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Aeolian Sediment Flux Derived from a Natural Sand Trap

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ABSTRACT

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In 2011, a mega-nourishment (the 'Sand Motor') was constructed along the Dutch Coast. Since it is a pilot project, its evolution is closely monitored. This paper presents first results on the temporal variation in aeolian sediment transport across the nourishment, based on (a) the rate of infill over a 4 year period of a small lake in the nourishment, (b) one year of semi-hourly collected video imagery and (c) four year of hourly-averaged wind data. It appeared that, apart from approximately the first half year, the infill occurred quite linearly over time at an average rate of about $1.9 \cdot 10^4$ m^3/yr. The rate of infill in the first half year period was equivalent to an annual rate of $8.4 \cdot 10^4$ m^3/yr. From the combination of video image data and wind data, it was derived that aeolian sand transport (by saltation) was only observed at hourly averaged wind speeds of at least 7 m/s. The monthly frequency of occurrence of above 7 m/s wind speed, was reasonably well correlated with monthly frequency of occurrence of aeolian transport (r=0.79). Nevertheless, when hourly wind speed exceeded 7 m/s, transport was only observed about 23% of the time, indicating the importance of supply limiting conditions for aeolian transport from the Sand Motor.

ADDITIONAL INDEX WORDS: *Nourishment, aeolian sediment transport, video monitoring, meso-scale.*

INTRODUCTION

In 2011, a peninsula shaped, 21.5 Mm3 nourishment was constructed on the west coast of the Netherlands (Figure 1). It is a pilot project, named the Sand Motor, which is expected to protect multiple kilometers of coastline for approximately 20 years, which is much longer than regular nourishments. As dunes function as flood defense along large parts of the Dutch coast, one important aspect in this pilot is to assess and understand spatio-temporal variation in aeolian sand transport at the Sand Motor and its effect on dune development.

Dune development at the coast is the result of intermittently occurring transport events of both aeolian and marine origin. Due to the high elevation of the Sand Motor (Figure 2a), the development of the dunes backing the Sand Motor so far has only been influenced by aeolian bio-geomorphological processes, and this is expected to be so for the upcoming years. Therefore, spatio-temporal variation in aeolian sand supply from the Sand Motor may be an important explanatory factor in the development of dunes at the original coastline.

The study presented here aims at assessing the magnitude, and temporal variation therein, of longer term aeolian sediment flux across the mega-nourishment, and at identifying the conditions during which the contributing aeolian transport events do occur.

METHODS

On the nourishment, a small lake is present that acts as an effective 'natural' trap for aeolian sand transport (Figure 1 and Figure 2b,c). Topographic changes in this area are solely due to aeolian transport events, since there is no connection to the sea at any time. Therefore, the rate of infill can be used to quantify longer term aeolian sediment fluxes (Van der Weerd and Wijnberg, 2015). In our current study we consider a higher temporal resolution and a longer time span. Since August 2011, about every two months bathymetric and topographic surveys were done (by 'SHORE Monitoring & Research'). In this

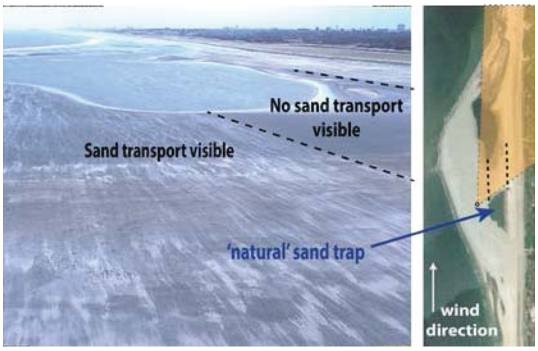

Figure 1. Natural sand trap at the Sand Motor. Left: Argus image (camera 1) showing aeolian streamers except in lee-side of the Lake area. Right: top view of the Sand Motor, showing the Lake that serves as a sand trap. Shaded area is field of view of Argus image.

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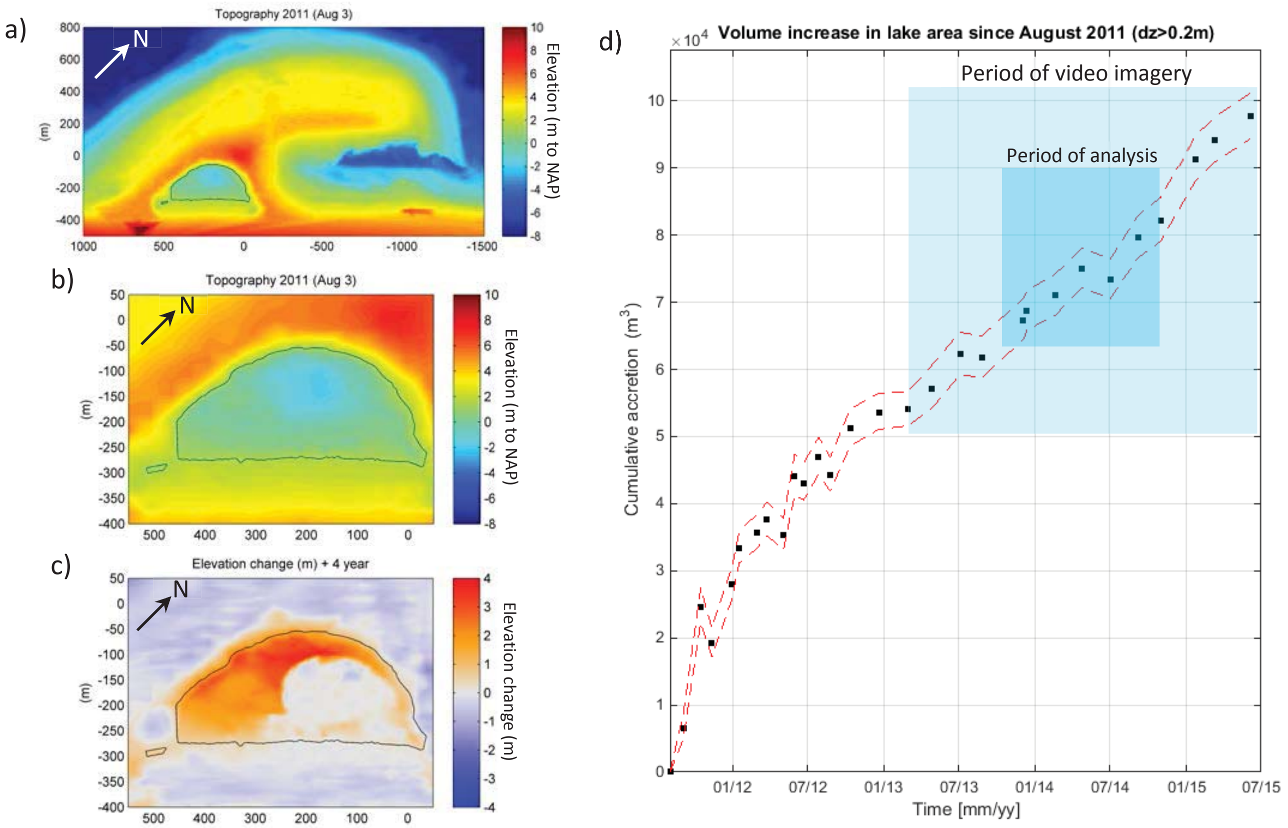

Figure 2. Volume changes in the lake area. (a) Topography Sand Motor area (Aug 3, 2011), (b) Topography lake area (Aug 3, 2011), (c) Four year elevation change in lake area since Aug 2011 survey, (d) Volume change in lake area since Aug 2011, with error band estimate (dashed lines).

study we used 29 surveys until June 2015 to obtain volume changes in the lake area. First, the elevation data were linearly interpolated to a 2x2m grid. Next, for all surveys the volume increase since August 3, 2011 was calculated for all grid cells in the accretionary part of the lake area where elevation change (since Aug 2011) exceeded +0.2 m. An error band for volume change was estimated by accounting for a 5 cm vertical offset (positive and negative) of the complete survey (pers. comm. surveyors *SHORE Monitoring & Research*). The contribution of the random error per survey point, and its propagation through interpolation, was assumed to approximately average out in the summation of volumes per grid cell to obtain total volume change.

To characterize the contributing transport events, Argus video imagery and wind data were used. In February 2013, an Argus video monitoring system consisting of 8 cameras, covering the seaward side of the mega nourishment and the lagoon area, was mounted on a 40 meter high tower in the middle of the Sand Motor. These cameras are taking snapshot and time-exposure images semi-hourly during daylight hours, and cover a large part of the Sand Motor surface. These images form a unique, high temporal resolution data set, covering both a long time period (*i.e.* several years) and a large spatial scale (*i.e.* almost the total Sand Motor area).

To identify which wind conditions lead to aeolian infill, we first visually identified the occurrence of aeolian transport from all snapshot images between November 1st 2013 and November 1st 2014, of the Northeasterly viewing camera. This period was chosen because it is a year without large gaps in image data. It also contains the period of the MegaPEX field campaign. For this period almost 9000 images were visually inspected.

Aeolian activity was identified by (i) presence of aeolian streamers and, during very high transport rates, (ii) the movement of aeolian bedforms. Every time, two consecutive images were compared to verify that bedforms had moved or that an isolated sediment 'cloud' (intermittently occurring during low transport conditions) was not some local, small-scale deposit of a preceding transport event.

The Northeasterly viewing camera was used because it is directed towards the quite low-lying surface near the lagoon (Figure 1), which generally has a darker color due to its moisture content. This dark color provides a good contrast with the dry, light-colored sand in transport. Especially during periods with low transport rates, streamers could be detected more easily here than on images from the other cameras.

Next, to characterize wind conditions during the identified transport events, hourly wind data of wind station "Hoek van

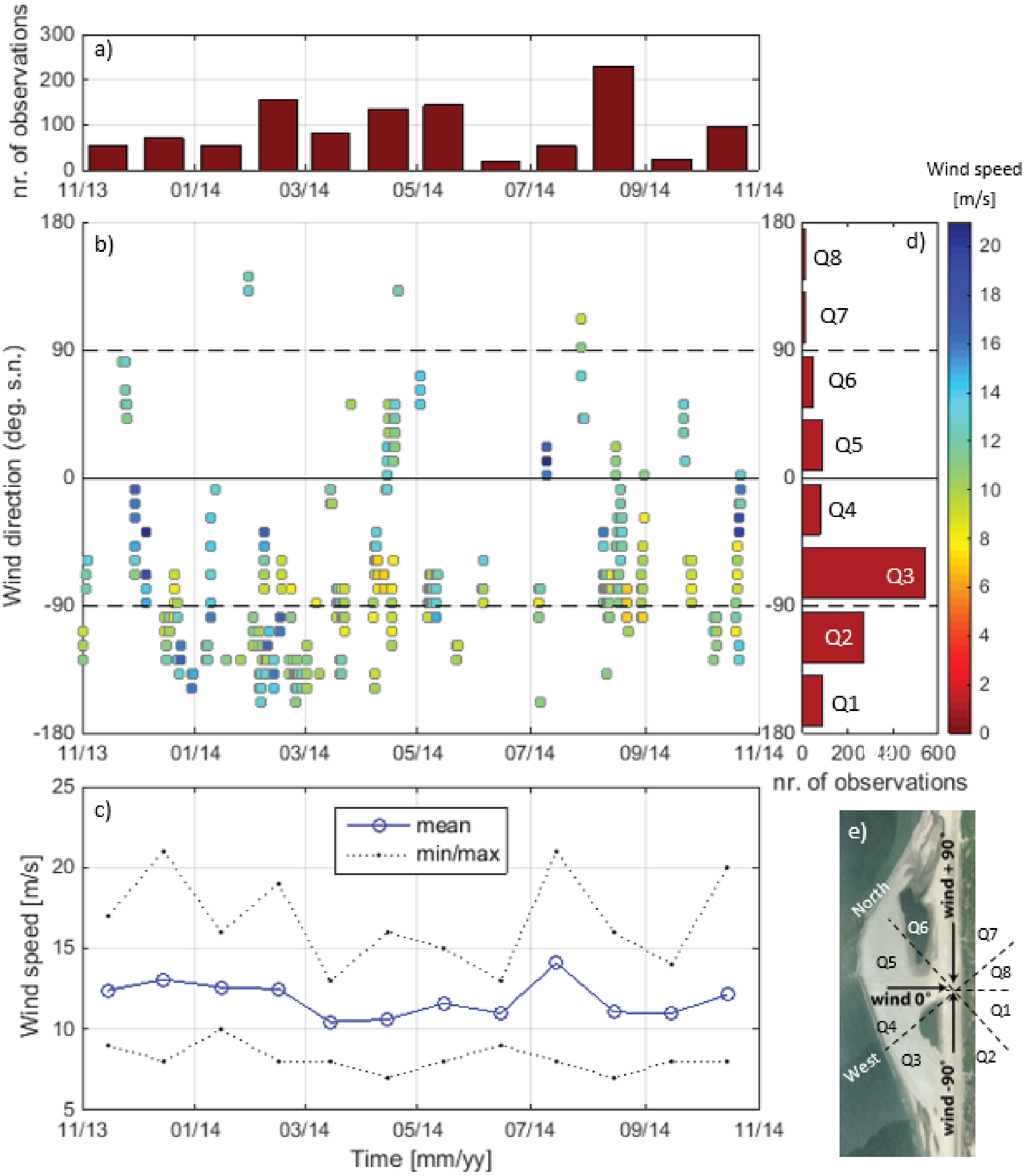

Figure3. Analysis of Argus images combined with wind data from Hoek van Holland. a) Monthly number of images on which transport was identified. b) Identified transport occurrences coupled to the co-occurring wind speed (color) and wind direction. c) Monthly wind statistics of wind conditions during transport, d) Number of transport events per directional sector, e) Definition sketch of wind direction and directional sectors.

Holland” (8 km south of study area), from the Royal Dutch Meteorological Institute were used. In this study we analyzed hourly averaged wind speed and direction. The wind directions were transformed such that 0º refers to the shore normal direction (Figure 3e), the shore normal (s.n.) direction being 318 degrees North. For images taken at the half hour, the wind data at the next full hour was used, as the hourly-averaged values refer to the preceding hour.

To assess the extent to which time-varying supply limitation may play a role in transport occurrence (*e.g.* sand surface conditions, availability of intertidal area as source area), we then summarized transport occurrences and above-threshold wind conditions into monthly statistics. The threshold wind condition was defined as the minimum wind speed for which transport was identified on the imagery. As transport events could only be identified during daylight, monthly wind statistics were adapted to apply to daylight hours only, ranging from only 8 hours in December and January, to 16 hours in June and July.

RESULTS

The sediment volumes in the lake area show an ongoing accretionary trend since August 2011 (Figure 2d). This observation is in line with Van der Weerd & Wijnberg (2015), who considered a 3 year period, instead of 4 year, and using annual surveys only. The higher temporal resolution used in this study revealed that the higher infill rate in the first year after construction can be attributed mostly to the first half of that year. Apart from the first half year, the infill occurred quite linearly over time at an average rate of about $1.9 \cdot 10^4$ m^3/yr. The rate of infill in the first half year period was equivalent to an annual rate of $8 \cdot 10^4$ m^3/yr. A possible explanation for this higher infill rate in the first half year could for instance be more windy conditions or different surficial sediment conditions right after construction. Before looking into this further, we first assessed the actual wind conditions during which transport occurred at the Sand Motor.

Figure 3b presents all transport occurrences identified on one year of image data, with co-occurring wind conditions in terms of hourly averaged wind speed (color) and direction. It appeared that about 12% of the time (daylight hours) aeolian transport activity was identified.

Regarding wind directions during transport, most of the transport events (72%) occurred with 'Southwesterly' quadrant (Q2, Q3) wind directions (Figure 3d). This observation matches well with the observed accretion pattern in the lake (Figure 2), supporting our assumption that the lake area is acting as an effective sand trap. Further, it can be derived that about one third (33%) of the transport events coincided with wind conditions that had an offshore directed component (Q1 ,Q2, Q7, Q8), hence blowing sand back into the sea.

In terms of wind speed, transport was observed to occur with hourly wind speeds from 7 m/s and up (Figure 3c). We therefore considered 7 m/s as the threshold wind speed for sand transport (by saltation) in our further analyses. The fact that this minimum wind speed for transport varied by month is most likely explained by the generally few transport events occurring per month, such as in June 2014 (Figure 3a). (An event being a set of consecutive hours with transport.) The onset or waning of the transport event may have been missed in a particular month due to daylight hour restrictions. Also, a particular transport event might actually have had a larger threshold wind speed, for instance due to coincidental rainfall.

To obtain further insight in the extent to which time-varying supply limitation may play a role in transport occurrence, we compared the monthly occurrence of above transport threshold wind speeds with the actual occurrence of transport events. Although the frequency of occurrence of above threshold wind speeds exhibited an obvious seasonal variation, this pattern disappeared when only daylight hours were considered (Figure 4a). This may partially explain why no obvious seasonal signal was seen in the monthly variation in number of transport observations (Figure 4a). It was found that the transport occurrences were reasonably well correlated (r=0.79) with the occurrence of above threshold wind speeds (considering only daylight hours) (Figure 4b). Nevertheless, when hourly wind speed exceeded 7 m/s during daylight, transport was only observed about a quarter of the time(23%). This indicates that supply limiting conditions, and temporal variation therein, play an important role for sand transport occurrence across this mega-nourishment.

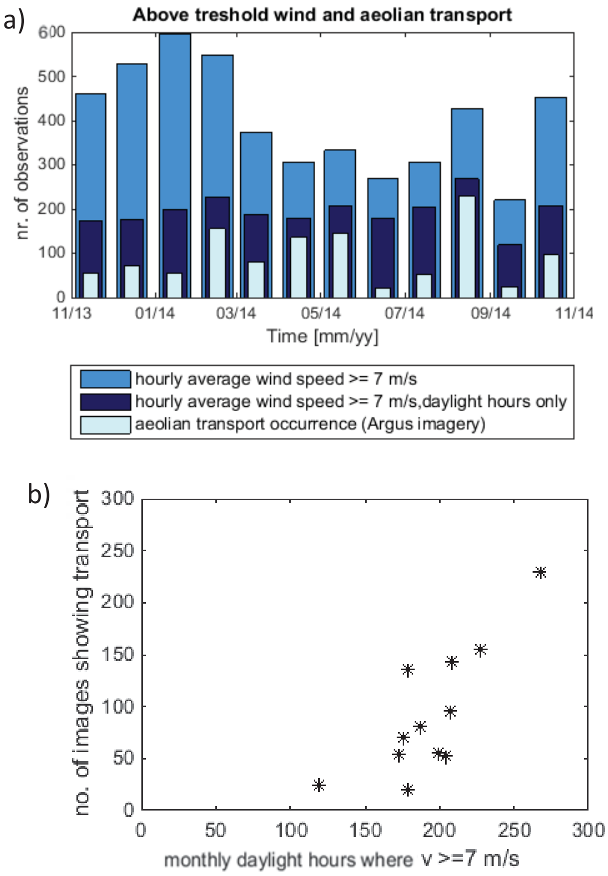

Figure 4. a) Monthly number of transport observations (from semi-hourly imagery), and monthly number of hours with wind speed above threshold speed for transport (7 m/s). b) Relationship between occurrence of transport and occurrence of above threshold wind speed during daylight hours.

Finally, returning to a possible explanation for the initially high rate of aeolian infill of the lake area, we looked into the number of hours of above threshold wind conditions in the first half year in comparison to other half year periods (Figure 5). The first six months did not have the most hours of above threshold wind speeds. However, when considering only the directional sectors that, according to the pattern of infill of the lake (Figure 2c), contributed most to the aeolian infill (Q2 to Q5), the first six months exhibited the most hours of above threshold wind speeds. Further study is needed, however, to address the magnitude of sand transport generated by these above threshold wind conditions.

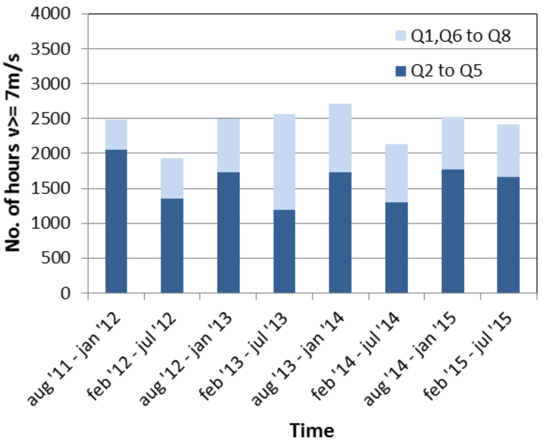

Figure 5. Temporal variation in the number of hours of above transport threshold wind conditions (≥ 7 m/s). Directional sectors Q1 to Q8 are defined in Figure 3e.

DISCUSSION

The use of video remote sensing is a powerful tool to link the scale of individual aeolian transport events to meso-scale aeolian sediment supply (*e.g.* Delgado-Fernandez and Davidson-Arnott, 2011). A limitation of using image data is that aeolian transport occurrence can only be identified as saltation occurs. Consequently, milder wind conditions during which only transport by creep occurs are not taken into account. Therefore, the 'threshold wind condition' we defined in this study cannot easily be compared to a threshold wind speed for initiation of motion.

The analysis in this study further showed that about 12% of the time aeolian transport occurred at the mega-nourishment during day-time. Assuming that day-time conditions for aeolian transport are representative of night-time conditions, this implies that per year, about 1000 hours of aeolian transport occurred.

With respect to the high transport rates in the first half year after construction, it is likely that apart from somewhat more windy conditions, also sediment sorting has played a role. A nourishment consists of unsorted sand of which the fines will be transported first, leaving coarser grains and shell fragments as an armoring layer at the surface of the nourishment (Van der Wal, 1998). Most likely this process contributed to the higher aeolian transport rates in the first half year after construction

CONCLUSIONS

In the first half year after construction of the Sand Motor mega-nourishment, the aeolian transport rates were highest, as the lake area filled in at a rate equivalent to an annual rate of $8{\cdot}10^4$ m^3/yr. In the years afterwards, transport rates decreased considerably, as the infill rate of the lake area reduced to about $1.9{\cdot}10^4$ m^3/yr. The first six months were somewhat more windy, but the large difference in infill rate is more likely explained by the sorting of the sand. Right after construction of the nourishment the fine sediment can be blown away, causing higher transport rates.

This study further showed that about 12% of the time aeolian transport (by saltation) occurred at the mega-nourishment, indicating that on an annual basis about 1000 hours of aeolian transport occurred. Transport events, occurring throughout the year, were dominated by winds from the South-West quadrant (72%), hence including obliquely offshore directed winds. In total, 33% of the transport events occurred during wind conditions with an offshore directed component, hence blowing sand back towards the sea.

From the combination of video image data and wind data, it was also derived that aeolian sand transport (by saltation) was only observed at hourly averaged wind speeds of at least 7 m/s. The monthly frequency of occurrence of above 7 m/s wind speed was reasonably well correlated with monthly frequency of occurrence of aeolian transport (r=0.79). Nevertheless, when hourly wind speed exceeded 7 m/s, transport was only observed about 23% of the time, indicating the importance of supply limiting conditions, and time variation therein, for aeolian transport from the Sand Motor

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