EFFECTS OF SHELLS ON AEOLIAN SEDIMENT TRANSPORT ON A NATURAL BEACH

Glenn Strypsteen, KU Leuven, glenn.strypsteen@kuleuven.be
Pieter Rauwoens, KU Leuven, pieter.rauwoens@kuleuven.be

INTRODUCTION
Studying aeolian sediment transport in coastal areas is challenging. Therefore, a location with a small number of supply-limiting elements (e.g., shells, moisture and vegetation) and a long fetch length is frequently chosen to allow for a better comparison of predicted and observed transport rates (Strypsteen et al., 2021). Many natural beaches, however, contain an abundance of shells and shell fragments/hash due to pounding and fracturing in the surf zone and literature on this topic is rather scarce. The majority of the existing literature on aeolian sediment transport across shells is based on wind tunnel experiments (e.g., Tan et al., 2013 and McKenna Neuman et al., 2012). Sometimes, observations in the field are described but are not directly measured as total mass fluxes with vertical sand traps (e.g., Hoonhout & de Vries, 2017). Direct field studies on the impact of shells on aeolian sediment transport rates have been limited. This study reports on a two-day measurement campaign on the upper beach of Koksijde, Belgium, where data on aeolian transport rates, mass flux profiles, surface moisture, wind conditions, and grain size distributions were collected. The goal of the experiment was to measure aeolian sand transport on the upper beach as input for dune growth and to find out how a shell pavement affected these transport rates during a strong, oblique onshore wind.

Figure 1 - Koksijde upper beach and dunes with MWAC traps and aeolian sand strips during a high transport event (image taken on 24/11/2016).

STUDY AREA
Detailed field measurements on aeolian sand transport rates, flux profiles, surface moisture, wind conditions, and grain size distributions were conducted on the upper beach of Koksijde (coastal section 50) in Belgium on November 24-25, 2016. Koksijde beach is located on the southwest side of the Belgian coast, close to the French border. The beach is natural and consists of sand (d_{50} = 220 µm) with small-scale bed irregularities (ripples) and many shell hash and shell fragments with heights ranging between a few millimeters to 30 mm on the upper beach (Figure 1).
Due to wave uprush, many patches of crushed, small, and large shells were present in a region 40 to 60 m in front of the dune foot. Larger crushed shells were more visible in front of the dune region, whereas smaller crushed shells were more concentrated near the high waterline. The study area is located in a dissipative macro-tidal environment, oriented from southwest to northeast direction and has seaward facing dunes.

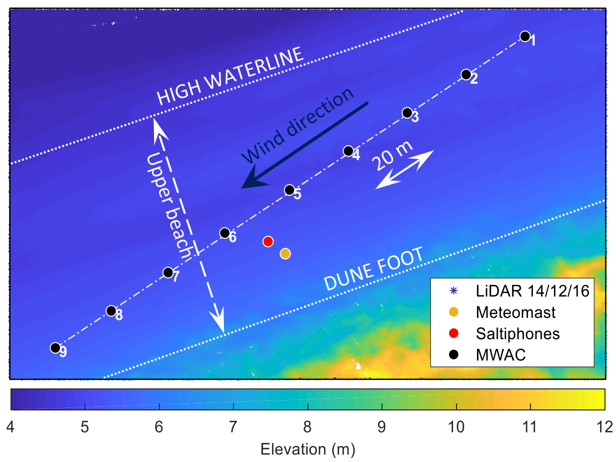

Figure 2 - Instrumentation placement: MWAC sand traps, meteorological station, and stacked saltiphones. The topography was obtained three weeks after the campaign (14/12/2016) via a LiDAR flight. All the instruments are located on the upper beach.

METHODOLOGY
Aeolian sand transport rate measurements were performed in a transect parallel to the prevailing NE wind direction which was highly oblique onshore. The spatial variation in sediment transport rates was measured in downwind direction on November 24, 2016 starting close to the high waterline, across the upper beach, towards the dune foot (Figure 2). To evaluate the rate of aeolian sand transport, nine Modified Wilson And Cook (MWAC) vertical sand traps were exposed to the sand-laden wind (Figure 1 and 2).
Four to five bottles were used at a height of 0.065, 0.135, 0.21, 0.285, and 0.54 m above the surface in the MWAC sand trap array. Each bottle has an 8 mm diameter glass inlet and outlet tube (≈ 50 mm² or 5.10^{-5} m²). To calculate transport rates in kg m^{-2} hr^{-1}, the mass of sand (in kg) collected in the bottle is divided by the inlet tube area (in m²) and exposed time (in hours). An efficiency factor was not used to correct trap values. The samples collected from the MWAC bottles were analyzed for grain size distribution. Topographic elevation was also measured along the transect at the beginning of the experiment.

Saltating sand grains were counted using two stacked high-frequency saltiphone sensors positioned at 0.05 m and 0.15 m above the beach surface. The total number of impacts was collected and stored every 20 seconds on a CR800 Campbell Scientific datalogger.

Wind speed and wind direction were measured using eight cup anemometers (Vector Instruments A100R) and a wind vane (Vector Instruments W200P) on a 3-m high meteorological station, positioned on the upper beach near the dunes.). The elevations of the cup anemometers were: 0.04, 0.22, 0.49, 0.91, 1.29, 1.67, 2.02 and 2.40 m respectively. The wind vane was installed at an elevation 2.02 m. The wind speed data were recorded once every 20 seconds and saved on the CR800 Campbell Scientific datalogger. The wind speed measurements were used to calculate the aerodynamic roughness length, z_0, and wind bed shear velocity, u_*, derived from the vertical log-wind profile.

Surface moisture content was determined in the upper 0.06 m of the sand surface with an ML3 ThetaProbe Soil Moisture Sensor at each MWAC sand trap.

The characteristics of the shells and shell-fragments were not determined but it was represented by complex and heterogeneous clustering. Qualitative evaluations were made by determining locations and coverages of the shells.

RESULTS

During the field campaign, the weather was dry and sunny, with a strong wind gusting to 14.6 m/s (measured at a height of 2.02 m above ground level, AGL). During the campaign, the temperature reached a high of 9 °C (Figure 3). The average wind speed for the entire experiment was 9.1 m/s (or u* = 0.51 m/s). The wind was highly oblique towards the dunes, with an average direction of 70 degrees north, or 8 degrees from the dune foot line. The tidal elevation ranged from 0 to +4 m TAW. Throughout the campaign, aeolian sand transport took the form of continuous streamers.

On November 24, the MWAC sand traps were subjected to high aeolian sand transport during two experiments. Experiment 1 began at 10:55 and ended at 12:40, for a total sampling time of 1 hour 45 minutes. The average wind speed (at 2.02 m AGL) and shear velocity during the first experiment were 10.4 m/s and 0.60 m/s, respectively. The upper intertidal beach was completely saturated with water an hour before the first experiment, resulting in measured moisture contents of up to 25%. As a result, the leading edge of erodible sediment was well defined, with the limit of wave up-rush defining the wet-dry boundary. During Experiment 1, aeolian sand transport began immediately from that boundary. Experiment 2 began at 12:40 and ended at 16:55, immediately following Experiment 1 (4 hours 15 minutes sampling time). During the second experiment, the average wind speed (at 2.02 m AGL) and shear velocity were 11.5 m/s and 0.68 m/s, respectively.

Significant spatial variations in transport rates were found along the transect with distance downwind. Figure 4 shows that the highest transport rates were found close to the high waterline (up to 230 kg/m/hr) and the lowest close to the dune region (down to 20 kg/m/hr).

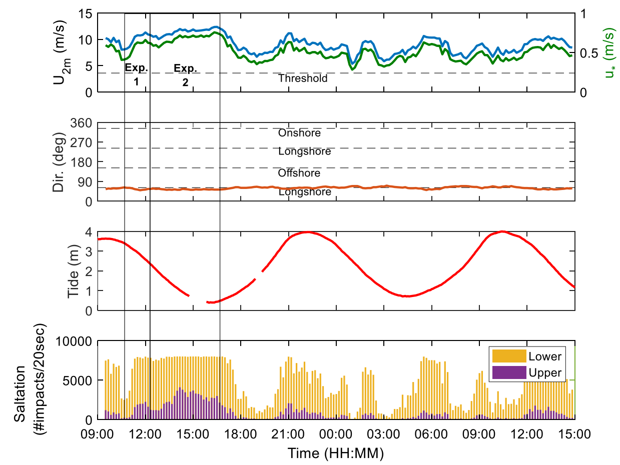

Figure 3 - 10-minute averaged time series of measured wind speed, shear velocity, wind direction, tide and saltation impacts during the entire field experiment. The threshold shear velocity is 0.24 m/s based on Bagnold (1954).

The general observed trend is that transport rate decreased downwind over a distance of 162 m by a factor of 10. Reduced sand transport rates resulted in localized sand deposition on the upper beach. This accumulation of sand was observed on top of the shell pavement in the form of large rippled sand strips with well sorted sand (see Figure 1).

The grain size of the transported sand (salting particles) along the transect was comparable in both experiments and was unaffected by the shells. The presence of roughness elements did not cause a deviation in the typical flux profiles, at least in the measuring range of the MWAC sand traps. The relatively consistent decay rate (less than 10% variation), along the transect also indicates that the roughness elements had little influence on the vertical distribution of sand particles.

Along the entire transect, the moisture content in the top 6 cm of the sand surface was consistently less than 4%. The moisture content in the top 2 cm was typically less than 1%. Figure 4 demonstrates that, in contrast to the transport rates observed between MWAC 4 and 5, there was a greater decrease in sand transport between MWAC 5 and 6 (about a factor of 2). The localized wetter surface conditions and shell cover (12% compared to 2% surface moisture) in that relatively small area were the main contributors to the larger decrease.

DISCUSSION

Fetch distance was not unrestricted at all traps, especially the traps close to the high waterline or wet-dry boundary (MWAC 1 to 2). It is possible that the fetch effect occurred at the first two upwind sand traps since the high waterline was approximately 40 m upwind of the first trap and sand transport commenced there. Even though wind speed during Experiment 2 was slightly higher than during Experiment 1, and fetch distance was longer due to a receding tide, maximum sand transport rate during Experiment 2 was lower. Presumably a maximum transport rate had been reached upwind of the sand traps. The significant reduction of aeolian sand transport further downwind (relative to MWAC 2 and 3) was caused by the dominant combination of an increase in bed roughness due to the shells and negative morphological feedback with the wind. Spatial variations between traps were caused by local differences in bed surface properties.

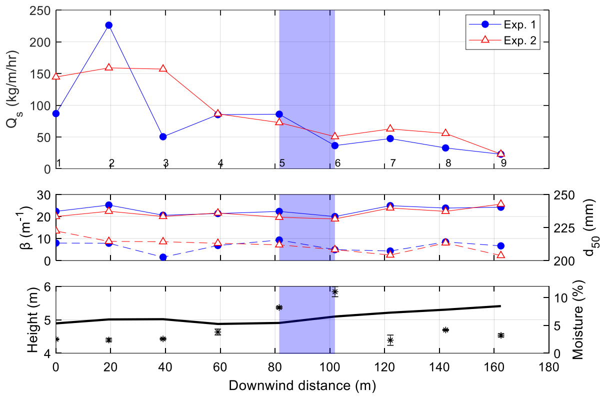

Figure 4 - Downwind measured transport rates, decay coefficient β, median grain size, and surface moisture.

Due to more larger shells downwind (based on visual observations), the remaining upwind sand grains were further being trapped. Saltation was being hampered to almost zero transport in front of the dune foot. According to McKenna Neuman et al. (2012), transport is reduced by a factor of 5 to 10 by increasing the cover of shells from about 15% to about 30-40% which was most likely the coverages found on the upper beach. Large shells are also more effective in hampering saltation than crushed shells which was found above the high waterline in this study in minor patches.

However, this study did not consider the measurement of shell coverages along the transect and thus has its limitations as a direct link between shell coverage and aeolian transport is missing. Wind tunnel and especially field experiments are therefore strongly recommended for expanding the knowledge of bed roughness factors and moisture on aeolian sediment transport on sandy beaches.

Because of the shells, the main cause of the sand transport reduction is most likely connected to a reduction in wind speed at the lowest layer above the sand surface (Van Rijn, 2022). This resulted in localized sand deposition on the upper beach in the form of large rippled sand strips with well sorted sand. This could explain the fairly consistent decay rate, β, along the measured transect partially covering the shells and thus limiting their influence on the vertical distribution and median grain size of saltating sand particles. The magnitude of the exponential decay rate in this study (> 20 m^{-1}) is what typically is found on other sandy beaches along the Belgian coast without the presence of shells or other roughness elements (Strypsteen et al., 2020).

Different environmental conditions were needed to be favorable for aeolian sand to reach the dunes. Hoonhout and de Vries (2017) observed similar findings on the Sand Motor and discussed that aeolian transport is a phased process. Aeolian sand from the intertidal beach is being deposited just above the high waterline which coincides with a berm and shell pavement. This area acts as a temporary source of sand to be transported by wind during different environmental conditions to the dunes. However, it is also possible that swash uprush during storm events may remove the sand accumulated on the upper beach.

CONCLUSIONS

Direct field studies on aeolian sand transport rates and the impact of a shell pavement have been limited. We conducted a field experiment across a large scattered shell pavement and conclude that:

- Aeolian sand transport dropped by a factor of 10 within a downwind distance of 162 m;
- The vertical distribution of saltating sand particles was unaffected by the roughness features and moist areas of sand;
- Across the beach, the median particle size of saltating sand above the surface was similar;
- The decrease in mass flux resulted in large rippled sand strips being deposited locally on the upper beach and served as a new source area for aeolian sand to be transported to the dunes;
- Although missing, future aeolian transport rate studies should always consider the measurement of shell characteristics and coverages as a direct link between shell coverage and aeolian transport is essential.

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