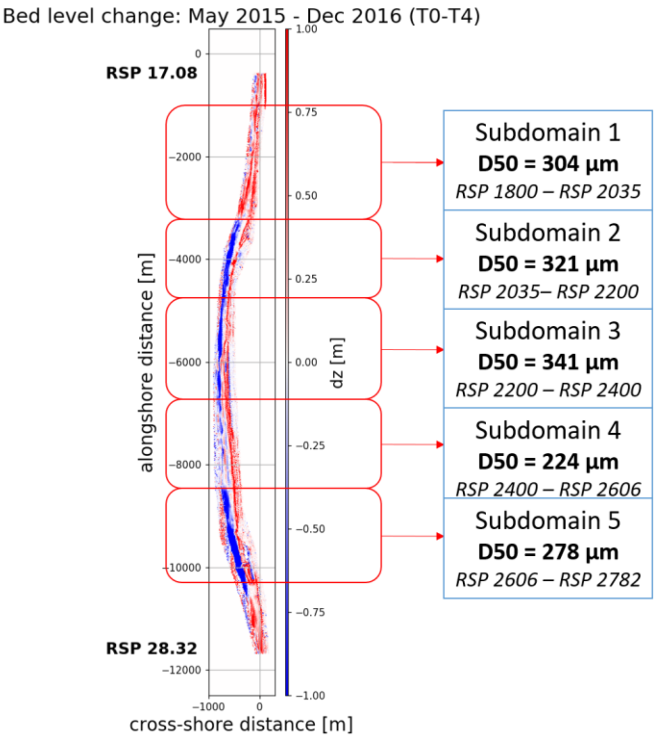

Figure 9. Top overview of the model domain. The HD system is divided into five subdomains (S1-S5) in order to simulate measured alongshore variations in median grain size. The RSP-coordinates provide information about which dune profile types are part of the subdomain.

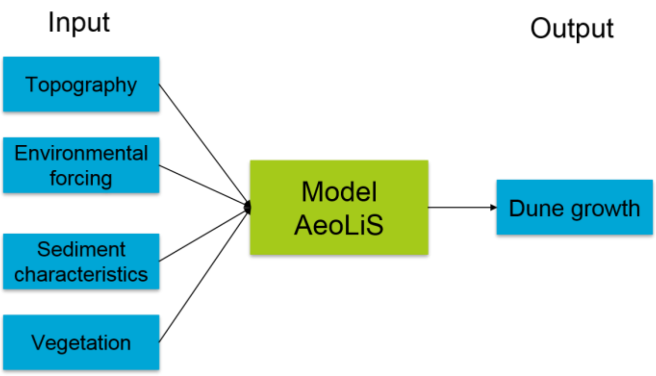

Figure 10. Model input schematization of AeoLiS for the five subdomains which is divided into four categories: Topography, Environmental forcing, Sediment characteristics and Vegetation.

MEASURED PROFILE EVOLUTION

The results obtained from the data analysis are shown in Figure 11 and reveal strong alongshore variations in beach (left) and dune (right) development. Morphological changes were most pronounced in the seven months after construction. High beach volume losses were observed along the HD with an average value of 29 m^3/m/y for the entire Hondsbossche Dunes since May 2015. Predominantly, erosion was measured along the Southern shoulder, as can be seen along subdomain 5 in Figure 11 - left. This mainly occurred due to the initial adaptation of the system to the environmental forcing, wind and waves, which was measured to be higher in the first seven months after construction and in landward direction (Wittebrood, 2017)

The volumetric losses of the foreshore and beach resulted in a shoreline retreat of on average 37 m/y and a steepening of the beach slope. The volumetric losses were transported in alongshore direction resulting in accretion of the beaches Northwards and Southwards of the HD. Accretion of the beaches resulted in a shoreline extension up to 9 m/y and the development of milder beach slopes (Wittebrood, 2017).

Cross-shore transport of beach losses resulted in an average dune growth (above +3.5 m NAP) of 28 m^3/m/y, as can be seen in Figure 11- right. The five man-made dune profile types responded differently to the environmental forcing; a minimum dune growth of 14 m^3/m/y at profile type 1 (subdomain 2) in the North to 48 m^3/m/y at profile type 2 and 3 (subdomain 4) in the South. Dune growth was observed to be significantly higher in the first seven months after construction. Higher wind velocities and landward directed wind were measured in the first period than during other measurement periods. This is illustrated in Figure 12 in which the wind rose of the first period (May 2015 – December 2015) and the last period (September 2016 – December 2016) are shown. Moreover, nourished sand contains a large amount of finer grains which can be easily picked up by the wind and transported towards the dunes.

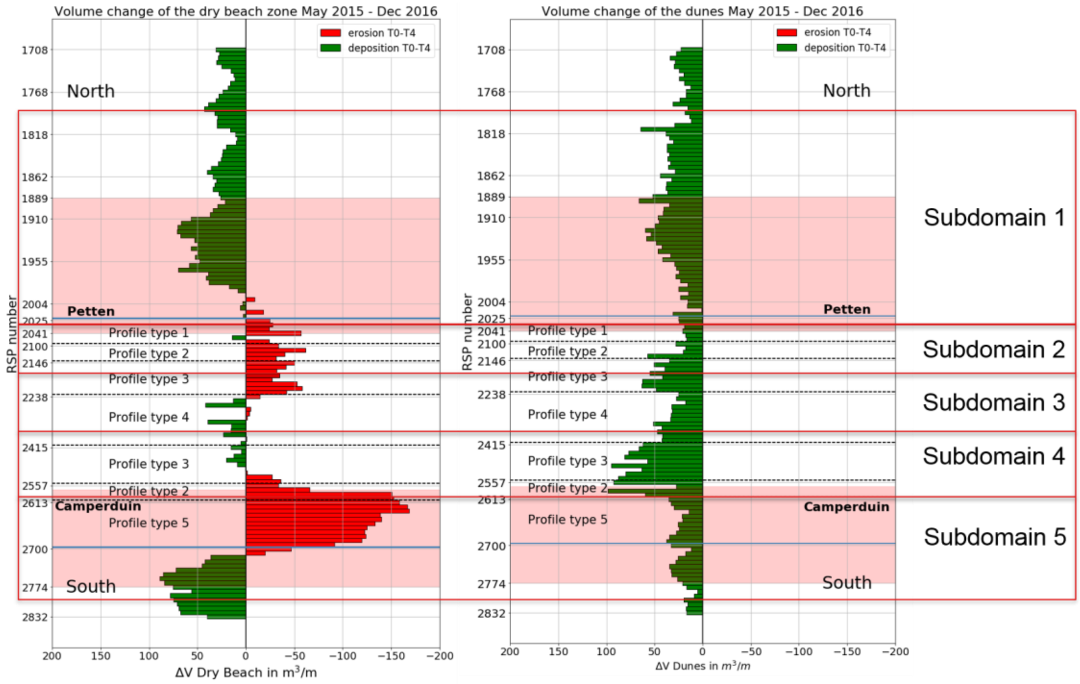

Figure 11. Cumulative net volume change of the dry beach zone (left) and the dunes (right) between May 2015 - December 2016. Note that the figure has the same orientation as the Dutch coastline which means that North is at the upper part of the figure and South at the lower part of the figure. The sea is located at the left side of the origin and the main land is located at the right side of the origin; erosion (red colored) means that the coastal area retreats (negative values on the x-axis) and deposition (green colored) means that the coastal area extends (positive values on the x-axis). Difference in length of the bars indicates spatial variability in volume changes. The blue lines indicate the boundaries of the Hondsbossche Dunes and the black dashed lines distinguish the five different dune profile types. The five red rectangles indicate the five subdomains as used in the model and the two red shaded areas indicate the locations of the Northern and Southern shoulder.

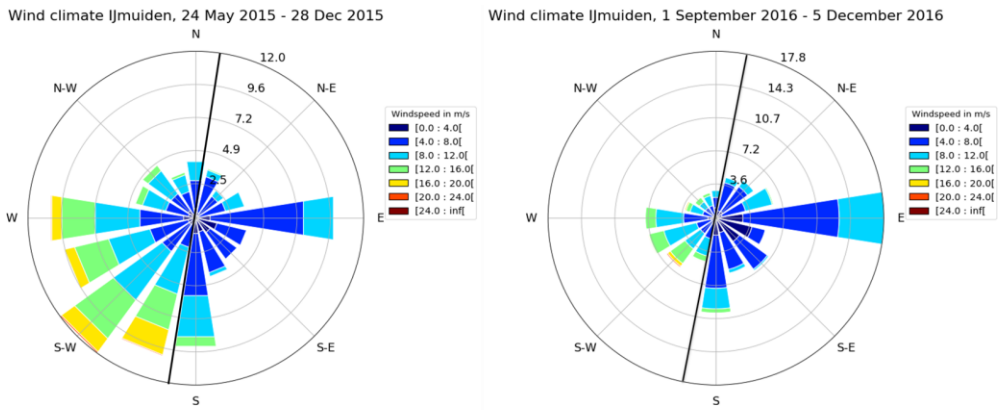

Figure 12. The wind climate for station IJmuiden during the first measurement period (May 2015 – December 2015) and the last measurement period (September 2016 – December 2016), the average coastline orientation of the Hondsbossche Dunes is plotted (black line). Wind velocities were higher in the first period and in landward direction.

MODELLING DUNE DEVELOPMENT

Detailed calculations using the AeoLiS model show an overestimation with respect to the measured growth rates with a factor 1.2 (subdomain 3) to 3 (subdomain 2), depending on the alongshore location, see Figure 13. This discrepancy between the measurements and simulations is possibly caused by the negligence of a bed topography update over time since the morphological feedback loop is not included in the model and the negligence of soil moisture effects in the model. The first is relevant for beach areas with high volume losses measured over time caused by marine forcing, for example subdomain 2, which resulted in a significant reduction of the beach width and steepening of the beach slope. In other words, wide and mild beaches at LiDAR's first survey (May 2015) imposes the model with more available sediment for aeolian sediment transport towards the dunes, causing higher simulated dune growth rates than actually measured.

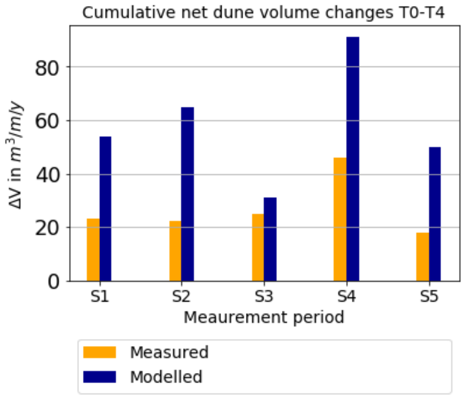

Figure 13. Comparison of cumulative dune volume changes for the five subdomains S1 (North) - S5 (South). The left bar (yellow) depicts the measured dune volume changes derived from LiDAR measurements and the right bar (blue) depicts the modelled dune volume changes predicted by the AeoLiS model. Alongshore variation in overestimation is derived.

Despite this quantitative offset, the simulations managed to qualitatively reproduce alongshore variations in dune growth as a result of spatial variations in sediment availability, grain size and profile shape and a simplified interaction with vegetation at the dune area. Figure 14 shows a 2D-plot of the measured and modelled sedimentation and erosion areas for subdomain 4. Two observations which the model predicts well is:

1. Erosion of the beach in the intertidal zone as a result of aeolian sediment transport (blue color - left black dashed line)
2. Sedimentation along and landwards of the dune foot due to interaction with vegetation (red color - right black dashed line)

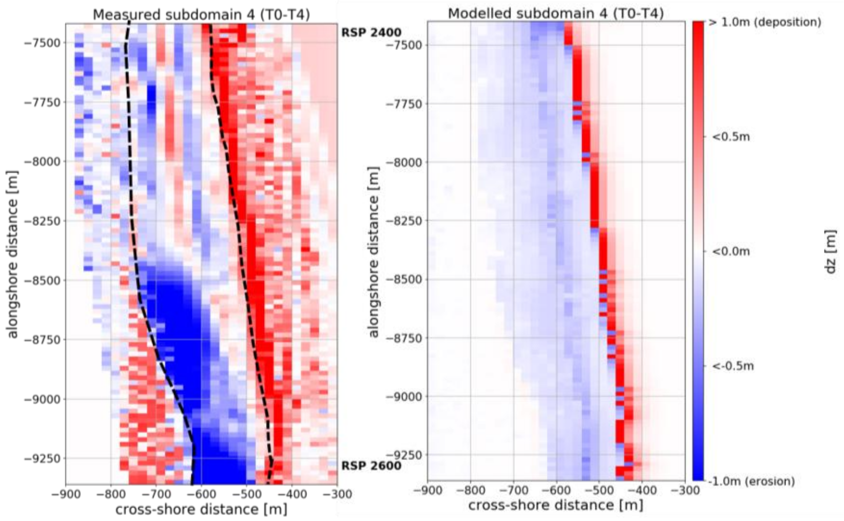

Figure 14. Measured (left) and modelled (right) sedimentation (red) and erosion (blue) between May 2015 - Dec 2016 of subdomain S4, Northern direction is upwards. The black dashed lines in the measurement plot indicate the position of the intertidal zone at the left and the dune foot at the right. Model results only include aeolian sediment transport and dune development as a result of measured environmental forcing and a constant influence of vegetation for this period.

CONCLUSION AND OUTLOOK

We conclude that based on our results, the Hondsbossche Dunes (HD) reveal strong alongshore and temporal variations in beach and dune development. Firstly, the dune growth of a profile type at the HD is likely to be determined by a temporal and alongshore variability in local processes at the beach that determines the aeolian sediment supply towards the dunes. The capacity of aeolian sediment transport to build dunes is higher if the beach slope and beach width show low spatial and temporal variations. Besides, fine grains at the beach, a characteristic of nourished beaches, promote the pick-up and transport of sediments towards the dunes for onshore directed winds. Secondly, the dune geometry determines the capacity of the profile type to capture the sediments and therefore partly contributes to the alongshore variation in dune growth. Dune growth at the Hondsbossche domain is higher if the dune consist of a lower foredune with a mild slope and a large supply of sediments towards the dunes.

The Hondsbossche Dunes is an example of a man-made beach and dune system where natural dynamics are part of the design and maintenance strategy. This study shows the relevance of both marine and aeolian processes in such man-made dynamic systems that are comparable to natural systems with respect to erosion and sedimentation.

At this moment no change in the current management and maintenance strategy is required. However, for future management it is recommended to conduct a yearly assessment of beach and dune volume changes in order to discover changes in the morphological development of the system and if needed reshape the dune profile to stimulate dune growth. Additionally, continuing the monitoring and modelling of this system will improve the quantitative knowledge for design optimization of the Building with Nature philosophy.

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