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AEOLIAN SAND TRANSPORT AT THE BELGIAN COAST: FIELD CAMPAIGNS AND FIRST RESULTS

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Abstract

During field experiments, designed to measure wind flow and sediment transport over a nourished and a natural beach in Belgium, measurements were made in 2016. Measurements of the wind profile across the upper beach, with arrays of cup anemometers, show that there is a direct relationship between the wind speed at 2m-height and the shear velocity. The ratio is depending on the surface roughness conditions of the area of interest. When the traditional Bagnold model is applied on the datasets, overestimations of the observed sand flux are made. The model does not account for supply limitations and critical shear velocities. However, it is shown that the count of impact of saltating grains, measured with two saltiphones, placed at different heights above the surface is related to the wind speed to the third power.

Key words: Aeolian transport, field measurements, Belgian coast, saltiphone, MWAC sand catcher, shear velocity

1. Introduction

With a Southwest-Northeast orientation (235-55°), the Belgian coast is 67km long and consists of sandy beaches, which are up to 600m wide in the southwest and only 200m in the northeast. The beaches along the entire coast are very gently sloping, although the slope increases from 1% to 2% towards the west (Deronde et al., 2008). For natural conditions, the average diameter of the sediment is about 250µm. Due to a natural gradient and an increase in nourishments towards the northeast, the sand becomes gradually coarser along the coast, from 150µm in the west to up to 400µm in the east (Deronde et al., 2008). The tidal range along the Belgian coast is large, it varies between 3.5m at neap and 5m at spring tide, and the beaches are therefore in the macro-tidal regime. This tidal range results in significant tidal currents, of over 1m/s in the nearshore area (Haerens *et al*., 2012).
A thorough understanding of Aeolian processes in coastal environments is necessary for several reasons. Aeolian sand transport is crucial for the restoration of dunes between storms. Coastal dunes serve as a protection barrier against the destructive forces of the sea. Half of the Belgian coastline consists of sandy beaches with natural dunes, and their ecological significance is considerable. The other half consists of sandy beaches with artificial dikes. In those regions, Aeolian transport has a negative economical impact, since it results in sand deposition on roads and tram tracks. Each year, coastal municipalities invest in the maintenance of their streets, sewer systems and damaged buildings (Rauwoens, 2017). Up to date, no accurate quantitative data on the amount of Aeolian sand flux is available at the Belgian coast. Knowledge of the processes concerning beach and dune development by wind lacks scientific background. However, it is essential for the prediction and evaluation of many management activities.
In order to assess the impact of Aeolian sediment transport in the overall sediment budget and to derive quantitative relations between the amount of sand transported by wind and parameters describing the hydro-meteorological state, monthly field campaigns are scheduled at the Belgian Coast. The field campaigns are carried out both in natural and artificial environments. This paper presents the preliminary results from field measurements done over one day on an artificial sandy beach with a dike structure and a natural sandy beach with coastal dunes.

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The first models for predicting Aeolian sediment transport were developed in desert environments and wind tunnels, where sediment availability is abundant (e.g. Bagnold, 1954). These transport models are solely based on physical principles and the assumption that the transport rate, q, is proportional to the shear velocity to the third power. In coastal areas, however, Aeolian sediment transport rates and volumes are generally overestimated making long-term Aeolian flux estimates highly unreliable (e.g. Davidson-Arnott et al., 2009; Jackson and Cooper, 1999; Lynch *et al*., 2008). The limitation of the existing models is that the transport flux calculations do not cover the influence of supply-limiting factors like moisture content and fetch effects (e.g. Wiggs *et al*., 2004; Davidson-Arnott *et al*., 2008; Bauer *et al*., 2009). Moreover, these supply-limiting factors are highly variable in space and time (Baas and Sherman, 2005; Ellis *et al*., 2012). Accurately quantifying Aeolian sediment patterns still remains a challenge.

2. Materials and methods

2.1 Study Area

Five field campaigns were conducted on the artificial beach of Mariakerke-Bad and the natural beach of Koksijde (West-Flanders, Belgium). These were conducted on May 13th 2016, September 29th 2016, November 21st 2016 respectively and on October 19th 2016 and November 24th 2016. The study areas are located at the Belgian coast, which is situated at the southern edge of the North Sea basin (Figure 1).

Mariakerke-Bad has a disturbed beach, where human interventions take place. It is also a weak link in the coastal protection of the Belgian coastline. To protect this site against the impact of a 1000-year storm event, the Belgian Master Plan for Coastal Safety plans a combination of hard (raise the dike locally) and soft measures (nourishments of the beach and shoreface). The soft measures have been implemented in 2014. The shoreface nourishment was carried out as part of a pilot project to be evaluated as an alternative measure for maintaining nourished beaches. Aeolian sand transport from the beach towards the dike has resulted in sand deposition on roads and tram tracks behind, requiring costly removal. Previous studies have revealed that Aeolian sand transport over the dike under oblique onshore winds is facilitated by a wind speed-up (Tresca *et al*., 2012). Nevertheless, knowledge on Aeolian sand transport on dikes and their influence on infrastructure is still limited. Being protected by a combination of dike and sand nourishments, this disturbed beach is generally 250-300m wide. Due to the nourishments in this zone, the sand has an average grain size of 310µm.

At Koksijde, the sand bank Broersbank is visible during neap tide and acts as a natural island in front of the Belgian coastline. In the framework of the Vlaamse Baaien project a monitoring campaign is operational since November 2013 to better understand and characterize wave propagation and dissipation towards the Belgian coast, and specially the influence of the shallow sand banks on it. This zone has more or less a natural ecosystem (beach and dune) without much anthropogenic interaction. The site is characterized by strong wind and wave dynamics, constructing bedforms and embryonic dune development. Human influence on this part of the beach is minimal compared with the study site in Mariakerke-Bad.

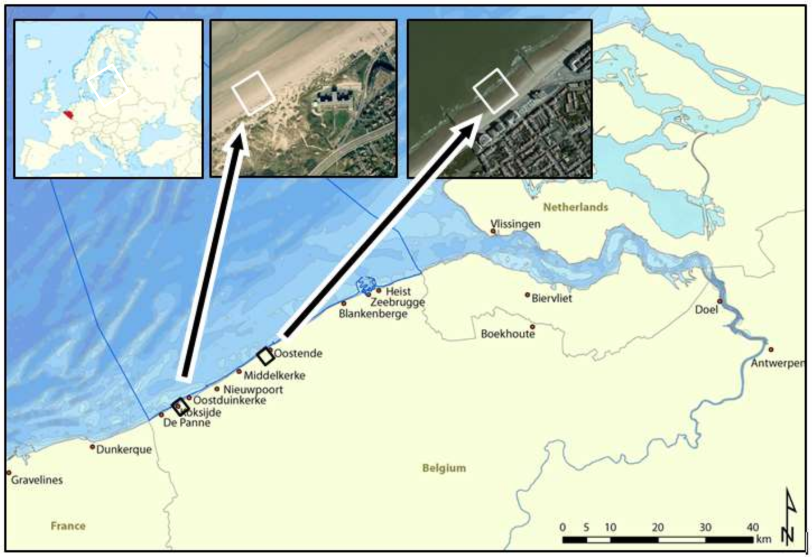

Figure 1. Location of the study areas. The study site at Koksijde is located in the south of West-Flanders, near the border of France. Mariakerke-Bad is located next to harbour city Oostende.

2.2 Data Collection

In the study area, twelve Modified Wilson And Cook (MWAC) sand traps were used to measure mass fluxes (see Figure 2). They are extensively used in numerous studies (e.g. Van Pelt, Peters and Visser, 2009; Sterk and Raats, 1996; Goossens, Offer and London, 2000; Poortinga *et al*., 2013a; Youssef *et al*., 2008), where efficiencies between 42% and 120% were reported. The sediment catcher contains seven plastic bottles with glass tube inlets, placed horizontally at seven different levels ranging from 0.065m to 1.00m. The rotating pole with wind vane makes sure that the bottles are always aligned with the wind direction. However, when wind-blown sediment transport occurs, the saltating layer seldom reaches heights above 25cm. Therefore, only the four lower bottles will capture sediment. The sediment flux per meter beach width is calculated based on the exponential curve fitted through the four data points.
Two meteorological stations each with an array of four anemometers, a wind vane, a temperature sensor and two saltiphones were installed on the dry beach in the study area. The intensity of sediment transport was measured with two saltiphone sensors located around the meteorological stations, close to the surface. The sensors consist of a tube of about 0.3m in length and 0.02m in diameter that can move freely along their vertical axes, according the wind direction. The saltiphones were connected to a CR800 Campell Scientific datalogger, which registered the total amount of hits per second. The meteorological stations were always positioned in the dry beach and they measured wind speed at a minimum of four elevations. The elevations from the anemometers changed per measurement campaign and per study site. The wind speed data, recorded every second, were averaged over one minute periods and saved in the CR800 Campell Scientific datalogger. The wind vane placed at a height of two meter measured the wind direction.

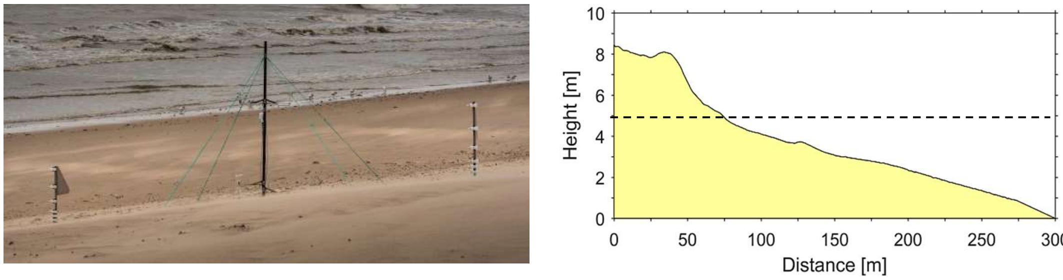

Figure 2. Left: Field experiment setup in the artificial study site at Mariakerke-Bad during Aeolian sand transport. The specific equipment consists of a meteorological station and MWAC sand catchers. Right: Cross-sectional profile of the study site in Mariakerke-Bad. A steep slope connects the upper beach with the intertidal area. The dashed line gives the average high water line.

3. Results and discussion

The combined field experiments resulted in an extensive dataset on Aeolian sand transport with consistent and reliable data. All the campaigns were performed on the upper beach in dry conditions with average wind speeds ranging from 4-16m/s. In this paper, we focus on the importance of wind profile measurements, the transport rate flux related to wind speed and we compare the Bagnold model predictions with the observed data.

3.1 Importance of measuring wind profiles

In most sand transport studies, two-level or multilevel wind velocity measurements are rarely available and the wind speed climatology must be measured at two or more levels to establish the shear velocity, u* and the surface roughness Z_0. The shear velocity is the most important forcing parameter in Aeolian models used to predict sediment transport rates (Sherman, Bailiang, 2012; Valance *et al*., 2015). In the field campaigns carried out in natural and artificial environments at the Belgian Coast, a minimum of four anemometers was used to extract wind profiles. Figure 3 gives a snapshot of an eight-level wind velocity profile measured at Mariakerke-Bad (artificial) and Koksijde (natural). The wind speed measurements are averaged over a period of one minute to smooth out fluctuations due to wind gusts. The best fit is found to be a logarithmic curve described by the Prandtl-von Karman equation (Valance *et al*., 2015). At that time, due to the shell fragments present at the upper beach of the natural study site at Koksijde, the surface roughness is greater than the artificial study site at Mariakerke-Bad, where nourishments took place. The wind profiles presented in Figure 3 have a high correlation up to almost 1.00.

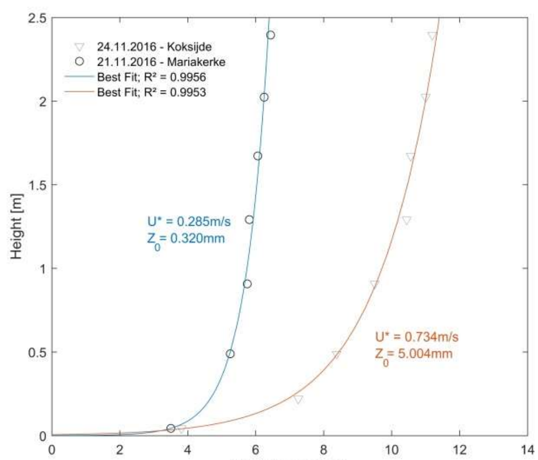

Figure 3. Measured wind profiles at Mariakerke-Bad and Koksijde. The corresponding shear velocity and surface roughness is given.

Based on measurements at six beaches, Hsu (1977) established a relationship for the shear velocity in terms of the wind speed measured at a height of 2m. His relationship for the dry beach area is given by $U_* = 0.044\ U_{2m}$. In figure 4, a direct relationship is found for both study sites. A linear curve exists between the calculated shear velocity and the measured wind speed at a height of 2m above the surface.

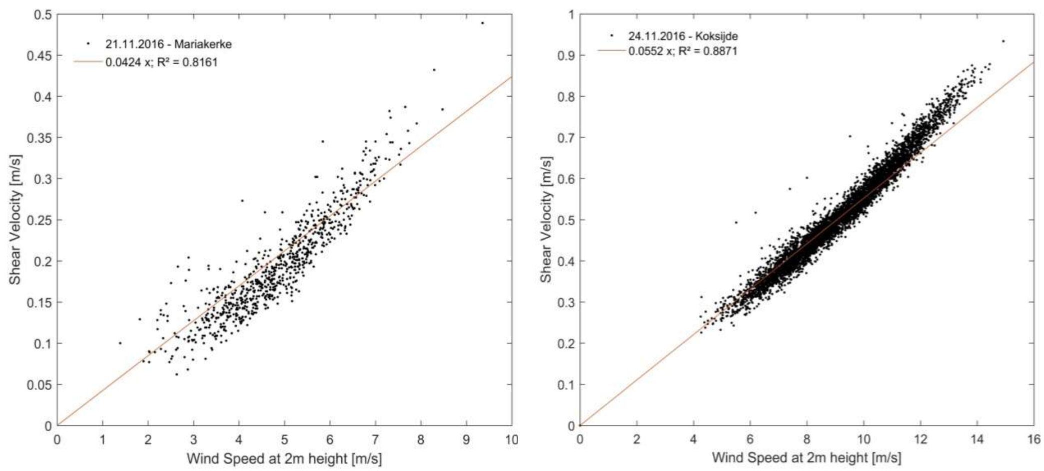

Figure 4. Relationship between the calculated shear velocity and measured wind speed at a height of 2m.

In Table 1 the ratio, with corresponding correlation and surface roughness height, between the shear velocity and the wind speed at 2m for the five field campaigns (three for Mariakerke and two for Koksijde) is given. The coefficient depends critically on the height of the surface roughness. Greater roughness heights correspond with a greater ratio between the shear velocity and wind speed at 2m height. It is important that the coefficient is used for beaches with roughness conditions similar to those for which the ratio was developed. The coefficient that Hsu (1977) found for dry beaches is valid for roughness heights around 0.225mm. Figure 5 indicates that the observed data follows the results found by Hsu (1977) seamlessly. If the wind speed is measured at one specific height, in this case 2m, with known surface roughness condition, the shear velocity immediately can be calculated.
However, Table 1 indicates that the surface roughness height, Z_0, is not constant per study site and can be influenced by roughness elements, variation in grain size, micro-morphological changes of the beach surface, wind speed and wind direction. Therefore, measuring the wind profile is a necessary tool to calculate surface roughness heights.

Table 1. Ratio between the shear velocity and the wind speed at 2m. The data is averaged for the whole length of the performed experiments.

Date	U_*/U_{2m}	Z_0 [mm]	R^2
Mariakerke-Bad			
13.05.2016	0.0377	0.088	0.6917
29.09.2016	0.0469	0.595	0.7389
29.09.2016	0.0469	0.555	0.6874
21.11.2016	0.0424	0.236	0.8161
Koksijde			
19.10.2016	0.0430	0.374	0.5075
21.11.2016	0.0552	1.616	0.8871

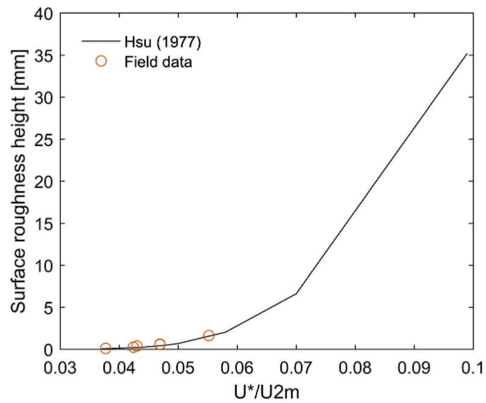

Figure 5. Comparison between the surface roughness height and the coefficient relating the shear velocity with wind speed at 2m height. The solid line represents the field measurements carried out by Hsu (1977).

3.2 Transport flux rate as a function of wind speed

The short-term field measurements of Aeolian sediment transport, ranging from a few hours to over a day, were carried out using two saltiphones, which counts the number of impacts of sand grains on a microphone. Every second, the total number of impacts was recorded. Traditionally, Aeolian sediment transport is calculated using Bagnold-type expressions, where the sediment transport is related to shear velocities to the third power. This approach is quite accurate when sufficient sediment supply is available to achieve high transport flux rates, where the capacity of the wind governs Aeolian transport (de Vries *et al.*, 2012). At beaches, the sediment supply is limited because of some important influencal parameters, like surface moisture, armoring layers and fetch effects.

Figure 6 and 7 show the relationship between grain impacts and wind speed, determined on the study site of Koksijde and Mariakerke-Bad. The wind speed is taken at a height of 2m for all the datasets. For each dataset, a cubic and a linear fit are plotted. Fitting the linear curves through these datasets provides decent fit, but the cubic trend has a more distinct character. The gradient of the linear fit is the average sediment concentration. The zero crossing of the linear and cubic fit defines the threshold wind speed.

When looking at the results of the campaigns carried out at Mariakerke (Figure 7), the cubic curve has an overall better correlation than the linear curve when wind directions were onshore. When the wind direction was alongshore or even offshore, more spreading is found on the data and the linear fit has a slightly better result fitting the data. The buildings on the dike and the dike itself are a clear obstruction when winds are blowing alongshore and offshore. More specifically, on September 29th and November 21st 2016, one saltiphone was placed at the low side of the beach slope of the study area (see Figure 2). When the wind direction was alongshore or slightly offshore, sand grains encountered a gravitational speed run-up over the slope, which had an influence on the amount of grain impacts per second. A lower critical wind speed was required to have sand transport as can be seen in the cubic curve fits.

Figure 6, which represents the data at the natural study site of Koksijde, shows similar results when a cubic and a linear curve is fitted. It has to be noted that on 24 of November 2016 at Koksijde, the saltiphone placed 5.5cm above the surface achieved the maximum rate of total impacts per second. However, Figure 6 indicates that the critical wind speed needed to induce sand transport is lower when the saltiphone is located closer to the surface. At a certain critical wind speed, the lower saltiphone has more chance to register grain impacts that the saltiphone placed higher above the surface.

Unfortunately, the saltiphone is a grain counting device. Mass fluxes are not recorded directly. In all the cases, observed transport occurred in dry conditions. During the campaigns, mass fluxes were recorded directly with MWAC sand catchers over a period of time. The period of time depended on the intensity of transport and varied from a period of minutes to over a day. Overall, it can be concluded that the shear velocity or wind speed in general to the third power, is an important parameter to predict sediment transport rates.

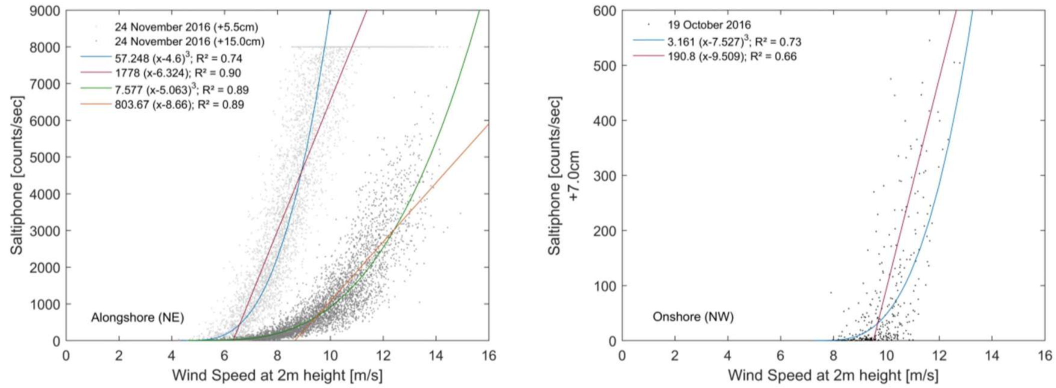

Figure 6. Relationship between saltiphone counts and wind speed at 2m height at Koksijde. A cubic and linear curve is plotted through the datapoints. The wind directions are given as well.

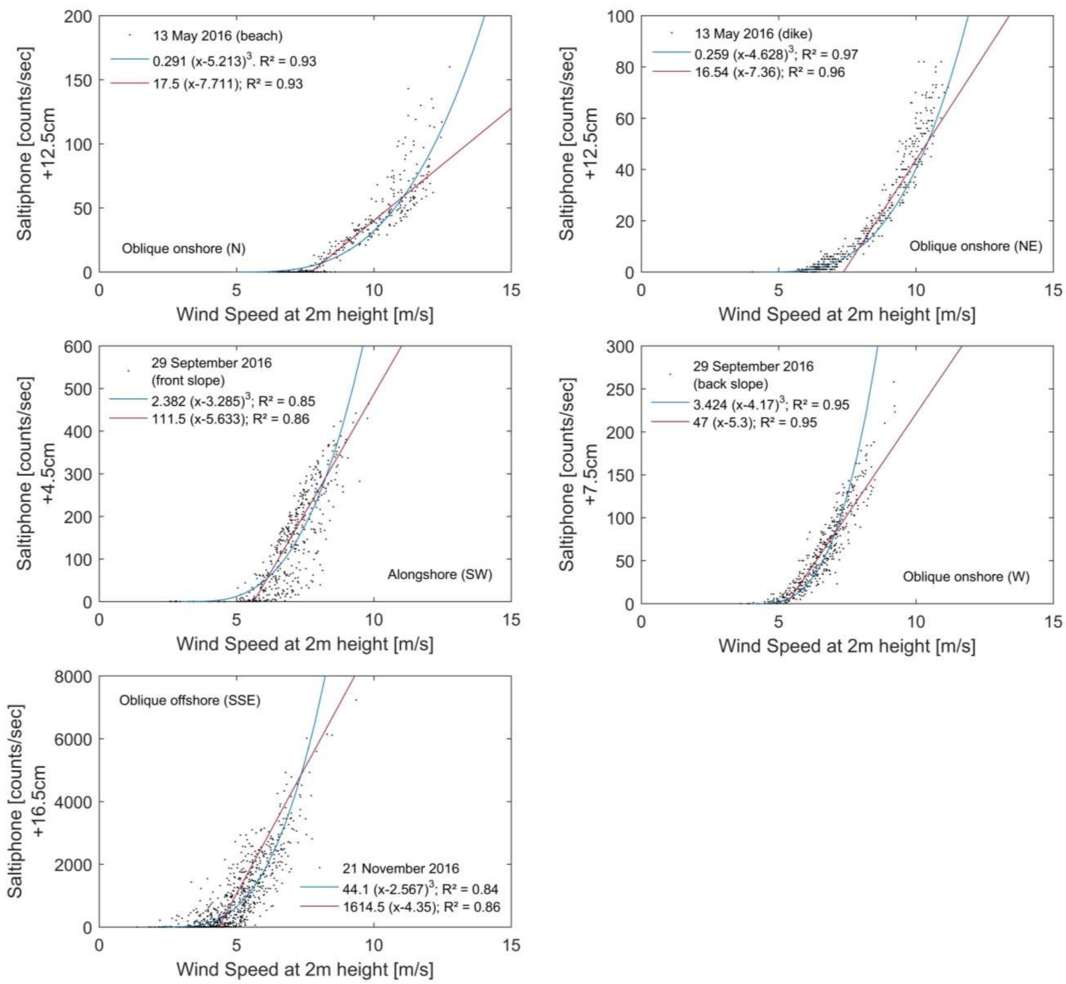

Figure 7. Relation between the saltiphone counts and wind speed at a height of 2m for the Mariakerke-Bad study site. A cubic and linear curve is plotted through the datapoints. The wind directions are given as well.

3.3 Bagnold as a reference model

There are many Aeolian sand transport models based on physical principles and the assumption that the transport rate, q, is proportional to shear velocity to third power. Therefore, the amount of sand captured (amount of kilogram sand per meter width in one minute), in a certain timeframe, by the MWAC sand traps at both study sites is related to the average shear velocity in the same timeframe (Figure 8). Each graph is a summary from all the campaigns carried out per study site. Each campaign is characterized with a specific marking point. Through all the datasets, the best cubic and linear curve is fitted. Both curves give a good correlation, however, the cubic curve has a more representative and distinct character. Figure 8 also shows that the critical shear velocity needed to induce sediment transport is 0.22m/s for Mariakerke-Bad (nourished beach, D_{50} = 310µm) and at 0.16m/s for Koksijde (natural beach, D_{50} = 235µm). It is directly related to the mean grain diameter. The threshold shear velocity derived from the Bagnold equation is:

$$u_{*t} = A\sqrt{gd\left(\frac{\rho_s - \rho}{\rho}\right)} \tag{1}$$

The constant A is emperical determined and is typically taken as 0.085 during saltation. The absolute density of the sediment is not measured, but is set to a standard value of 2650kg/m³. Based on equation 1, the threshold velocity for Koksijde is 0.185m/s and 0.218m/s for Mariakerke-Bad. Based on the measurements and Figure 8, corresponding values for the threshold shear velocities are found.

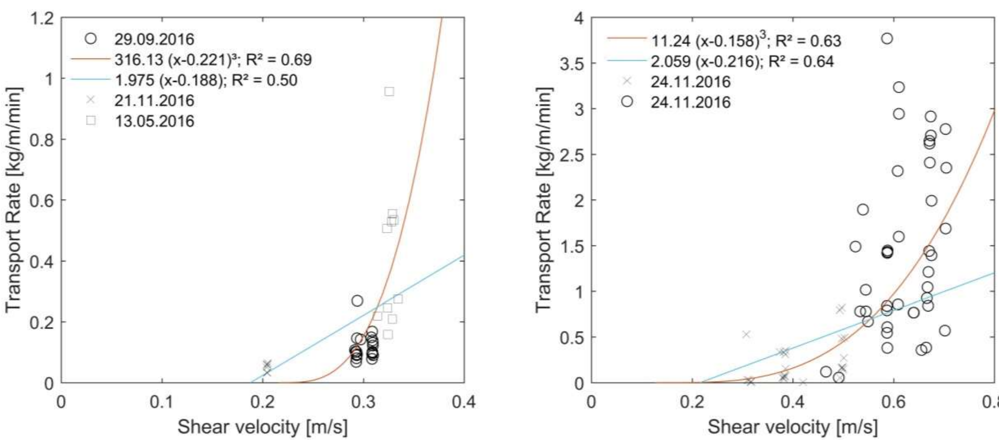

Figure 8. Relation between the transport rate and wind speed at 2m. Left graph represent the study site at Mariakerke, while the graph on the right represent the study site at Koksijde. Each campaign is characterized with a specific marking point.

The Bagnold Aeolian sand transport model (1937) is evaluated using the field data from the two study sites. Three datasets were used for the Mariakerke study site and two datasets for the Koksijde study site. More transport models could be evaluated, but Bagnold is used as a starting point. Bagnold predicted sediment transport as a function of shear velocity to the third power. The shear velocities are calculated using the measured wind profiles at the study sites and the von Karman constant of 0.4. It has to be noticed that the models where not adjusted to surface moisture content or local morphological effects. The model of Bagnold, used to estimate sediment transport, is given below.

2.1.1. *Bagnold*

Bagnold was the first to incorporate boundary-layer theory and a physical/mechanical approach into an aeolian transport model. He generalised his findings to the following formulation:

$$Q = C_b \sqrt{\frac{d}{D}} \frac{\rho}{g} u*^3 \tag{2}$$

Where the mean sediment grain size is 310µm for Mariakerke-Bad and 235µm for Koksijde. The constant C_b is 1.8 for sand that is fairly good sorted, D is a reference grain size of 250µm, ρ is the air density (1.29kg/m³), g is the gravity constant (9.81m/s²) and u* is the shear velocity derived from the velocity profiles measured above saltation clouds. At the moment the shear velocity exceeds the threshold shear velocity, sand transport occurs. However, the threshold shear velocity and supply limitations are not implemented in Bagnold's formulation.

In order to quantify the performance of the Bagnold model, linear regression is used to compare the observed and the predicted transport rates. Figure 9 shows the comparison of the model at both study sites. In general, the best result would have the largest correlation, a best-fit line slope closest to 1.00 and the smallest intercept.

According to Figure 9, the model of Bagnold yields a good correspondence between observed and predicted transport rates for both study sites. The correlation between the measured and the predicted transport rate is rather low. In general it can be concluded that the predicted rates are almost always larger than those observed rates.

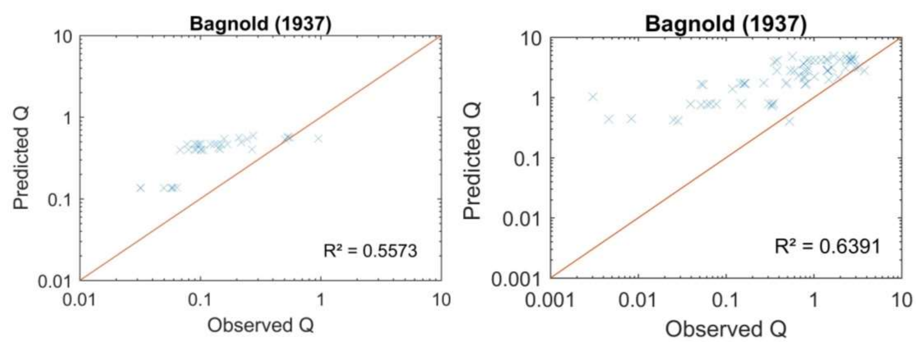

Figure 9. Comparison of observed and predicted rates of transport using the Bagnold model at Mariakerke-Bad (left) and Koksijde (right). The solid line represents a one-to-one correspondence between prediction and observation. The transport rates are given in kg/m/min.

4. Conclusions

Field measurements designed to measure wind flow and sediment transport over a nourished and a natural beach at Mariakerke-Bad and Koksijde respectively, along the Belgian coast, were made in 2016. Relationships have been obtained on the basis of the experiments. In general, the artificial beach has been nourished and was composed of medium-grained, well-sorted quartz sand. The median grain size was 310µm. The natural beach, backed by coastal dunes, was composed of fine-grained, well-sorted quartz sand. The median grain size was 235µm.

Based on the wind velocity measurements at the two study sites, a linear relationship is found for the shear velocity in terms of the wind speed at the 2m height. The coefficient depends critically on the height of the surface roughness. Greater roughness heights give a greater ratio between the shear velocity and wind speed at 2m height. It is important that the coefficient is used for beaches with roughness conditions similar to those for which the ratio was developed. However, results indicate that the surface roughness height, Z_0, is not constant per study site and is variable in time. The surface roughness is influenced by shell fragments, variation in grain size, micro-morphological changes of the beach surface, wind speed and wind direction. Therefore, measuring the wind profile still is a necessary tool to calculate surface roughness heights and shear velocities.

The results of the saltiphone counts related to the wind speed indicate that wind speed to the third power is the important forcing parameter when it comes to estimating Aeolian sand transport. An estimation of the threshold shear velocity can be determined based on the curve fitting of the datasets. It has to be mentioned that the position of the saltiphones above the surface has an important influence in the determination of the threshold shear velocity. At a certain critical wind speed, the lower saltiphone has more chance to register grain impacts that the saltiphone placed higher above the surface. Therefore, lower critical shear velocities are found of saltiphones closer to the surface.

When the traditional Bagnold model is applied on the datasets, overestimations of the observed sand flux are made. The model does not account for supply limitations and critical shear velocities. However, the critical shear velocity, based on our results is found to be 0.22m/s for the nourished study site and 0.16m/s for the natural study site. These values correspond with the critical shear velocities calculated by Bagnold's equation.

5. Further research

In the next two years, monthly field campaigns are scheduled covering the short-term Aeolian processes. This is combined with three-yearly long-term campaigns, typically two weeks, to identify and quantify Aeolian sand transport processes, controlling the post-recovery of the beach – dune system.

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