Spatial variability of aeolian sand transport rates in a foredune notch

Master Thesis

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The photo on the cover was taken at Bloemendaal aan Zee, the Netherlands by the author during a fieldwork in October 2022. All pictures in this thesis are taken by the author, unless indicated otherwise.

Abstract

After decades in which the dominant coastal management strategy in the Netherlands consisted of planting of vegetation to suppress dune dynamics, nowadays dune management projects intent to restore natural dynamics. The fixed foredunes resulting from the previous management strategy act as an almost complete barrier to aeolian transport from the beach towards the back dunes. This has resulted in a decline in biodiversity. Additionally, this has prevented dunes from growing vertically with the rising sea level. New forms of management strive to prevent further loss of biodiversity, and stimulate the vertical growth of dunes. At multiple locations, management projects have consisted of the excavation of foredune notches. That has been done to simulate natural blowouts, in which winds are able to freely transport beach sediments through the dune towards the hinterland. Previous research has focused on wind flow patterns in excavated notches, but the spatial variability in aeolian sediment transport is yet unknown. To study this variability, measurements were carried out in a foredune notch at Bloemendaal aan Zee, in October-November 2022. Additionally, the relation to wind speed and direction was studied, as well as the effects on the morphology. This was done using sand catchers, ultrasonic anemometers and RTK-GPS surveys. This study shows that the spatial variability of sand flux through the notch is dependent on the offshore wind direction and the local morphology. Sand fluxes in the notch varied between 1.02 and 177.72 g m^{-1} s^{-1}, and the highest fluxes were measured on the landward side of the deflation basin. With increasing oblique approaching winds, the sediment flux in the notch increased landward, while notch axis-parallel winds resulted in decreased transport through the notch. This pattern is caused by topographical steering, and the fact that oblique approaching winds tend to accelerate within the notch, gaining more potential to transport sediment. The local morphology steers the local wind direction, creating the observed sand transport patterns within the notch.

Contents

1 Introduction

1.1 Societal relevance

Coastal dunes are natural landforms in coastal systems. Dunes are not only highly appreciated for their ecological and recreational value, but they also form an important and natural safety barrier against marine flooding. These coastal dune areas consist of foredunes, where the white dune habitat can be found and the more landward back dunes where one can find the grey dune habitat. In the past 50 years the habitat of the grey dunes has increased Europa-wide (Riksen et al., 2016). Currently this habitat is threatened by a loss of dynamics, which will evidently result in loss of biodiversity (Houston, 2008). The loss of biodiversity can be caused by various processes, such as increased nitrogen deposition and reduced disturbance by rabbits, but also by management of the foredune (Ruessink et al., 2018). This management has traditionally focused on suppression of dynamics to prevent natural sand drift and improvement of the foredune as coastal defense. The planting of vegetation such as marram grass has been a common practice to achieve this. Transported sediments are captured by the vegetation creating the fixed foredunes, which are present in all major coastal dune areas in the Atlantic region. The extensive planting of marram grass was also done to create higher and wider dunes. The lack of sand transport from these fixed dunes towards the grey dunes, diminishes the quality of the biodiversity of the grey dunes. The lack of input of sand reduces possibilities of pioneer species to grow, favoring the grey dunes to evolve toward late-successional, species-poor vegetation (Riksen et al., 2016). The fact that sediment can no longer reach behind the dunes not only effects the biodiversity, but also prevents the back dunes to increase in elevation or to develop landward. This has implications in regards to the rising sea level. The rising sea level is threatening coasts all over the world, especially lower lying coastal areas such as the Netherlands. The fact that sediment can no longer reach behind the dunes, makes this country even more vulnerable to the rising sea. To increase resilience under climate change, new methods of coastal dune management have been introduced, such as *dynamic coastal management* in the Netherlands (Arens et al., 2013). This management strategy not only strives to increase resilience, but also tries to build on the re-establishing of dune dynamics thus preventing further loss of dune habitats like the grey dunes. This strategy wants to create semi-natural systems that can be self-maintaining after the strategy has been implemented.

This research focuses on foredune notches. The excavation of foredune notches is one of the strategies of dynamic coastal management. The aim of this strategy is to restore the back dunes by removing the main cause of back dune degradation, namely the decrease of dune dynamics. This method creates a potential system that will need minimal management (Elliot et al., 2007). The excavating of foredune notches strives to imitate natural trough blowouts, where wind can freely transport sand from the beach into the hinterland. Natural blowouts are formed when vegetation in the dunes is lost. This loss could be caused by burrowing or disturbance by animals. High wind speeds remove and transport sediment from the beach towards the back dunes (Smyth, Jackson, & Cooper, 2014). In natural blowouts, there is a strong correlation between the length of the blowout deflation basin and the depositional lobe landward of the blowout. This correlation reflects a trend where, as the deflation basin extends, sediments are transported from the deflation zone further into the depositional lobe and thus extending it. Additionally, as the blowout width increases, the depositional lobe increases with a ratio of 1:2. The deflation basin of the blowout will erode until a base level is reached. This base level can be at the lowest water table level, a cemented sediment layer or an armored layer (Hesp, 2002).

The foredune notches are excavated through the foredune on locations where this does not affect flood risk. This is done at several locations, for example in the United Kingdom (Pye & Blott, 2014), in the St Kilda foredune, New Zealand (Nguyen et al., 2021) and in the Netherlands near Bloemendaal aan Zee (**Figure 1**) and on Ameland (Riksen et al., 2016). The characteristics of these notches differ per location. For example, the notches in Bloemendaal aan Zee were excavated at the height of 6 meters above mean sea level (MSL) and have a sloping notch floor, while the notches on Ameland were excavated at a height of around 15 meters above MSL with a flat notch floor. The incision depths were on both locations around 6 m, but the width differed substantially. At Ameland the width was quite narrow, around the 20 meters, while the notches in Bloemendaal aan Zee were 50 to 100 meters wide (Ruessink et al., 2018; Riksen et al., 2016). The notches created in New Zealand are positioned seaward of a dike, and are smaller in width as well as incision depth, compared to the notches excavated in the Netherlands.

Figure 1: *Excavated notch at Bloemendaal aan Zee, the Netherlands. For this specific notch, the width is approximately 50 m and the length 100 m (Picture taken 26 Oct '22).*

1.2 Review of wind patterns and sand fluxes in foredune notches

Studies have shown that creating foredune notches results in increased sediment transport rates and more deposition behind the foredune (Riksen et al., 2016; Ruessink et al., 2018). The dune dynamics in the excavated notch strongly increase in the first three years. This not only comprises increased transport and deposition, but also increased erosion, mainly restricted to the notch walls. Additionally, there is an increase in the area of bare sand and a positive sediment budget. Around 75% of the sediment that is transported after excavation is deposited landward of the foredune. This implies that the notches have been highly effective in transporting sediment into the landward dunes (Ruessink et al., 2018). The transport of beach sediment through excavated notches is a long-term process, during which there are changes in wind conditions, both in strength and direction. Studies have shown that the approach angle towards the notch axis is the main driver of wind patterns in a notch. Nguyen et al (2021) found that the incident wind direction is the critical factor for notch activation, in other words when sand is transported through the notch. The threshold of windspeeds needed for notch activation increases when the approach angle increases. The resulting wind patterns in the notch influence the sediment flux rates and patterns of erosion and deposition. This causes sediment flux rates within a notch to be able to strongly vary spatially, even at quite small distances (Nguyen et al., 2021; 2022). Within the notch, maximum erosion and sediment transport happen in the deflation basin and onto the depositional lobe. Additionally, sand transport can be significant along the erosional walls. Sediment, such as avalanche material and slump blocks, comes from the adjacent slope walls and is transported through the notch, together with beach sediment (Hesp & Hyde, 1996).

A study of Smyth, Jackson & Cooper (2014) found that when the variability of wind flow increases, the sediment flux is reduced. This results in the highest sediment fluxes on the erosional wall crest, where wind flow is compressed and accelerated. The lowest flux rates were measured in the deflation basin, since this area was subject to topographic flow steering and deflection during oblique incident wind (Smyth, Jackson, & Cooper, 2014). Furthermore, the degree of aeolian dynamics depends on the beach sediment budget. A research of Pye, Blott & How (2014) observed that the largest dynamics were present where notches were position at wide, high beaches with a positive sediment budget, which resulted in high sediment flux rates. The notches that were most effective in transporting sediment, were the ones that force the wind to accelerate. This acceleration can be caused by a convex deflation basin, or by landward narrowing of the notch (Pye & Blott, 2016). The morphological evolution of a notch after excavation depends on wind speeds and the dominant wind direction. The specific wind characteristics result in patterns of erosion and deposition in and around the notch. Many natural blowouts become larger overtime and eventually turn into parabolic dunes (Hesp, 2002).

As mentioned before, oblique winds can cause the flow in a notch to be topographically steered. The degree of steering is depending on the local topography in the notch. Oblique winds cause turbulent flow and corkscrew vortices. This can cause the wind flow to be turned against the original approach angle. This process results in a s-shaped flow pattern (**Figure 2**) (Hesp & Hyde, 1996). The relationship between the approach angle and local deflection by the topography is complex. When the wind approaches from within 50 degrees of the axis, the steering of airflow is caused by the topography of the blowout trough. The wind is funneled through the blowout or notch, causing acceleration. When approach angles become more oblique, the amount of steering increase as the flow is forced into the notch mouth. If the wind approaches more oblique than 50 degrees, flow separation is the dominant mechanism in the blowout, resulting in turbulence and secondary flow. These winds are no longer steered into the mouth, and instead flow across and over the notch, perpendicular to the axis. (Pease & Gares, 2013).

a b

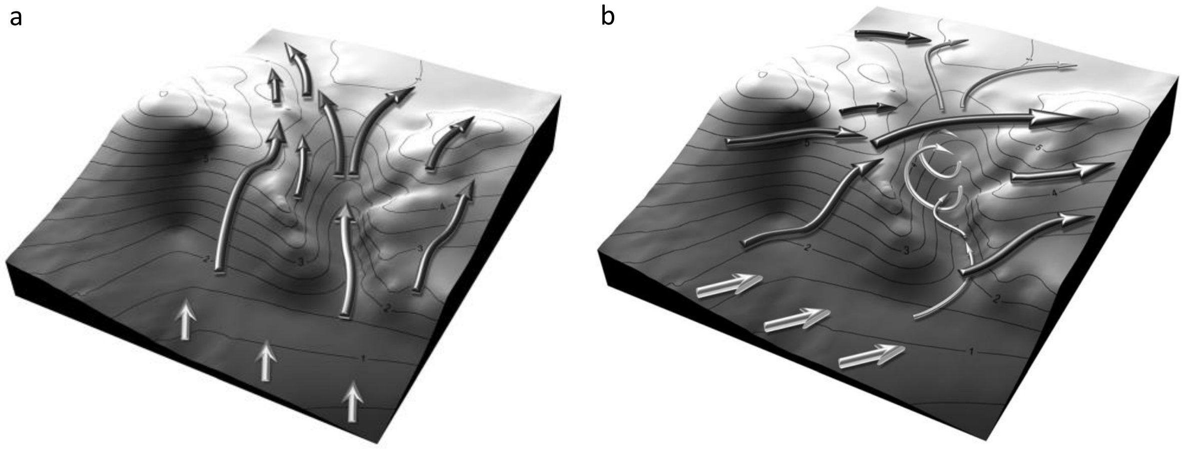

Figure 2: *Model showing a) generalized airflow through a notch with winds approaching from within 50° of the notch axis and b) airflow when oblique winds approach with angles greater than 50° of the notch axis (Pease & Gares, 2013)*

As described in this chapter, plenty research as been done to the wind flow through blowouts and notches. Especially Nguyen et al. (2021, 2022) did extensive research on flow patterns in excavated notches. The specific notches in their research however, are rather small compared to natural blowouts and most excavated notches. Additionally, it is yet unknown how sediment transport rates vary spatially through foredune notches, how the flux rates are dependent on wind patterns and how the spatial patterns of sediment flux result in depositional patterns. The only research that comes close to this is Smyth, Jackson and Cooper (2014) who studied the aeolian transport in a natural blowout. To gain more insight in the functioning of excavated notches, and their ability to transport beach sediment toward the hinterland, it is useful to investigate spatial variability of aeolian sand transport, transport pathways and patterns of erosion and deposition.

1.3 Aim and research questions

The main objective of this research is to improve the understanding of the spatial variability in aeolian sand transport rates and resulting morphological change in foredune notches. In order to achieve this objective, the following research questions are posed:

1) What is the spatial variability in aeolian sand transport rates in the notch?
2) How does this variability depend on the wind speed and direction?
3) What are the short-term (observed) morphological changes in the notch?
4) To what extent are temporal variations in morphological change related to different sand transport pathways and hence depend on offshore wind characteristics?

2 Methods

2.1 The study area

The study area is located at the west coast of the Netherlands (**Figure 3**), in the dunes of the National park Zuid-Kennemerland. The study area is north of Bloemendaal aan Zee, and south of IJmuiden. In 2012, five notches were created here, spread over 850 meter coastline. Prior to excavation, a 20 m high foredune was present. This dune was almost completely covered by marram grass, which was planted there to prevent sand loss. The creation of these notches was part of the Noordwest Natuurkern project in which PWN, the regional drinking water company, Natuurmonumenten, a nature conservation organization and HHNK, the local water authority worked together to increase dune dynamics. The notches, termed N1 to N5 (**Figure 3**) were dug in a V-shape, and all had a different width and orientation towards the land. N2, the notch that will be further investigated in this research, was dug with a 50 meter width and a length of approximately 100 meters. The incision into the dune started around 6 meters above MSL at the seaward side, and ended at 9 meters above MSL, thus creating a slope. Since 2012 the walls, as well was the notch floor, have eroded and created large depositional lopes behind the foredune (Ruessink et al., 2018). Under the influence of the offshore wind, the V-shape has been transformed in a more natural U-shape. The strongest and most frequent winds in the study area are from the south west. The shore-normal direction at this part of the coast is 287° which makes the dominant wind direction strongly onshore oblique. Westerly and northwesterly winds are substantially less frequent, but can still be strong (>12 m/s). There is a relative large fraction of easterly winds, which is specific for this location. It most likely reflects the effect of the Noordzeekanaal, which is located near IJmuiden, which is east-west oriented (Ruessink et al., 2018; Schwartz et al., 2021).

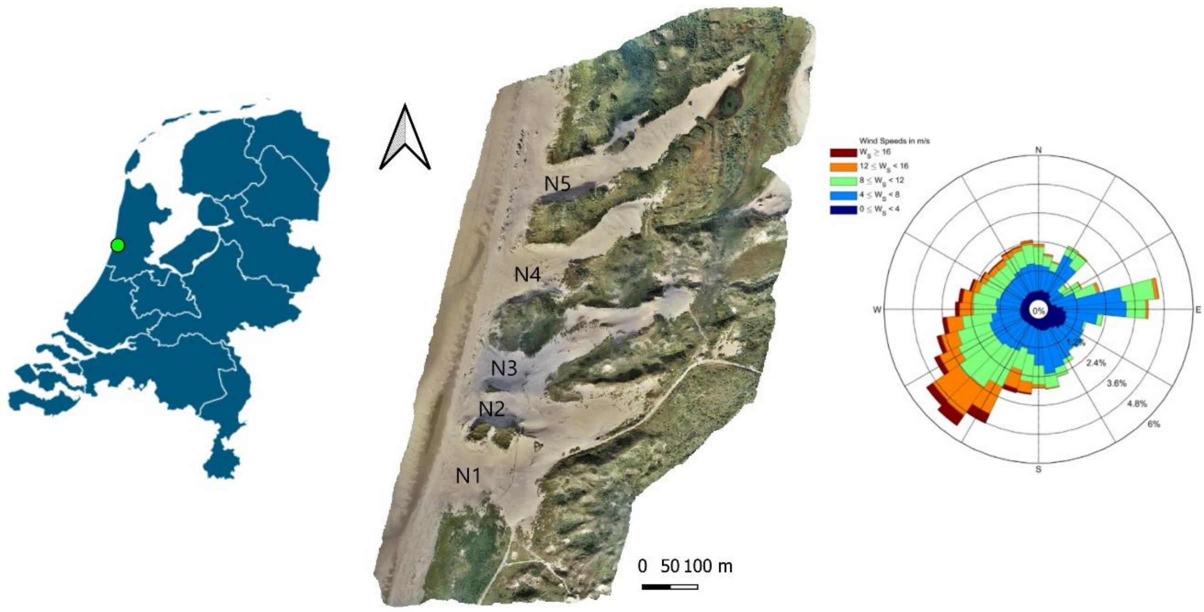

Figure 3: *Location of the study area, indicated with a green dot on the left. In the middle a close up of the study area, where the five notches are visible (image taken 11 Oct '22). On the right the general wind characteristics at offshore station IJmuiden (Ruessink et al., 2018)*

2.2 Fieldwork

To provide data to answer the research questions, a month-long fieldwork was conducted in October – November 2022. This fieldwork took place in the second notch (N2).

Sand transport

Modified Wilson and Cook sand catchers (MWACs, (Sterk & Raats, 1996)) were used to measure sand transport rates in different parts of the notch (**Figure 4**). These sand catchers were placed in a landward transect on the notch floor. Typically with 4 MWAC's, labeled L1 to L4 in landward direction. This transect was determined by the visible sand flux patterns in the notch. This resulted in different measurement locations for each field day. Each sand catcher catches sediment at seven different heights in logarithmic spacing, namely at 3, 9, 15, 21, 34.5, 59.5, and 95.5 cm above the surface. Each plastic bottle has two glass tubes that enter through the lid. One of these tubes allows the sediment and surrounding air to enter, while the other tube allows the air to escape the bottle. The bottles can rotate freely around a fixed pole, assuring orientation in the present wind direction. The content of the bottles was measured every time after being used. Additionally, the operating period was timed to the second. Typically the operation time was about one hour. This way the amount of sediment transported at a specific location, height and time period was determined, as will be detailed in section 2.3. The location of each sand catcher was determined using a differential global positioning system (DGPS). This measured the exact location and elevation in Dutch RD-coordinates (EPSG: 28992). The GDPS has a standard deviation of 0.05 m.

Figure 4: *a) Sand catcher (indicated by the red arrow) next to the most seaward ultrasonic anemometer (blue arrow). b) Close up of a sand catcher, in the background the northern wall is visible. Both pictures are taken at 16 Oct '22*

Wind speed

The wind speed and direction across the notch floor were measured using four multiple ultrasonic anemometers (UAs), operating at a sampling frequency of 10 Hz during the entire fieldwork. UAs measure the wind velocity and direction in three dimensions, using the transit time of ultrasonic acoustic signals. The measuring height of these UAs was at 0.9 m above the surface. Offshore wind speed and direction were available from an offshore KNMI station at IJmuiden. This station measured at 10 m above surface.

Morphology

During the fieldwork, observations were made about patterns of deposition and erosion visible in the notch. At the start of each measuring day, the present morphology, especially on the erosional walls, would be shortly described. Additionally, at the start of the field campaign a time-laps camera was placed next to the most seaward UA, facing the notch. This camera took a picture every two hours during the daylight for the duration of the whole field campaign. On these pictures, changes in morphology as well as the presence of sand drift was visible. The observations were quantified using RTK-GPS surveys. On 11 October and 14 November, a drone made large-scale images of the research area. These are used to create elevation models of the area, and will thus give the opportunity to calculate the change in elevation in the notch during the research period. Processing of the data was carried out as in Ruessink et al (2018).

2.3 Data analysis

Sand transport

The content of the sand traps was oven-dried for 24 hours on 105 °C, and then measured. The scale had a standard deviation of 0.05 g. Resulting in the rounding of all weights to the nearest 0.05 grams. Weights lower than 0.05 gram could not be measured and were therefore excluded from the analysis. Using the dry weight and the noted operating time of the specific bottle, the wind-blown mass flux (Q_b^z) per bottle at elevation *z* in g m^{-2} s^{-1} was calculated:

$$Q_b^z = \frac{1}{A}\frac{m}{t}$$

In this equation, *A* is the circular surface of the tube opening (50.3*10^{-6} m^2), *m* is the mass of the sediment (g) and *t* the duration in time (s). A vertical profile was drawn of the sand mass flux of the seven bottles, and an exponential best-fit curve was fitted to it. For this step, the following function was used; ${Q_{fit}}^z = \alpha * e^{\beta z}$. Values of α and β were obtained by minimizing the squared difference between Q_b^z and ${Q_{fit}}^z$. To obtain the total mass flux (*Q*) at the location of the sand catcher, the fitted curve was vertically integrated over the height of 0-1 m (Ellis et al., 2009). The efficiency of the specific sand catchers used in this research was tested in a wind tunnel experiment, using sediment of another Dutch beach. This resulted in a trapping efficiency factor of 35% (De Winter, et al., 2018).

$$Q = \frac{1}{0.35}\int_0^1 {Q_{fit}}^z \, dz$$

A requirement for fitting an exponential curve is the availability of at least three measurement per sand catcher, since an exponential curve cannot be properly fitted through two points. To estimate the goodness of the fitted function, the 95% confidence intervals of the fitted parameters α and β were calculated. The fitted parameters represent respectively the intercept and the slope of the fitted function

To quantify the spatial variability in *Q*, the normalized flux for each measurement was calculated. As reference, the flux of the measurement next to the most seaward UA (SA1) was taken.

$$Q_{norm} = \frac{Q}{Q_{loc1}}$$

Wind speed

The obtained UA data were pre-processed by removing data with error flags. With the pre-processed data, the total wind speed (*U*) and the wind direction (*Θ*) could be calculated. Wind speed is based on the mean wind velocity components $\overline{u}$ (horizontal, east-west direction), $\overline{v}$ (horizontal, north-south direction) and $\overline{w}$ (vertical). The 10 Hz timeseries of *u, v* and *w* was smoothed into a series of 3 s running means. The mean windspeed and wind direction were then calculated as 10-minute averages based on these running means.

$$U = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2}$$

The wind direction, north is 360°.

$$\theta = \arctan(\overline{u}, \overline{v}) * 180/\pi$$

Because sand catcher measurements generally took about an hour, the 10-minute average windspeeds were again averaged over the measuring period. Since no specific windspeed and direction next to each sand catcher was measured, the data from the closest UA was used.

The change in windspeed in the notch was calculated as well as the difference of the offshore windspeed compared to the windspeed in the notch mouth using ratios. This was done for every 10-minjte average as well as for specific measurement periods. Windspeeds lower than 2 m/s were excluded from this calculation, as the corresponding rations were generally rather noisy.

$$Windspeed\ ratio = \frac{U_{landward}}{U_{seaward}}$$

2.4 Fieldwork conditions

Measurements were taken on 15, 16, 22, 24 and 26 October and November 1st. These days were chosen because sufficient wind speeds were forecasted, with no or little chance of precipitation. **Figure 5** shows the researched notch and the location of the four UAs. In the database, these are numbered as followed (seaward going landward); SA02, SA03, SA01 and SA04. For the readability of this report, the numbers are changed from SA1 being most seaward, to SA4 most landward. The transect of the UAs follows the alignment of the notch, which is ~ 95° E/ ~ 275° W. The landward border of the old foredune is near SA3, this can still be seen in the field as a line of old plant roots going from north to south. The measurement locations of the field campaign are also shown. The points excluded for analysis, because of a lack of sufficient data to do analysis, are not shown on the map. The first number refers to the field day, the second to the position in the field, where 1 is most seaward and 4 most landward. Since no measurements were taken near SA4, this data will not be used during this research. Since no specific windspeed and direction next to each sand catcher was measured, the data from the closest UA was used. In general, this means that the data from SA1 was used for the locations L1 and L2, and the data from SA2 for L3 and L4. On 22-1-22 (series 3) five sand catchers were placed. Here SA3 was used for L5.

The notch floor is convex, which means that the sand catchers near SA1 are higher than the ones near SA2. Near the northern wall, the elevation also slightly increased, after which a small channel was present, just below the wall. Some of the sand catchers (L2.2, L4.2, L4.3 and L6.2), are placed in this channel, or on the sloping side of the elevation. The notch floor is at its lowest landward of SA2, after which it increases again towards SA3 and the end of the old foredune.

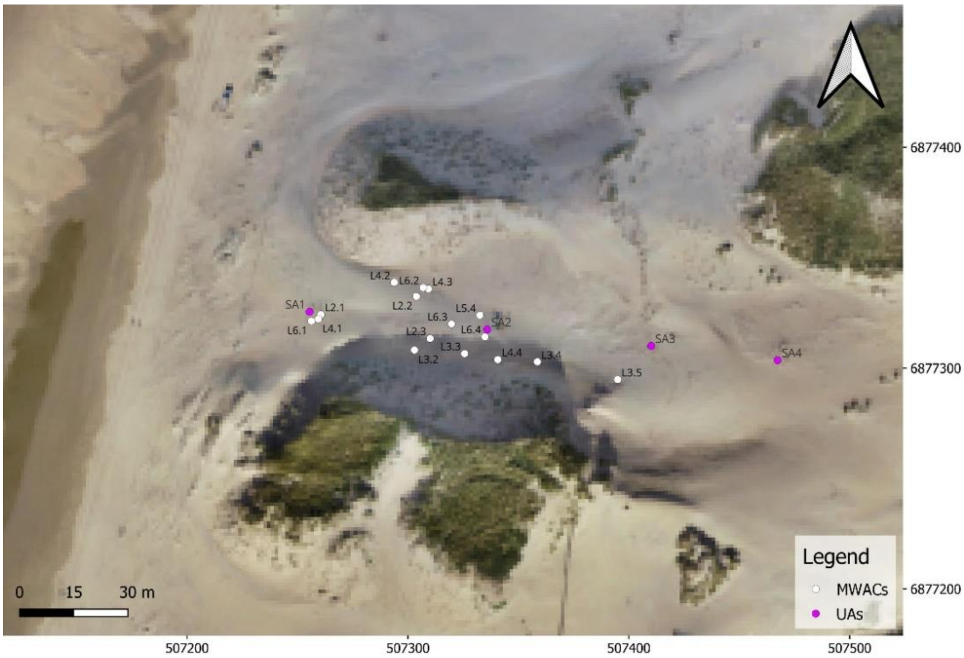

Figure 5: Measurement locations (drone image taken at 11 Oct '22)

The weather conditions varied during the field campaign (**Table 1**). On the 15th of October measurements were done. It was very wet and even though sufficient wind speeds were predicted, there was little transport. This resulted in no usable measurements on this day. After this day, it was decided to no longer do measurements during rainy weather. Most days, multiple runs were done, as indicated in **Table 1**. In total 15 runs were done, resulting in 57 measurements overall. Of these measurements, 30 could be used for further analysis. Measurements were done on days with general high windspeeds. Offshore windspeeds on measuring days varied between 11 and 19 m/s, while windspeed measured in the notch varied between 4 and 11.5 m/s. The highest windspeeds were recorded on day 4 and 6.

Table 1: *General conditions of the measuring dates. Averages are taken over the measuring period. All times are in UTC+1.*

Day	Date	Run	Start time	End time	$\overline{U_{offshore}}$ (m/s)	$\overline{\theta_{offshore}}$	Condition
1	15-10-2022	1	10:10	13:40	6.73	183.8°	Moist sand, showers of rain
		2	14:10	15:15	9.10	228.2°	
2	16-10-2022	1	9:45	11:00	12.31	241.0°	Sunny
		2	11:05	12:45	9.80	240.0°	
3	22-10-2022	1	9:30	10:40	11.11	218.5°	Moist sand, clouded, rain at the end of measuring period
4	24-10-2022	1	10:50	12:00	15.90	219.0°	Short rain showers, sun
		2	12:05	13:15	14.51	220.0°	
		3	13:20	14:25	14.37	214.9°	
5	26-10-2022	1	10:10	11:15	8.89	194.5°	Sunny
		2	11:20	12:30	9.62	203.7°	
		3	12:30	13:35	10.01	204.1°	
6	1-11-2022	1	10:40	11:45	17.66	208.0°	Sunny
		2	11:50	12:50	17.09	206.8°	
		3	12:55	14:05	16.22	205.1°	

The change of elevation during the field campaign is shown in **Figure 6**. The change in elevation in the researched area ranged from -0.7 to 1.7 m. The largest changes are on or underneath the erosional walls and behind the old foredune. The map shows an area of deposition seaward of this border as well as landward of it, specifically near the southern wall. Underneath the northern wall, on the seaward side, sand was deposited. This was mainly in the erosional tunnel described before.

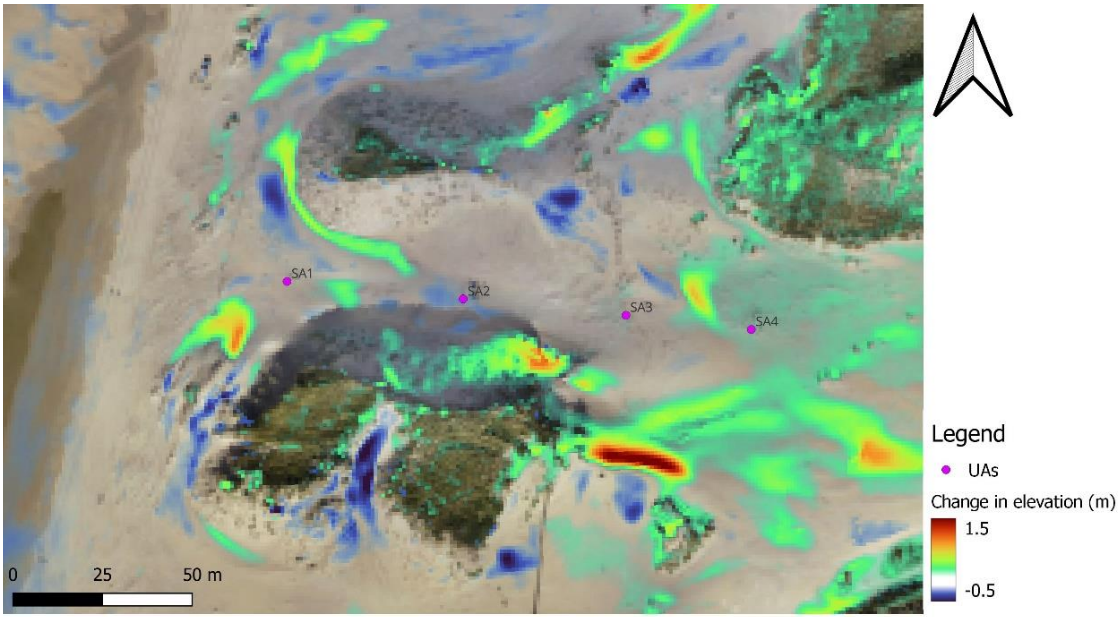

Figure 6: *Morphological change in the research area.*

3 Results

3.1 Sand transport

3.1.1 Goodness of the fitted function

Of the 57 runs that were performed, 30 contained enough data to be used for further analysis. The fit seemed to be quite good for the values at the lower elevations, but less for the higher elevations. For measurements with transport only up till 0.21 m, the fit often was almost perfect, or only the highest trap was slightly off. For most sand catchers that caught sediment above 0.21 m, the higher elevations are less accurately predicted. There are some exceptions, were the fit seems quite accurate even for the higher elevations (e.g. **Figure 7a**), but for most of the higher elevations, the measured value is higher than the fitted. This is most strongly the case for measurements above 0.595 m (e.g. **Figure 7b**). The underprediction of the higher elevations consequently results in an underprediction of the integrated mass flux.

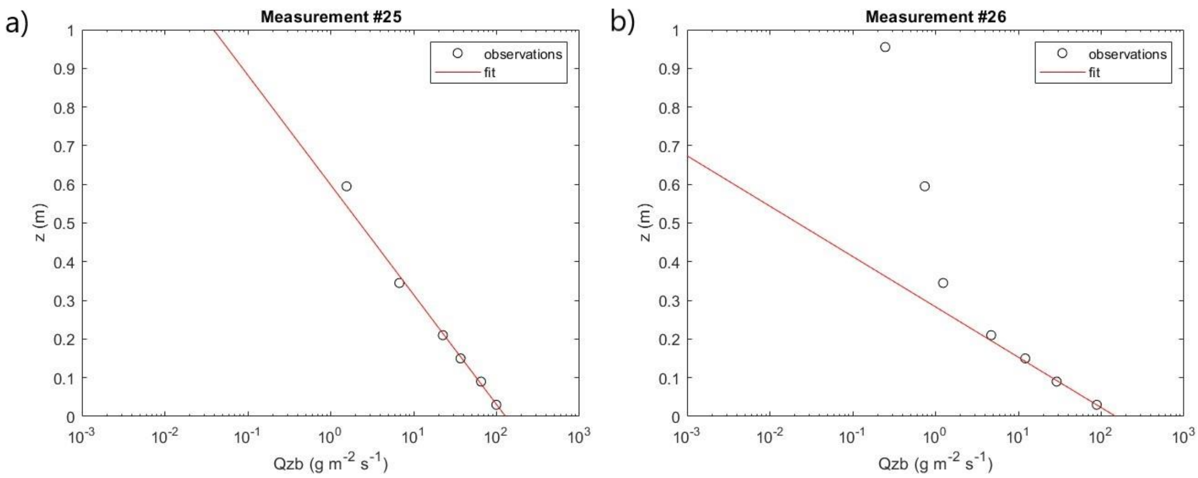

Figure 7: *Example of the fit for two measurements, were a) is quite good, while b) shows that the higher elevations are underpredicted. (Location L4.4 (a) and L4.1 (b))*

The fit produced parameters α and β. The values of α varied between 6 and 669 g m^{-1} s^{-1}. Parameter β varied between -30 and -8 m. The parameters are plotted against the local windspeed, of the UA that was nearest to the measurement point (**Figure 8**). The slope (β) indicates the distribution of sediment over the traps in the sand catcher. If β is small, this means that the sediment is evenly distributed, while if β is strongly negative, this means that the mass difference between low and high elevations is larger. The intercept (α) indicates the flux rates at the bed (z = 0 m). There is a relationship between the local windspeed and α, where α becomes higher when windspeeds increase. This indicates, that higher windspeeds cause an increase in sediment flux at the bed. The figure also shows, that scatter slightly increases with increasing wind speed. For U < 6 m/s the intercept is relatively low. For windspeeds between 6 and 8.5 m/s, α increases the strongest. For U > 8.5 m/s α is highest, but as said, the scatter is also the largest. This scatter is however mainly caused by one specific measurement. There is no clear relation between β and windspeed.

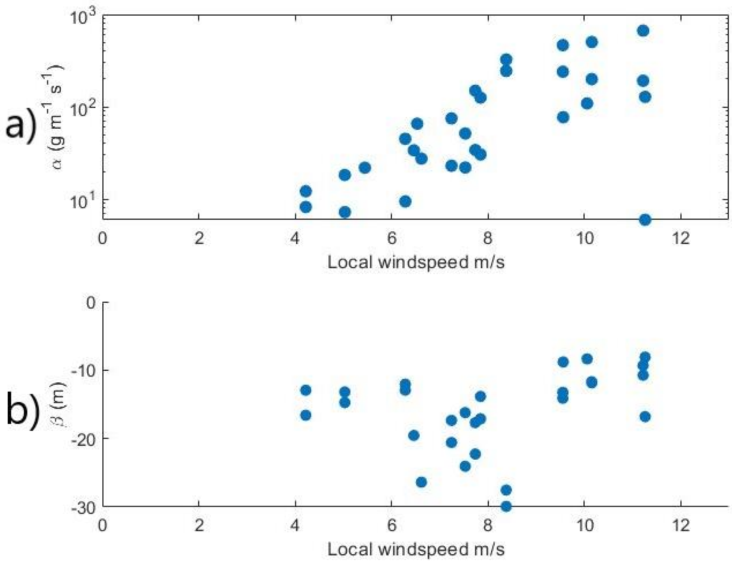

Figure 8: *Fitted parameters α and β plotted against the local windspeed*

3.1.2 Integrated mass flux

The integrated sand flux (*Q)* varied between 1.02 and 177.72 g m^{-1} s^{-1}. There is a relationship between the local windspeed and the amount of transport. The overall trend is that a higher local windspeed results in more sand transport (**Figure 9a**). This is in agreement with the trend shown in **Figure 8a**. The increase in *Q* is largest for local windspeeds between 5 and 10 m/s. As windspeeds increased, the scatter increases as well, this is especially the case for $U > 10$ m/s. Transport during the research period only happened with offshore wind directions varying between 204° and 241°, and local wind directions between 230° and 305°. There is a clear distinction between the seaward and landward part of the notch. At the seaward side of the notch (SA1), the wind directions resulting in transport varied between 230° and 256°, while more landward (SA2) the wind direction varied between 291° and 304°. This corresponds with topographic steering, as explored below. Most measurements were done with local wind directions around 300° (**Figure 9b**). Since this wind direction was only measured at SA2 and not SA1, this indicates that transport happened more frequently on the more landward side of the notch. Consequently, often measurements at location L1 are lower or missing from measuring sequences.

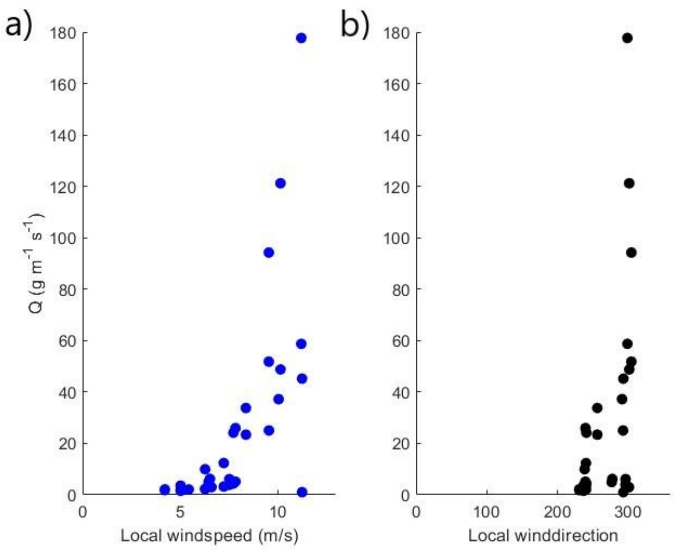

Figure 9: *The relationship between de local windspeed (a) and direction (b) and the integrated mass flux*

Figure 10 gives an indication of the spatial variability of sand transport in the notch. Measurements without reference were left out (3.2-3.5 and 5.4). There is a trend visible where the measurements near the northern wall (L2.2, L4.2, L4.3 and L6.2) were lower than the reference near SA1. More landward, the sand catchers showed a higher normalized flux (L4.4, L6.3, L6.4). The overall observed spatial trend is that Q increases landward. This is also what one would expect. Series 3 (*22 Oct '22*), although not shown on the map, also showed a landward increase, with exception of sand catcher 3.5. This catcher was located on the border of the old foredune near the large deposition area. The mass flux is slightly smaller than at 3.4. In this trend, series 2 (*16 Oct '22*) forms an exception. This series declines landward.

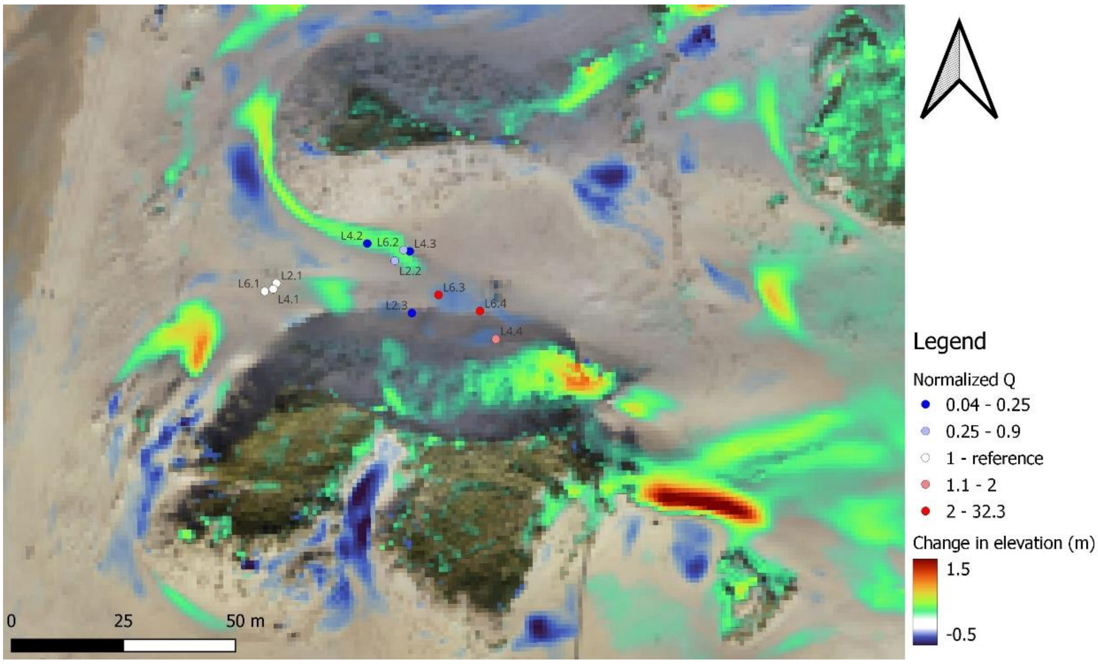

Figure 10: Spatial variability of sand transport

3.2 Wind measurements

During the field campaign, a wide variety of windspeeds and wind directions was recorded in the notch as well as at the offshore station near IJmuiden (**Figure 11**). In the notch windspeeds ranged from ~ 0 to 13.76 m/s, while the offshore windspeed was generally larger than in the notch, with peaks at ~ 20 m/s. The windspeeds at SA1 were generally larger than at SA2 and SA3, but under some angles the wind seemed to accelerate in the notch, resulting in increased windspeeds further landward. Figure 10b shows the wind direction as well as the axis of the notch (95°E/275°W). The figure shows that the wind direction at the offshore station was quite variable. The wind directions in the notch however, are mainly following the orientation of the notch. This effect is strongest for SA2. The most seaward station, SA1, most closely followed the direction of the offshore wind direction, although it is already visible that the wind direction steered towards the orientation of the notch.

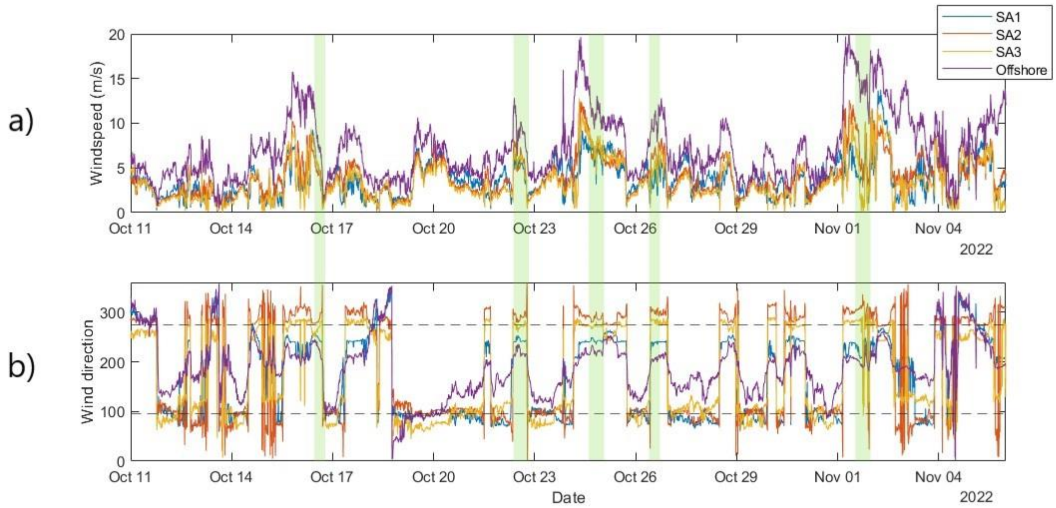

Figure 11: Windspeed and wind direction records. The measurement days (with usable samples) are highlighted in light green. The dotted lines represent the orientation of the notch.

This effect, where the wind is steered by the morphology, is also called the tunneling effect. The tunneling effect can be recognized by the fact that there are two, mostly opposite, dominant wind directions. This tunneling effect in the notch becomes more clear when looking at the wind roses of all four measuring locations (**Figure 12**). The offshore station shows that the dominant wind direction was south-south west during the research period. This can also be seen when looking at the most seaward UA (SA1). This already shows that the wind is more tunneled, but also has a dominant SSW wind direction. SA2 shows that the dominant wind directions are in line with the orientation of the notch. The opposite peaks in western and eastern winds indicate that the wind only blows through the notch, while winds from other directions are blocked by the walls. It is noteworthy, that SA2 shows a peak in wind directions around ~310°, which is more north western than the orientation of the notch. This could be caused by steering by the local notch morphology. The wind flow, after entering the notch, has to flow towards the opposite wall, after which it is steered back into the notch. The most landward UA (SA3) shows a bit more variability in eastward winds, but overall follows the orientation of the notch.

The most wind reaching the notch, results from offshore wind directions between ~90 and ~175 degrees (**Figure 13a**). These are seaward wind, during which no measurements were done. For angles below 90° or between 175° and 225°, there is almost no wind reaching the notch. Here the offshore wind blows along the beach and is not sucked into the notch, thus not reaching the notch itself. For angles larger than 225°, the windspeed increases again. These wind directions (θ<90° and 175°<θ<225°) represent the threshold for wind reaching the notch. The ratio of windspeeds between UA stations SA1 – SA3 and SA1 – SA2 show overall the same trend (**Figure 13b,c**). The deceleration effects are stronger over a longer distance (SA1 – SA3), while the acceleration is stronger between SA1 and SA2. For wind directions between ~185° and ~230°, the ratio is > 1, indicating accelerating wind speeds in the notch. As said, these effects are strongest between SA1 and SA2, where the windspeeds can accelerate up to a factor of 3. These approach angles correspond with the dominant offshore wind direction. For angles lower than 200° or higher than 230°, the wind decelerates. **Figure 13b,c** shows that the wind conditions during the measurements coincide with the general wind characteristics in the notch. Generally, the figure shows that incident approaching winds result in more acceleration in the notch.

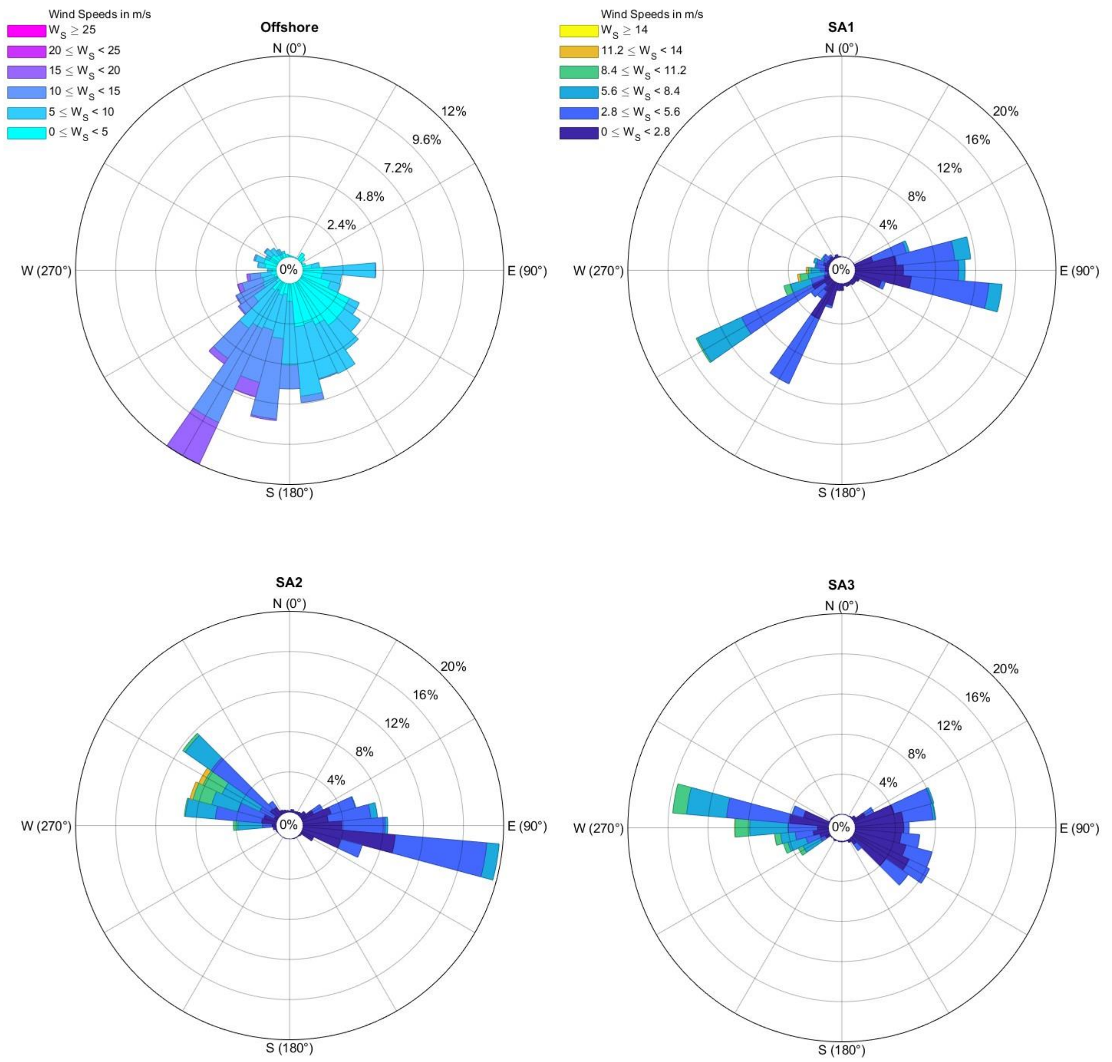

Figure 12: *Wind roses of the research period from the offshore reference station and the UAs in the notch expressed as radius, from most seaward to most landward*

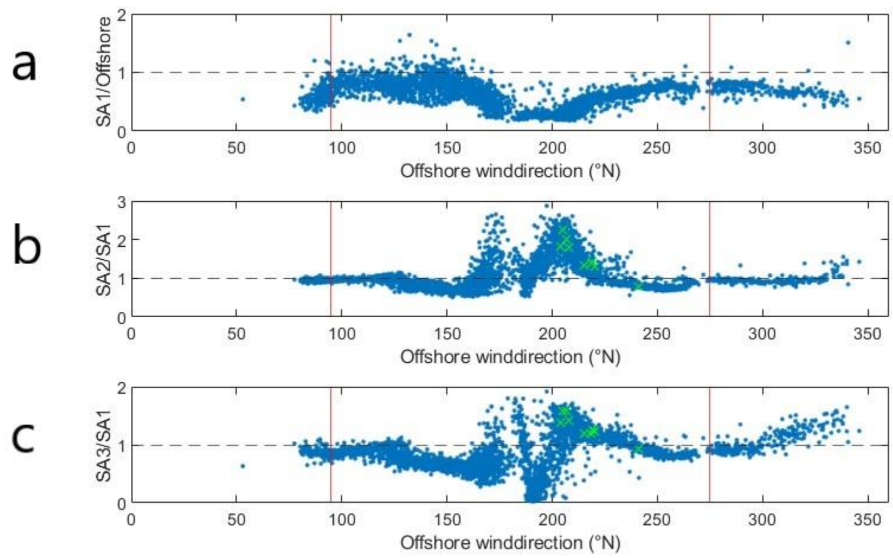

Figure 13: *Ratio of windspeeds indicating the acceleration in the notch as well as in comparison with the offshore windspeed. Red lines indicate the orientation of the notch. Wind ratios during measurements (which could be used for analysis) are indicated by x*

3.3 The relationship between Q_{norm} and wind characteristics

On measuring days, offshore windspeeds varied between 11 and 19 m/s, while windspeeds measured in the notch ranged between 4 and 11.5 m/s. During these days, the highest local windspeeds were recorded at SA2. On day 4 and 6 the highest windspeeds were measured, as well as the highest sediment flux rates.

As described in *section 3.1.*2, normalized fluxes (Q_{norm}) generally increased landward. There is a relationship between the normalized fluxes, and the ratios of windspeed in the notch (**Table 2**). With increasing ratios, the sediment flux rates through the notch increased as well in a landward direction. Oblique winds resulted in more acceleration, which agrees with the general trend shown in **Figure 13**. The comparison between the three measuring series, shows that the decrease in transport on day 2 is caused by decreasing windspeeds (ratio < 1) within the notch.

Furthermore, there is a relationship between patterns of deposition an erosion, and the normalized flux. Locations with deposition have lower normalized fluxes than locations with erosion (**Figure 10**). This follows the expectations, since deposition is an indication of a decrease in windspeed and thus potential for deposition, and the other way around for locations with erosion. **Table 2** shows that Q_{norm} at location L2 is always lower than the reference location (L1). These sand catchers at location L2 were, as earlier described, placed in a small channel near the northern wall. **Figure 10** shows high levels of deposition in this specific region. Additionally, sand catchers near SA2 (L4.4, L6.3 & L6.4) were located in an area were erosion took place. These are also the locations with the highest Q_{norm} compared to their respective reference location. This shows a clear relationship between the flux rates and depositional patterns.

Table 2: *Comparing normalized fluxes to wind characteristics*

Day	Date	Location	Q_{norm}	SA2/SA1	SA3/SA1	$\overline{\theta_{offshore}}$
2	16-10-2022	L2.1	1	0.78	0.92	241°
		L2.2	0.692797			
		L2.3	0.183285			
4	24-10-2022	L4.1	1	1.35	1.27	218°
		L4.2	0.212135			
		L4.3	0.03923			
		L4.4	1.768554			
6	1-11-2022	L6.1	1	2.02	1.53	206.6°
		L6.2	0.511324			
		L6.3	14.77199			
		L6.4	32.30108			

4 Discussion

This study investigates the spatial variability of sand transport in an excavated notch, and its relation to wind characteristics and changes in local morphology. In this chapter, the results of the sand flux, wind and morphological analyses will be put in context with existing literature, building up to the conclusion of the research.

4.1 The relation between sand transport pathways and morphology

The spatial variability of sand transport in the notch is dependent on the local morphology, wind speed and wind direction. The results of this research show that depositional areas in the notch show considerably lower fluxes than areas with erosion. Areas with deposition are related to a decrease in windspeed, resulting in less sand transport. For the areas with erosion, it is the other way around.

The spatial variability of the sediment flux rates is related to the wind speed ratios. Normalized fluxes through the notch increase with ratios exceeding 1. A decrease of wind speeds through the notch results in a landward decrease of normalized sand flux. The level of acceleration and deceleration, although influenced by the local morphology, is mainly dependent on the offshore wind direction. The acceleration in the notch is strongest for offshore wind angles between 185° and 230° (**Figure 13**). Most measurements showed an overall landward increase of flux, and had an offshore wind direction between 204° and 218°. During the research period there was one exception, which showed a landward decrease. On this field day (*16 Oct '22*), an offshore angle of 241° was measured, which resulted in decelerating wind speeds in the notch. It can be said that in this notch the sand transport increases with stronger oblique approaching winds, while winds approaching parallel to the notch axis result in decelerating windspeeds. The fact that transport increases landward, can be explained by sediment transport pathways in the notch. During the field campaign, transport pathways along the southern wall have been observed, which could have resulted in lower fluxes near SA1. Additionally, the fact that transport increases landward is an indication that sediment must have been picked up in the notch itself. This theory is supported by the analyses of elevation change in the notch during the field campaign. This analysis indicate areas of erosion on the notch floor, which means that sediment must have been picked up in the notch itself.

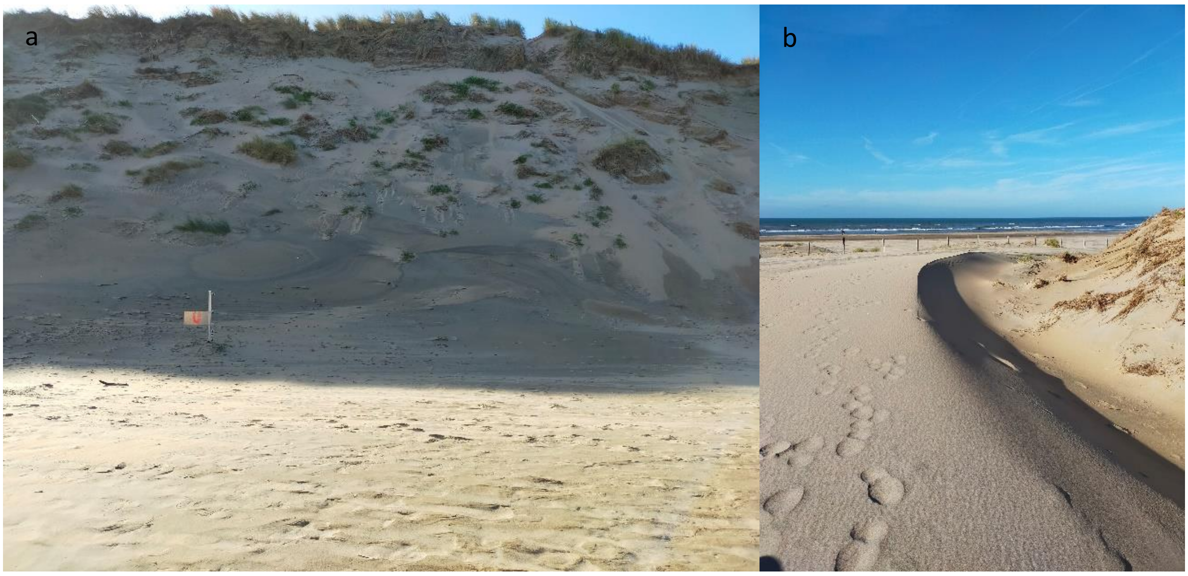

Figure 14: *a) the southern wall. On the wall are depositional areas visible, caused by overblowing wind. On the level of the sand catcher sand drift is visible, as well as scour marks (16 Oct '22). b) The channel under the northern wall, plant rests of the part of the wall that came down are visible (26 Oct '22).*

The morphological changes observed in the notch are mainly related to sand transport pathways. Patterns of erosion and deposition are related to acceleration in the notch, which itself is depended on the offshore wind direction. During the research period, the dominant wind direction was south-south-west. This caused deposition in the channel near the northern wall. Furthermore, it was observed that in this area part of the wall came down, and filled up part of the erosional channel that was present there. This was observed on the 26th of October (**Figure 14**). It was observed during the field campaign that wind blew up the southern wall, and deposited sediment behind the (old) foredune. During events with high wind speeds, sand was blown from the first notch N1 over the southern dune, into N2. This explains the erosion on the dune. There is also quite a lot of deposition visible on the southern wall, which is partly caused by this. Sand transport pathways along the southern wall were observed, on all field days with high windspeeds. This transport pathway is also visible on the time-laps camera placed at the mouth of the notch (**Figure 15**). More land inward, the amount of deposition increased. In the field it was observed that part of this sand was again transported from N1, into the toe of N2.

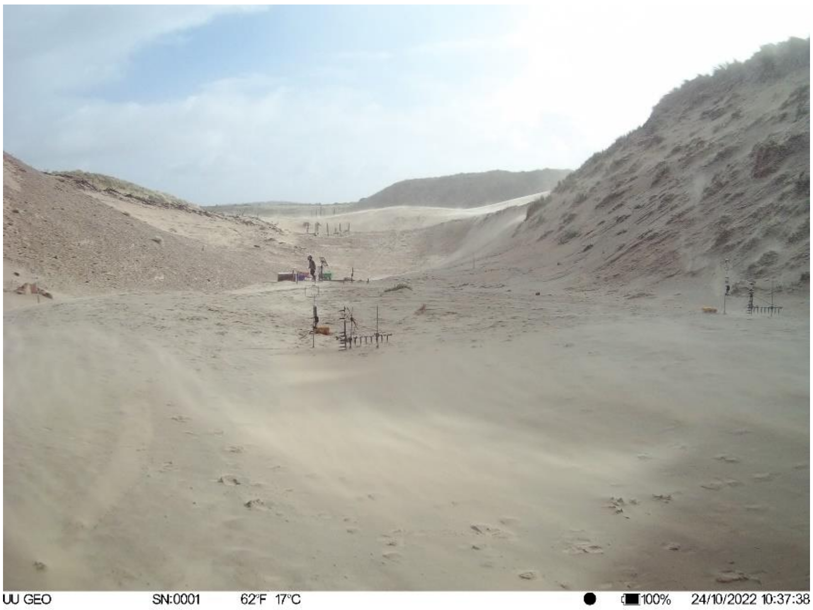

Figure 15: *Active sand transport in the notch. Transport along and on the southern erosional wall (on the right) is visible. Picture made with the camera in the notch mouth, facing eastward (24 Oct '22)*

4.2 Literature

Multiple studies looked at the vertical distribution of aeolian transport. These studies found that the intercept as well as the slope of the predicted transport increase with increasing wind speed (Rotnicka, 2013; Strypsteen et al., 2020). This is partly what was found in this study; the predicted values of sand transport in the notch show an increasing trend of the intercept (α) in relation to wind speed. While no real trend in the slope (β) could be found. It is not clear why no relation can be found for the slope. A possible explanation, is the difference in measuring height, both researches measured below 0.5 meters, while in this study, up till 0.95 meters was measured. This could have influences the fit, and thus the slope.

As shown in *section 3.3.1*, the fit for the sediment flux at higher elevations was not always accurate. Sterk & Raats (1996) describe that traps above 0.5 m start to deviate more from the predicted values, while the fit seems accurate for the lower traps. This was also observed during this research. They used multiple equations to compare the functioning of different models, and for all models this was the case (Sterk & Raats, 1996). The near bed transport is better predicted than at higher elevations, and thus forms the dominant factor for the fitted model (Sterk & Raats, 1996; Strypsteen et al., 2020). Furthermore, as windspeeds increase, more sand is transported at higher elevations, and less close to the bed. Thus potentially leading to underpredictions of higher sand transport (Rotnicka, 2013).

Sediment flux rates varied considerably through the notch. The highest fluxes were found on the landward side of the deflation basin (around SA2), and the lowest fluxes near the (northern) erosional wall. According to the research of Smyth, Jackson & Cooper (2014), flux rates should be greatest at locations where the steadiest and fastest wind flow occurred. They found that the highest fluxes are on the crest of the erosional wall, and the lowest in the deflation basin. This is in contrast with the spatial trends found in this research, although the mechanism that they describe is still valid in the researched notch.

To understand more about the dynamics in the notch, it is important to know what the threshold is for notch activation, i.e. when sand transport might occur in the notch. The study of Nguyen et al (2021) shows that notch activation is dependent on both the incident wind speed and direction. The threshold of wind speed for activation increases when the approach angle increases. The results of this research show a minimum of 4 m/s for substantial transport. The minimum wind speed needed for sand transport, is probably a bit lower, considering that sometimes transport was present but not measurable due to the methods used in this research. This study shows that oblique winds tend to result in more transport. This can explained by the fact that when the wind approaches the notch obliquely, the flow is topographically steered into the notch. This steering can reach such a degree, that the flow will be turned against the approach wind direction (Hesp & Hyde, 1996). This process becomes most visible when looking at the wind direction data from SA2. At this location directions of 310° were measured. This indicates that the wind has been steered, since this is more north-western that the notch axis. This process increases as the angle towards the entrance increases (Hesp & Hyde, 1996). Additionally, there is a relation between the approach angle and the ratio of windspeeds in the notch. Pye, Blott & Howe (2014) described that the acceleration in a notch is caused by convexity of the basin and landward narrowing, which is the case in the researched notch. Furthermore, the study of Nguyen et al (2021) also found that wind deceleration occurs when incident wind direction is notch axis parallel. This is also what was found in this study.

4.3 Limitations & recommendations

During the research period, winds were limited to south-west wind directions. According to previous research (Ruessink et al., 2018), even though south-west is the dominant wind direction, through the year there is a considerable amount of wind coming from the west and north-west. It would be interesting to measure sand transport under these conditions. Changes in morphology are caused by wind flow and transport pathways, which are both dependent on the offshore wind direction. By studying the effects of varying conditions on transport pathways and morphological processes in the notch, more insights will be gained in notch dynamics. It would also be useful to conduct this research in multiple notches with different characteristics.

To gain a more in depth image of the wind flow through a notch, and the influence on sediment transport pathways, it would be useful to have an UA next to each sand catcher. This was not done during this research, which resulted in a more general description of the wind flow patterns in the notch. Overall, the results show a correlation between the flux and wind speed ratios, with exception of one outlier. This was point L4.3, during the first round of day 4. This point showed a low flux (1.01) at a high windspeed (11.26 m/s). This is caused by the fact that the windspeed of SA2 has been used, while the sand catcher was actually placed in the channel underneath the northern erosional wall.

No measurements were performed during rain showers, since the wet sand would clog the bottles and influence the measurements. However, it was observed in the field that precipitation had an influence on the amount of sand transport. A moist top layer seemed to decrease sediment transport, since when the top layer dried, transport appeared to increase. It would be interesting to study to what extend the wetness of the sediment influence the amount of sand transport. This research does not provide enough data to answer that question.

5 Conclusion

During the research period, integrated sediment flux rates varied between 1.02 and 177.72 g m^{-1} s^{-1}. Overall the sediment flux in the notch increased landward, and the highest flux rates were measured on the landward side of the deflation basin. Additionally, it was observed that there was a relation between areas of erosion and deposition in the notch and the amount of sediment transported. In depositional areas the normalized sediment flux rates were lower (Q_{norm} = 0.04 – 0.9) than the flux rates in erosional areas (Q_{norm}= 1.2 – 32.2). The spatial variability of sand transport flux through the excavated notch can be explained by the offshore wind direction and the local morphology. More oblique approaching winds (185 - 230°N) resulted in more acceleration in the notch, and consequently in more sediment transport. Winds parallel to the notch axis (θ > 235°N) resulted in deceleration in the notch, and thus decelerating normalized flux rates landward. The notch morphology has an impact on the sediment transport through the notch. The local topography steers the wind, resulting in the observed wind patterns, and consequently influencing the sand flux. The changes in morphology are strongly effected by sediment transport pathways, and this dependent on offshore wind characteristics. To conclude, this research showed that the spatial variability of sediment transport rates are strongly related to offshore wind characteristics, where oblique winds result in higher transport through an excavated notch.

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