

1 Aeolian Sediment Supply at a Mega Nourishment

2 Bas Hoonhout^{a,b,*}, Sierd de Vries^a

3 ^a*Delft University of Technology, Faculty of Civil Engineering and Geosciences,*
4 *Department of Hydraulic Engineering, Stevinweg 1, 2628CN Delft, The Netherlands.*

5 ^b*Deltares, Department of Hydraulic Engineering, Boussinesqweg 1, 2629HV Delft, The*
6 *Netherlands.*

7 Abstract

Mega nourishments are intended to enhance growth and resilience of coastal dunes on medium to long time scales by stimulation of natural sediment transport processes. The growth and resilience of coastal dunes largely depends on the presence of a continuous supply of aeolian sediment. A recent example of a mega nourishment is the 21 Mm³ mega nourishment known as the Sand Motor. The Sand Motor is intended to nourish the entire Holland coast over a period of two decades. Four years of bi-monthly topographic measurements of the Sand Motor domain provide an opportunity to analyze spatiotemporal variations in aeolian sediment supply using an aeolian sediment budget analysis. It appears that 58% – 76% of all aeolian sediment deposits originate from the low-lying beaches that are regularly reworked by waves. Aeolian sediment supply from higher beaches diminished after half a year after construction of the Sand Motor, likely due to the formation of deflation lag deposits that constitute a beach armor layer. The compartmentalization of the Sand Motor in armored and unarmored surfaces suggests that the construction height is an important design criterion that influences the lifetime and region of influence for any mega nourishment.

8 *Keywords:* aeolian sediment transport; aeolian sediment supply; beach
9 armoring; sediment budgets; mega nourishment; Sand Motor

10 1. Introduction

11 Aeolian sediment supply is a prerequisite to growth and resilience of
12 coastal dunes that function as a natural protection against flooding from
13 the sea. Expanding human activities in coastal areas and growing uncertain-
14 ties related to climate change, increase coastal risks. Mitigation of these risks

15 resulted in the engineering of entire coastlines (Donchyts et al., 2016). Rigid
16 solutions and local nourishments are traditional solutions to a societal de-
17 mand for coastal safety (Hamm et al., 2002). With the increased confidence
18 in our ability to mitigate coastal risks, additional demands and functions for
19 coastal flood protections arose. Soft engineering solutions with limited en-
20 vironmental and ecological impact (Waterman, 2010; de Vriend et al., 2015)
21 gained preference over rigid solutions or local nourishments. Recently, the
22 exponent of soft engineering emerged as mega nourishments (Stive et al.,
23 2013). Mega nourishments pursue the idea of stimulating natural sediment
24 transport processes with the aim of increasing coastal safety. The idea is
25 based on the assumption that the incidental or concentrated interventions
26 necessary for the stimulation of nature are less intrusive than classic solu-
27 tions to coastal safety. Moreover, mega nourishments tend to accommodate
28 long-term monitoring and periodic adaptation and intervention that increases
29 flexibility with respect to planning and execution as well as the occurrence of
30 coastal hazards. The increased flexibility can make mega nourishments also
31 cost-effective (Van Slobbe et al., 2013).

32 The effectiveness of a mega nourishment depends on the sediment trans-
33 port pathways from nourishment to dunes. A small fraction of the sediment
34 moved in the nearshore ultimately arrives in the dunes (Aagaard et al., 2004).
35 It is this small aeolian sediment supply that provides us with the natural and
36 persistent coastal safety that mega nourishments aim for. In addition, this
37 small aeolian sediment supply gives coastal dune systems the natural re-
38 silience to storm impacts and the conditions for survival of persistent dune
39 vegetation that strengthens the dunes, like marram grass (Borsje et al., 2011).
40 It is also this small aeolian sediment supply that is least understood.

41 Mega nourishments affect aeolian sediment supply to coastal dunes in
42 various ways. First, sand used for nourishment is typically obtained from
43 offshore borrowing pits and differs from the original beach sand in terms
44 of size and composition, affecting the erodibility of the beach (van der Wal,
45 1998, 2000). Second, aeolian sediment availability (following the definition of
46 Kocurek and Lancaster, 1999) at beach nourishments that are constructed
47 above storm surge level can be significantly reduced by deflation lag de-
48 posits (Jackson et al., 2010). The absence of regular flooding and wave-
49 reworking allows lag deposits to develop a beach armor layer, resulting in
50 compartmentalization of the nourishment in armored and unarmored sur-
51 faces. McKenna Neuman et al. (2012) illustrated how deflation lag deposits
52 increase the shear velocity threshold significantly and reduce aeolian sedi-

ment availability and subsequently supply from the higher supratidal beach. Deflation lag deposits can therefore cause intertidal and low-lying supratidal beaches to gain importance over the high and dry beach as source of aeolian sediment. Third, the placement of a nourishment is known to affect nearshore processes (Grunnet and Ruessink, 2005; Ojeda et al., 2008; De Schipper et al., 2013). Synchronization between aeolian and nearshore processes, like onshore bar migration and welding, is reported to stimulate aeolian sediment supply to coastal dunes (Houser, 2009; Anthony, 2013). The importance of low-lying beaches as source of aeolian sediment might therefore also be affected by changing bar dynamics.

Jackson and Nordstrom (2011) emphasized the necessity for the quantification of the effect of large scale beach nourishment designs on aeolian sediment supply. Quantitative predictions of aeolian sediment availability and supply in coastal environments has proven to be challenging (Sherman et al., 1998; Sherman and Li, 2012). Limitations in aeolian sediment availability are often identified as reason for the discrepancy between measured and predicted sediment transport rates (Delgado-Fernandez et al., 2012; de Vries et al., 2014; Lynch et al., 2016).

Mega nourishments inherently cause spatiotemporal variations in aeolian sediment availability. The spatial variations are caused by compartmentalization of the beach. The temporal variations are induced by adaptation of the large coastal disturbance to the wave and wind climate, resulting in changing in beach width, slope and composition (de Schipper et al., 2016). Consequently, quantification of aeolian sediment availability and supply from mega nourishments requires differentiation in space and time.

This paper presents an aeolian sediment budget analysis of the 21 Mm³ Sand Motor mega nourishment based on four years of bi-monthly topographic surveys. The sediment budget analysis quantifies the net aeolian sediment supply to the dunes, dune lake and lagoon accommodated by the Sand Motor. The Sand Motor constitutes distinct areas that are either influenced by marine processes, by aeolian processes or by a combination of both. Therefore, the influence of marine and aeolian processes on aeolian sediment supply can be separated and spatiotemporal variations in aeolian sediment availability can be identified with reasonable accuracy. The observed compartmentalization of the Sand Motor is discussed in relation to limitations in aeolian sediment availability, as well as the design of mega nourishments like the Sand Motor as solution to coastal safety.

2. Field Site

The Sand Motor (or Sand Engine) is an artificial 21 Mm³ sandy peninsula protruding into the North Sea off the Delfland coast in The Netherlands (Figure 1, Stive et al., 2013). The Sand Motor is an example of a mega nourishment and is intended to nourish the Holland coast for a period of two decades, while stimulating both biodiversity and recreation.

The Sand Motor was constructed in 2011 and its bulged shoreline initially extended about 1 km seaward and stretched over approximately 2 km along the original coastline. The original coast was characterized by an alongshore uniform profile with a vegetated dune with an average height of 13 m and a linear beach with a 1:40 slope. The dune foot is located at a height of approximately 5 m+MSL.

Due to natural sediment dynamics the Sand Motor distributes about 1 Mm³ of sand per year to the adjacent coasts (Figure 1). The majority of this sand volume is transported by tides and waves. However, the Sand Motor is constructed up to 5 m+MSL and locally up to 7 m+MSL, which is in either case well above the maximum surge level of 3 m+MSL (Figure 2c). Therefore, the majority of the Sand Motor area is uniquely shaped by wind.

The Sand Motor comprises both a dune lake and a lagoon that act as large traps for aeolian sediment (Figure 1). The lagoon is affected by tidal forcing, although the tidal amplitude quickly diminished over time as the entry channel elongated. The tidal range of about 2 m that is present at the Sand Motor periphery (Figure 2c), is nowadays damped to less than 20 cm inside the lagoon (de Vries et al., 2015). Consequently, the tidal currents at the closed end of the lagoon, where most aeolian sediment is trapped, are negligible.

Sand used for construction of the Sand Motor is obtained from an offshore borrowing pit in the North Sea. The sand is predominantly Holocene sand with a significant amount of fines. The median grain size is slightly coarser than found originally along the Delfland coast. Apart from sand fractions, the sediment contains a large amount of shells, shell fractions, some pebbles and cobbles and an occasional fraction of a mammoth bone.

The dominant wind direction at the Sand Motor is south to southwest (Figure 2a). However, during storm conditions the wind direction tends to be southwest to northwest. During extreme storm conditions the wind direction tends to be northwest. Northwesterly storms are typically accompanied by significant surges as the fetch is virtually unbounded to the northwest, while

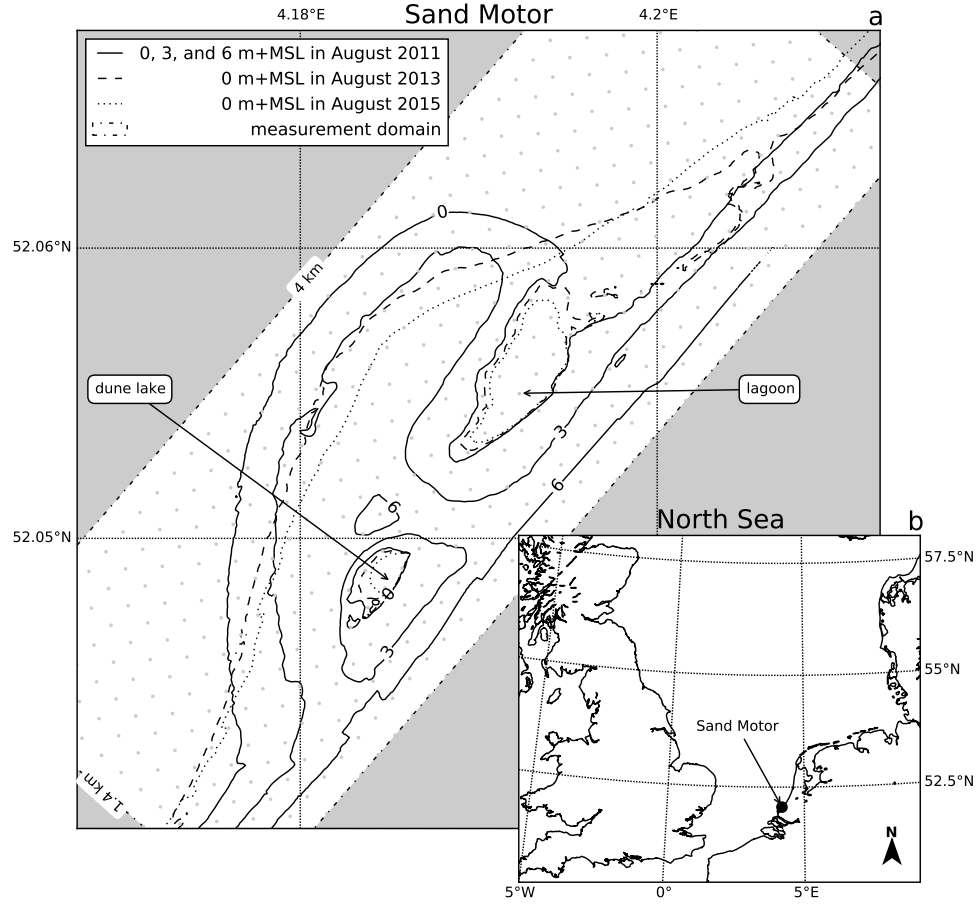


Figure 1: Location, orientation, appearance and evolution of the Sand Motor between construction in 2011 and 2015. The box indicates the measurement domain used in the remainder of this paper. A 100 x 100 m grid aligned with the measurement domain is plotted in gray as reference.

127 surges from the southwest are limited due to the presence of the narrowing
128 of the North Sea at the Strait of Dover (Figure 1, inset).

129 **3. Methodology**

130 Spatiotemporal variations in aeolian sediment supply in the Sand Motor
131 domain are identified using an aeolian sediment budget analysis. A sediment
132 budget analysis can be performed if frequent topographic measurements are
133 available (Davidson-Arnott and Law, 1990) and sediment exchange over the
134 border of the measurement domain is limited. In a sediment budget analysis
135 the morphological change in predetermined areas are converted to volumetric
136 changes (budgets) that are compared in a sediment volume balance.

137 A sediment budget analysis is particularly suitable for coastal sites with
138 a complex and dynamic topography, like the Sand Motor. The use of (dense)
139 topographic measurements ensures that any local variations in the topogra-
140 phy are included. Moreover, no assumptions on the local representativeness
141 of the measurements are needed and the methodology is applicable to a wide
142 range of spatial or temporal scales.

143 In the Sand Motor domain it is possible to separate the marine and aeolian
144 influence on erosion and deposition of sediment directly from a sediment
145 budget analysis. The high construction height of the Sand Motor and the
146 absence of regular storm surges in the first four years after construction
147 make that distinct areas exist that are either influenced by marine or aeolian
148 processes. The sediment budgets are determined along the borders of these
149 marine and aeolian zones.

150 *3.1. Topographic measurements*

151 32 topographic measurements of the Sand Motor domain obtained over
152 a period of four years are used to determine the overall sediment budget of
153 the Sand Motor domain (de Schipper et al., 2016). The measurement area
154 covers 1.4 km cross-shore and 4 km alongshore (Figure 1). The nearshore
155 bathymetry is surveyed using a jetski equipped with an echo sounder and
156 RTK-GPS receiver. The topography of the Sand Motor from the waterline
157 up to the dune foot is surveyed using an all-terrain vehicle (ATV) that is
158 also equipped with a RTK-GPS receiver. Inundated areas that are too shal-
159 low for the jetski, like the tidal channel and the dune lake, are surveyed
160 using a manually pushed RTK-GPS wheel. The survey is performed along

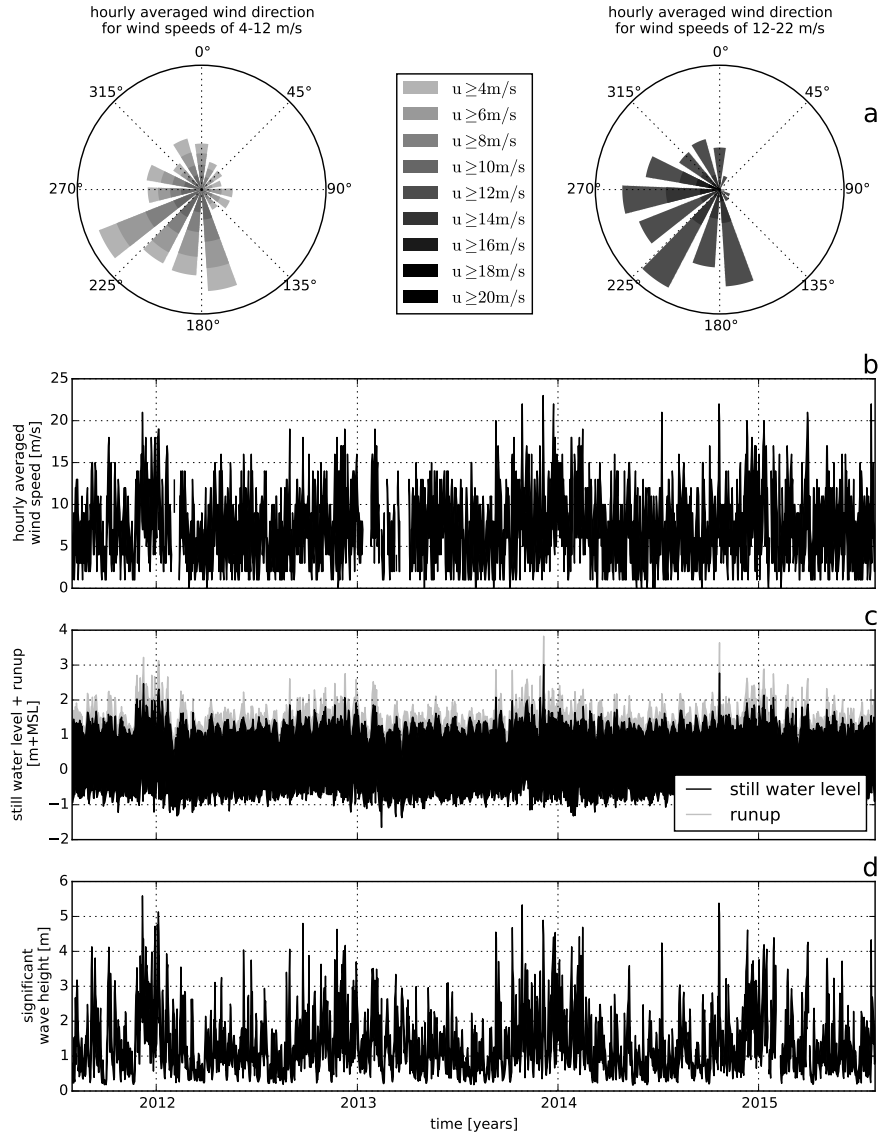


Figure 2: Wind and hydrodynamic time series from 2011 to 2015. Hourly averaged wind speeds and directions are obtained from the KNMI meteorological station in Hoek van Holland (upper panels). Offshore still water levels, wave heights and wave periods are obtained from the Europlatform (lower panels). Runup levels are estimated following Stockdon et al. (2006).

161 cross-shore transects that are 20 m apart. The resulting trajectories are in-
 162 terpolated to a regular 10 m x 10 m grid for the sediment budget analysis.
 163 Surveys that show a morphological rate of change that is more than two stan-
 164 dard deviations from the average are considered outliers. The measurements
 165 of September 4, 2011 and June 21, 2012 are discarded as outliers.

166 The topography in the dune area, which is not included in the RTK-GPS
 167 surveys, is monitored by airborne lidar. Half-yearly measurements from the
 168 southern Holland coast (Delfland coast) are available since 2011, prior to
 169 the construction of the Sand Motor. The lidar measurements have a spatial
 170 resolution of 2 m or 5 m. The measurements are corrected for the presence
 171 of vegetation and artificial objects, like beach pavilions, and interpolated to
 172 the same 10 m x 10 m grid and the same moments in time as the RTK-GPS
 173 measurements.

174 3.2. Zonation

175 The Sand Motor domain is divided into seven zones for the aeolian sedi-
 176 ment budget analysis (Table 1 and Figure 3). The zonation aims to separate
 177 areas with marine influences from areas without marine influences, and sep-
 178 arate areas with net aeolian erosion from areas with net aeolian deposition.

Table 1: Zonation of the Sand Motor domain into seven zones with and without marine influence. See also Figure 3.

<i>without</i> marine influence	<i>with</i> marine influence
aeolian zone	mixed zone (north)
dunes	mixed zone (south)
dune lake	marine zone
lagoon	

179 The zonation is based on the 0 m+MSL, 3 m+MSL and 5 m+MSL con-
 180 tour lines that roughly correspond to mean sea level, the edge of the berm or
 181 maximum runup level (Figure 2c) and the dune foot respectively. The con-
 182 tours are determined such that the spatial variance in the bed level change of
 183 the zones is minimized. The minimization ensures that the optimal division
 184 between erosion and deposition areas is found. Moreover, the 3 m+MSL and
 185 5 m+MSL contour lines have been relatively static since construction of the
 186 Sand Motor.

187 To ensure a constant shape and size of the zones during the analysis,
 188 the convex hull of all 3 m+MSL contour lines is used as zone boundary for

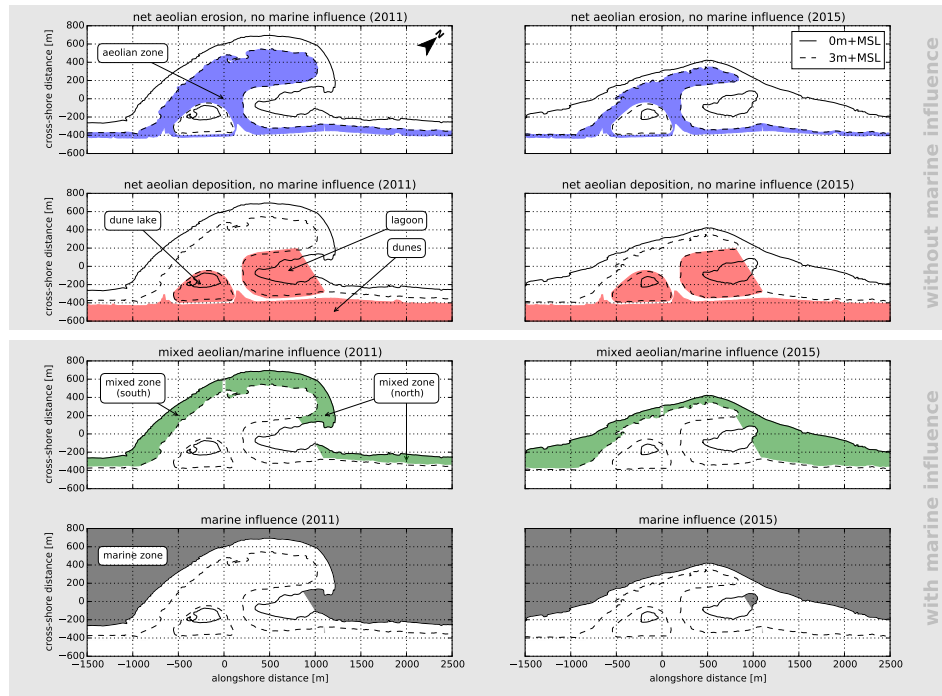


Figure 3: Zonation of the Sand Motor domain into zones with net aeolian erosion and no marine influence, net aeolian deposition and no marine influence, mixed aeolian/marine influence and marine influence. Left panels: 2011. Right panels: 2015.

189 the lake and lagoon. Also for the dunes minimal variations over time in
 190 zone shape and size are removed by using the most seaward position of all
 191 contour lines. Consequently, only the aeolian zone and mixed zones change
 192 in shape and size over time. The volumetric change between two consecutive
 193 measurements is determined for these zones within the smaller contour:

$$\Delta V^n = \hat{A}_c \cdot (\bar{z}_b^n - \bar{z}_b^{n-1}) \quad \text{where } \hat{A}_c = \min(A_c^n ; A_c^{n-1}) \quad (1)$$

194 with ΔV^n the volume change, A_c^n the surface area of the zone and \bar{z}_b^n the
 195 average bed level in the zone, all in time interval n . The (cumulative) sum
 196 over all time intervals of the volume changes in each zone is used in the
 197 analysis. By using the smaller of two contours in a comparison, a part of the
 198 larger contour is neglected:

$$A_{c,\text{neglected}}^n = \max(A_c^n ; A_c^{n-1}) - \hat{A}_c \quad (2)$$

199 The neglected area of the zone with the largest change in size, the aeolian
 200 zone, is on average 2% and never larger than 8%.

201 3.3. *Spatial variations in porosity*

202 The change in sediment volume is susceptible to changes in porosity. In
 203 order to relate the changes in sediment volume to the transport of sediment
 204 mass, variations in porosity need to be accounted for. Porosity values in the
 205 Sand Motor domain are obtained from core samples and used to account for
 206 the spatial variations in porosity. The core samples have a diameter of 8
 207 cm and depth of 10 cm from the bed surface in an attempt to capture the
 208 porosity in the aeolian active layer of the bed. Each sample is dried and
 209 submerged in water to determine the porosity. For comparison, all presented
 210 sediment volumes in this paper are converted to a hypothetical porosity of
 211 40% according to:

$$V_{40\%} = V \cdot \frac{1 - p}{1 - 40\%} \quad (3)$$

212 where V [m³] is the measured sediment volume and p [-] the porosity.

213 4. Results

214 The overall sediment budget of the Sand Motor domain is determined
 215 given morphological change in the net aeolian erosion and net aeolian de-

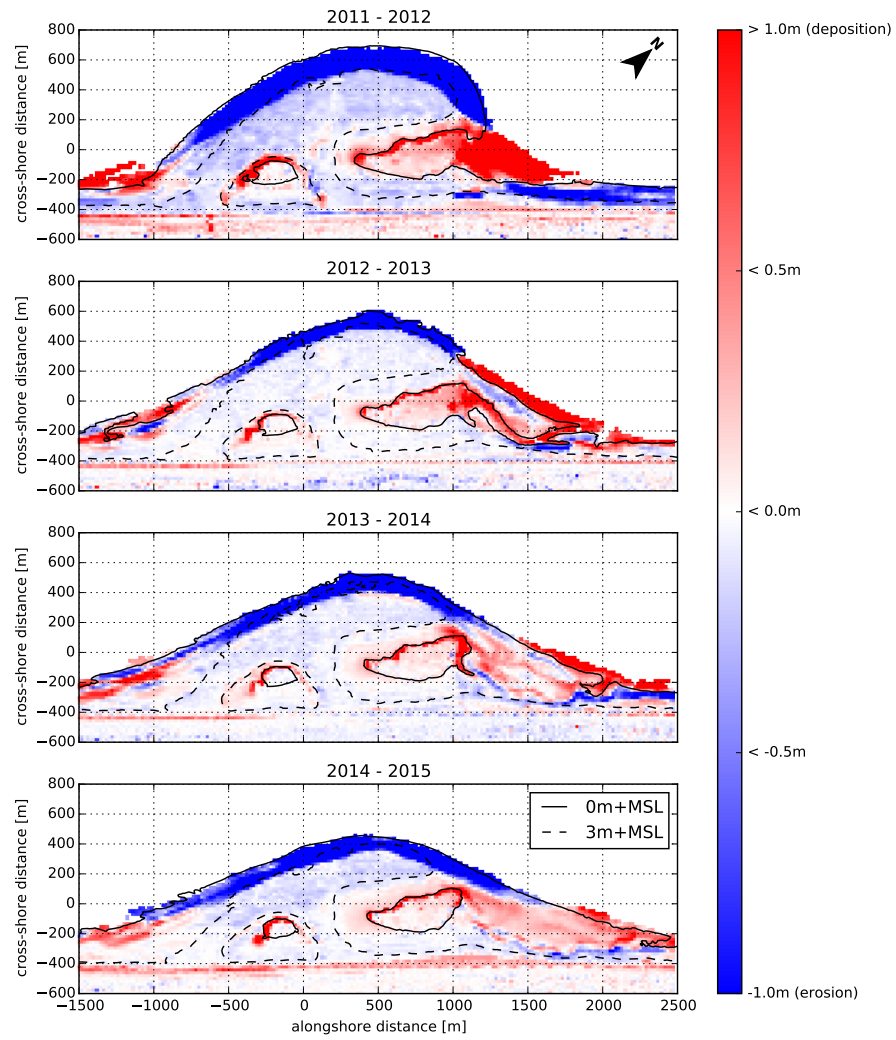


Figure 4: Yearly sedimentation and erosion above 0 m+MSL in the Sand Motor domain. Comparisons are made between the September surveys of each year.

Table 2: Measured porosity values in the Sand Motor domain. Each area is sampled at three different locations. The results per area are presented in ascending order. The last column presents the average porosity for each area that is used to convert the sediment volumes presented in this paper to a hypothetical porosity of 40%.

Area	Porosity			
	min.		max.	avg.
Aeolian zone	39.0%	39.4%	40.2%	39.5%
Mixed zone (north)	38.4%	39.8%	40.8%	39.7%
Mixed zone (south)	37.1%	38.4%	38.4%	38.0%
Dunes	36.1%	36.3%	37.1%	36.5%
Dune lake	34.7%	34.9%	36.3%	35.3%
Lagoon	46.3%	47.3%	49.0%	47.6%

position zones for the period between September 1, 2011 and September 1, 2015 (Figure 4).

4.1. Morphological change and porosity

The net morphological change within the 3 m+MSL contour can be accredited entirely to aeolian sediment transport as this area is not significantly affected by marine processes since the construction of the Sand Motor. Also the net contribution of alongshore sediment fluxes are assumed to be relatively small given that the beach width (< 100 m) is small compared to the alongshore span of the measurement domain (4 km). Within the 3 m+MSL contour sediment is deposited in the dunes and eroded from the aeolian zone.

The morphological change in the dune lake and the closed end of the lagoon is assumed to be driven predominantly by wind. Hydrodynamic forcing and consequently marine deposits in these zones diminished quickly over time, while significant amounts of fine aeolian deposits are found along the southwestern to northwestern shores.

The aeolian contribution to the morphological change in the mixed zones cannot be determined directly due to the presence of both marine and aeolian forces. However, by balancing the changes in sediment volume in the net aeolian deposition zones with the changes in sediment volume in the net aeolian erosion zones the aeolian sediment supply from the mixed zones is estimated.

18 porosity measurements from six zones (Table 2) are used to convert all measured sediment volumes to a hypothetical porosity of 40%.

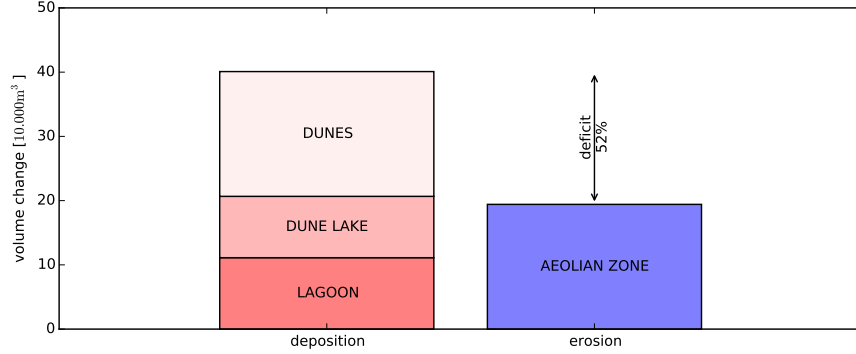


Figure 5: Aeolian sediment budgets in the Sand Motor domain in the period between September 1, 2011 and September 1, 2015.

239 4.2. Aeolian sediment budgets

240 The aeolian zone consistently provides less sediment than is deposited
 241 in the dunes, dune lake and lagoon (Figure 5). Over the four years since
 242 construction of the Sand Motor the volume deficit accumulates to $21 \cdot 10^4$
 243 m^3 , which is 52% of the total sediment accumulation of $40 \cdot 10^4 \text{ m}^3$. The
 244 total wind transport capacity (or cumulative theoretical sediment transport
 245 volume) in this period is roughly estimated as $110 \cdot 10^4 \text{ m}^3$ (Appendix A). As
 246 the actual sediment transport rates appear to be only about 35% of the wind
 247 transport capacity, the Sand Motor can be classified as an availability-limited
 248 system.

249 Late January 2012, the surveys show a net volume deficit of zero, while
 250 subsequent surveys show a more or less linear growth of the volume deficit
 251 (Figure 6). Fitting a linear trend reveals an average growth rate of $5.2 \cdot 10^4$
 252 m^3/yr , which is 67% of the total sediment accumulation rate of $7.7 \cdot 10^4$
 253 m^3/yr ($R^2 = 0.96$). The increase in growth rate of the volume deficit is
 254 likely caused by a significant decrease of the sediment contribution from the
 255 aeolian zone. The erosion from the aeolian zone in the first half year after
 256 construction of the Sand Motor exceeds the total erosion in the four years
 257 thereafter, while sediment continued to be accumulated in the dunes, dune
 258 lake and lagoon. The surface area of the aeolian zone decreased continuously
 259 (Figure 7).

260 The diminishing of the aeolian sediment supply from the aeolian zone
 261 is also reflected in the average bed level within the 3 m+MSL contour of

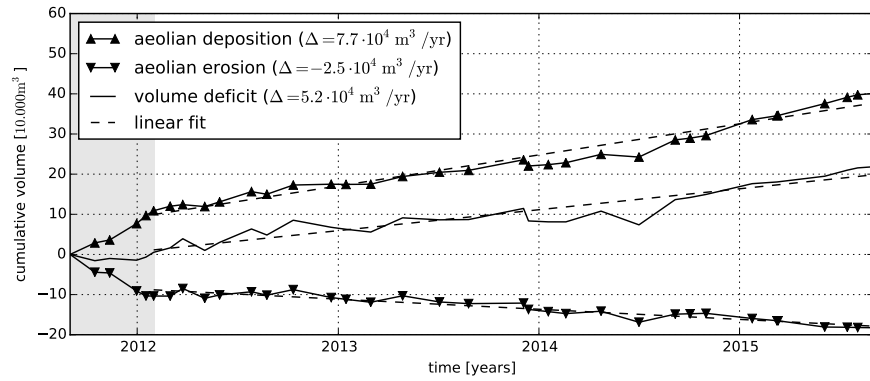


Figure 6: Cumulative change in sediment volume of all net aeolian erosion and net aeolian deposition zones and the volume deficit. For the linear fit the period prior to February 2012 is discarded (shaded).

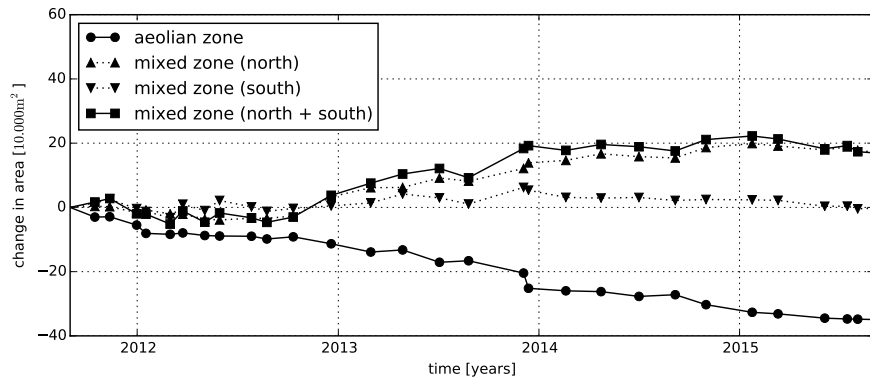


Figure 7: Change in size of aeolian zone and mixed zones since construction of the Sand Motor in 2011.

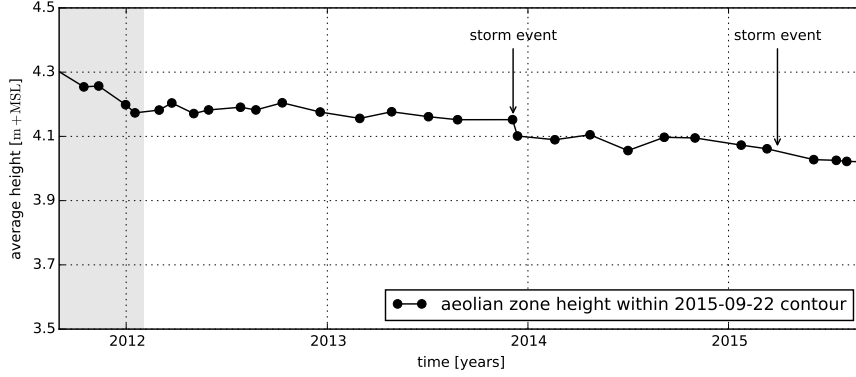


Figure 8: Average height of the aeolian zone in the most recent contour.

262 September 22, 2015 (Figure 8). The bed level within this contour has been
 263 almost constant since the volume deficit started to grow steadily from late
 264 January 2012. Only a few periods of significant erosion can be distinguished
 265 that can be related to storm events. Most notably, the event of December
 266 5, 2013 with wind speeds up to 34 m/s. That day $1.5 \cdot 10^4 \text{ m}^3$ of sediment
 267 was eroded from within the 3 m+MSL contour of September 22, 2015, which
 268 is 52% of the total erosion that year. Although this event is among the few
 269 events during which the runup levels exceeded the 3 m+MSL level (Figure
 270 2), the erosion can still be accredited to wind as the 3 m+MSL contour of
 271 September 22, 2015 was located about 100 m landward of the 3 m+MSL
 272 contour at the time of the storm event. Therefore the bed level in the more
 273 recent contour was not affected by the surge, which is confirmed by observa-
 274 tions from a local permanent camera station.

275 In general, the use of the 3 m+MSL contour as divide between the areas
 276 with and without marine influence appears to be valid for almost the entire
 277 four years after construction of the Sand Motor. Only four events have
 278 been registered in which runup levels exceeded the 3 m+MSL level (Figure
 279 2). Observations from a local permanent camera station indicate that only
 280 during the event of December 5, 2013 the surface of the aeolian zone was
 281 significantly affected by tides and waves. Pre- and post-storm topographic
 282 surveys that are available for this event indicate that the marine erosion from
 283 the flooded areas above the 3 m+MSL level was less than $1 \cdot 10^4 \text{ m}^3$.

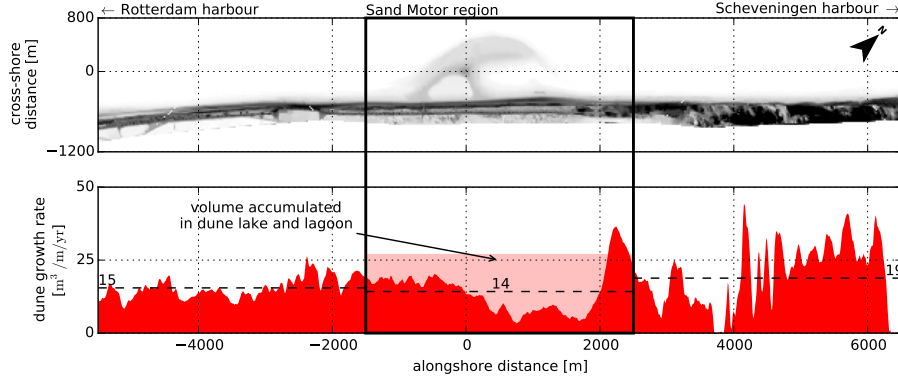


Figure 9: Comparison sediment accumulation rates in dunes (>3 m+MSL) for Sand Motor domain and adjacent coasts. Airborne lidar measurements from January 2012 until January 2015 are used. Horizontal dashed lines indicate local averages. The box indicates the Sand Motor domain depicted in previous figures.

284 4.3. Alongshore variation

285 The sediment deposits in the dunes show an alongshore variation. A
 286 depression in dune growth is observed in the lee of the dune lake and lagoon
 287 (Figure 9). South of the dune lake and in between the dune lake and lagoon
 288 a passage for aeolian sediment transport is present, which seems to result in
 289 a locally elevated dune growth. The average dune growth of $14 \text{ m}^3/\text{m}/\text{yr}$ in
 290 the Sand Motor domain is low compared to the dune growth rate along the
 291 adjacent southern ($15 \text{ m}^3/\text{m}/\text{yr}$) and northern ($19 \text{ m}^3/\text{m}/\text{yr}$) beach stretches.
 292 However, aeolian deposits in the dune lake and lagoon are of the same order
 293 of magnitude resulting in a total average sediment deposition of $27 \text{ m}^3/\text{m}/\text{yr}$
 294 in the Sand Motor domain, which is on average 56% higher than along the
 295 adjacent coasts.

296 5. Discussion

297 The volume deficit between the net aeolian erosion and net aeolian depo-
 298 sition zones can be accredited to the mixed zones that are affected by both
 299 marine and aeolian processes. The mixed zones in the Sand Motor domain
 300 are consequently estimated to provide 67% of the aeolian sediment in the
 301 Sand Motor domain. The aeolian sediment supply from the mixed zones is
 302 therefore significant, but still small compared to the 98% reported by Jackson

et al. (2010). The importance of the mixed zone cannot be explained by the size of the surface area as the mixed zones are initially smaller than the other main sediment source: the aeolian zone (Figure 7). Only from 2013 onward the surface area of the mixed zones exceed the area of the aeolian zone. However, the increase in surface area of the mixed zones is concentrated in the north where a low-lying spit develops (Figure 4). Given the dominant south to southwesterly wind direction and their position with respect to the lagoon that separates the spit from the dunes, it is unlikely that these intertidal beaches, provide a significant amount of sediment to dunes, dune lake and lagoon. Therefore, despite the periodic flooding and a size that is 40% – 60% smaller than the aeolian zone, the mixed zone (south) appears to provide the majority of the aeolian sediment in the Sand Motor domain.

5.1. Sources of inaccuracies

By accrediting the volume deficit to the mixed zones it is assumed that no sediment is exchanged over the boundaries of the Sand Motor domain and the sediment volume balance is thus closed. This assumption is not strictly valid, but the external sediment exchange with the Sand Motor domain is limited compared to the total sediment accumulation of $40 \cdot 10^4 \text{ m}^3$.

The predominantly southwesterly wind direction might blow sediment over the lateral borders that is not taken into account. However, the net alongshore sediment supply to the Sand Motor domain is estimated to be two orders smaller than the net onshore sediment supply, or less than 1% of the total sediment accumulation (Figure 10), because:

1. The onshore and alongshore sediment flux *per meter width* are estimated to be of the same order of magnitude (Appendix A), but the lateral beach cross-section ($< 100 \text{ m}$) through which the alongshore flux enters the Sand Motor domain at the southern border is an order of magnitude smaller than the alongshore span of the Sand Motor domain (4 km) through which the onshore flux enters the domain. Therefore, the absolute alongshore contribution to the total sediment volume balance is likely an order of magnitude smaller than the onshore contribution.
2. The contribution of the net alongshore sediment flux that enters the Sand Motor domain at the southern border is at least partially compensated by a net alongshore sediment flux of the same order of magnitude that leaves the domain at the northern border. Therefore, the

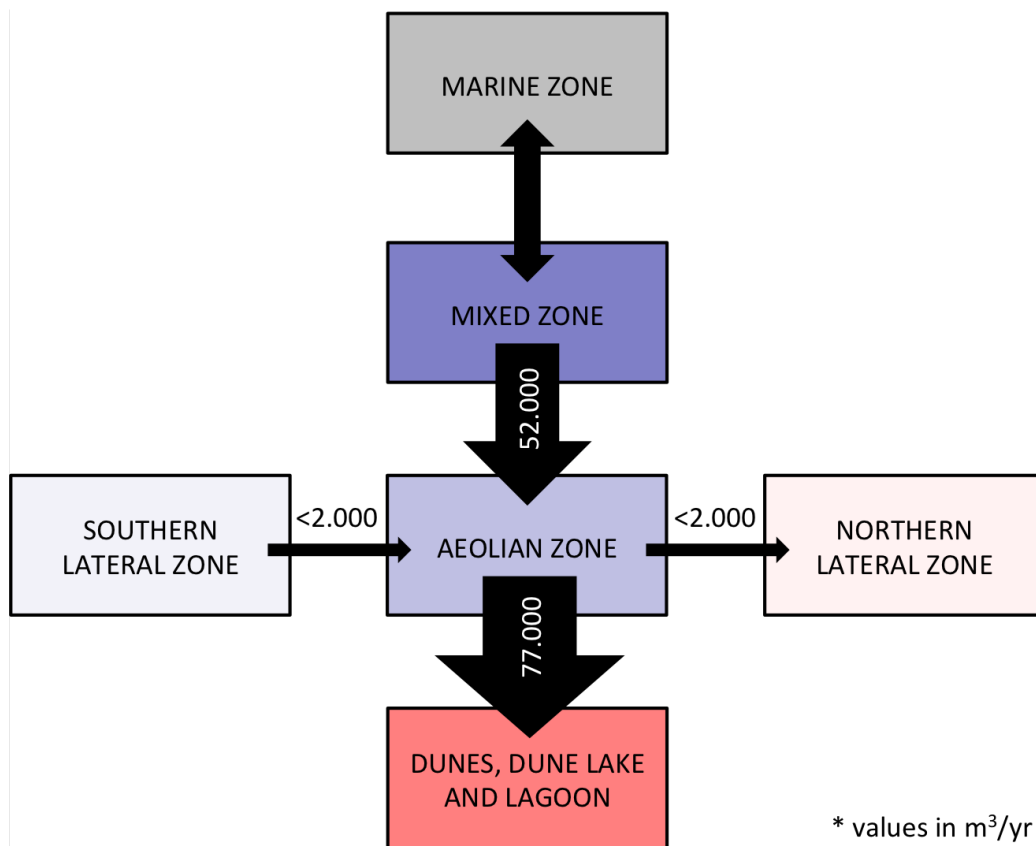


Figure 10: Aeolian sediment budget analysis of the Sand Motor

339 contribution to the total sediment volume balance of the southern and
340 northern alongshore sediment fluxes combined (alongshore sediment
341 transport gradient) is likely two orders of magnitude smaller than the
342 contribution of the onshore sediment flux.

343 In reality the contribution of the alongshore sediment fluxes is likely to be
344 even smaller as the sediment fluxes can locally be more onshore directed due
345 to local wind steering. In addition, the estimates of the order of magnitude
346 of the sediment fluxes are likely to be overestimated as possible limitations
347 in sediment availability are ignored.

348 The influence of marine deposits in the lagoon is estimated to be less
349 than 4% of the total sediment accumulation. 85% of the deposited sediment
350 in the lagoon has the form of a southwesterly infill protruding above water
351 and consisting of loosely packed, fine sediment and is therefore likely from
352 aeolian origin (Figure 4 and Table 2). 15% of the deposited sediment in the
353 lagoon, or 4% of the total sediment accumulation, is spread over a wider area
354 and is possibly from marine origin.

355 The influence of marine erosion of the aeolian zone during the limited
356 number of storm surges is estimated to be less than $1 \cdot 10^4 \text{ m}^3$ (Section 4.2),
357 or 2.5% of the total sediment accumulation. Similarly, the influence of the
358 changing size of the aeolian zone is estimated to be 2% of the total erosion in
359 this area (Section 3.2), or less than 1% of the total sediment accumulation.

360 In summary, the error that is introduced by assuming a closed sediment
361 volume balance is estimated to be less than 9% of the total sediment accu-
362 mulation. The volume deficit of 67% of the total sediment accumulation that
363 is accredited to aeolian erosion from the mixed zones therefore needs to be
364 nuanced and is estimated to be more than 58%.

365 5.2. Beach armoring

366 The relative importance of the mixed zones for aeolian sediment sup-
367 ply can likely be explained by a visually observed beach armor layer that
368 developed in the aeolian zone since construction of the Sand Motor. A
369 beach armor layer can reduce the availability of aeolian sediment significantly
370 (McKenna Neuman et al., 2012). Because the Sand Motor was constructed
371 several meters above common storm surge level, the aeolian zone has never
372 been influenced by waves or tides. Consequently, no process is present that
373 regularly resets the armor layer, except for the occasional high-energy wind

374 event. Moreover, salt crusts that form due to salt spray have a similar ef-
375 fect on the sediment availability as an armor layer. Small concentrations of
376 salt (≤ 7 mg/g) can already reduce the sediment availability by a factor two
377 (Nickling and Ecclestone, 1981).

378 In contrast, no beach armor layer or salt crusts develop in the mixed zones
379 as periodic flooding and related wave-reworking regularly deposit marine
380 sediments, mix the top layer of the bed, and wash shells and shell fragments
381 away. In addition, onshore bar migration and welding periodically provide
382 additional unarmored sediment that can be entrained by the wind during low
383 water (Houser, 2009; Anthony, 2013). However, aeolian sediment availability
384 in the mixed zones is also limited due to the relatively high soil moisture
385 contents in these areas. Also soil moisture content is known to increase the
386 shear velocity threshold (Wiggs et al., 2004; Edwards and Namikas, 2009;
387 Namikas et al., 2010) and limit the local aeolian sediment availability. Given
388 that the mixed zones appear to be a more important supplier of aeolian
389 sediment than the aeolian zone, limitations in sediment availability due to
390 beach armoring seems to outweigh limitations due to high moisture contents.

391 During a storm event even shell fragments and shells can be mobilized.
392 Consequently, the beach armor layer itself might be transported and its re-
393 ducing effect on the sediment availability is (partially) neutralized. Storm
394 events are regularly accompanied with surges that prevent wind erosion of
395 the mixed zones. Entrainment of sediment therefore starts at a relatively
396 high point along the fetch and much of the sediment transport capacity can
397 be used for erosion of the aeolian zone, which contributes to the removal of
398 the beach armor layer. If the surge is high enough it can also remove the
399 beach armor layer by wave action or bury it by deposition of marine sedi-
400 ments. The removal or burial of the beach armor layer can elevate sediment
401 availability from the aeolian zone also after the the storm passed. Only af-
402 ter development of a new beach armor layer the sediment availability and
403 transport rates approach the pre-storm situation.

404 5.3. *Mega nourishments as coastal protection*

405 The Sand Motor mega nourishment shows a morphological development
406 that is significantly different from natural beaches or the original Delfland
407 coast. Aeolian sediment supply at the Sand Motor shows larger spatial vari-
408 ations compared to natural beaches, while dune growth rates lag behind
409 compared to the adjacent coastal stretches. It can be questioned if such
410 exotic behavior is desired for a coastal protection that aims to stimulate

411 natural processes, or that, for example, it would be beneficial not to con-
412 struct future mega nourishments above local storm surge level and prevent
413 compartmentalization of the beach.

414 In this context, it is interesting to consider what would happen if the
415 Sand Motor was constructed up to local storm surge level (3 m+MSL). The
416 vast aeolian zone would not exist as the entire Sand Motor would be flooded
417 at least once a year. Compartmentalization would be minimized and aeolian
418 sediment availability be maximized as the formation of deflation lag deposits
419 is counteracted by wave-reworking. The dune lake and lagoon would be
420 filled in up to three times faster due to transport-limited aeolian sediment
421 supply. Soon, all aeolian sediment transport pathways would end in the
422 dunes, resulting in an up to six times larger dune growth than currently
423 observed. Marine sediment transport would enhance these relatively rapid
424 changes as more sediment is redistributed within the Sand Motor domain to
425 the lagoon, dune lake and offshore by overwash.

426 A lower construction height of the Sand Motor would therefore result in
427 a more rapid and more localized redistribution of sediment. Both rapid and
428 localized redistribution are at odds with the purpose of the Sand Motor to
429 nourish the entire Holland coast over a period of two decades. The static
430 behavior of the supratidal areas of Sand Motor might therefore prove to be
431 a crucial design criterion of a mega nourishment.

432 6. Conclusions

433 A sediment budget analysis is used to identify spatial variations in aeolian
434 sediment deposition and supply, and dune growth in the Sand Motor domain.
435 From the analysis the following conclusions can be drawn regarding aeolian
436 sediment transport and supply in the Sand Motor domain:

- 437 1. The (southern) low-lying beaches that are affected by both aeolian and
438 marine processes (mixed zone) currently supply more than 58% of all
439 aeolian sediment deposits in the Sand Motor domain, despite that this
440 area is periodically flooded and 40% – 60% smaller than the upper dry
441 beach areas (aeolian zone) that are only affected by aeolian processes
442 and supply less than 42% of the aeolian deposits;
- 443 2. The aeolian sediment supply from the aeolian zone diminished in the
444 first half year after construction of the Sand Motor, likely due to the
445 development of a beach armor layer;

- 446 3. The aeolian sediment supply from the aeolian zone tends to increase
447 temporarily during and after a storm event, likely due to (partial) re-
448 moval of the beach armor layer;
- 449 4. The dune growth in the Sand Motor domain is low compared to the
450 adjacent coasts, likely due to blocking of aeolian sediment transport
451 pathways by the dune lake and lagoon.

452 From the analysis the following conclusions can be drawn regarding mega
453 nourishments in general:

- 454 1. The construction height should be a design criterion of any mega nour-
455 ishment as it governs compartmentalization of the beach due to beach
456 armoring;
- 457 2. Compartmentalization of the beach can influence the lifetime and re-
458 gion of influence of a mega nourishment as it affects the balance between
459 local aeolian deposition and regional marine spreading of sediment.
- 460 3. The consequences of compartmentalization is not yet fully understood
461 as the contribution of the upper dry beach (aeolian zone) to local ae-
462 olian sediment supply can range from 42% as observed at the Sand
463 Motor to less than 2% as reported by Jackson et al. (2010).

464 Acknowledgements

465 The work discussed in this paper is supported by the ERC-Advanced
466 Grant 291206 – Nearshore Monitoring and Modeling (NEMO).

467 A. Theoretical Sediment Transport Volumes

468 The cumulative theoretical sediment transport volume Q [m³] in the Sand
469 Motor domain between September 1, 2011 and September 1, 2015 is esti-
470 mated from hourly averaged measured wind speed u_{10} [m/s] and direction
471 θ_u [°] measured at 10 m height by the KNMI meteorological station in Hoek
472 van Holland (Figure 2). The wind time series are used in conjunction with
473 the formulation of Bagnold (1937) to obtain the instantaneous theoretical
474 sediment transport rate q [kg/m/s] following:

$$q = C \frac{\rho_a}{g} \sqrt{\frac{d_n}{D_n}} (u_* - u_{*th})^3 \quad (\text{A.1})$$

475 with the shear velocity $u_* = \alpha \cdot u_{10}$ m/s, the shear velocity threshold $u_{*th} =$
476 $\alpha \cdot 3.87$ m/s, the conversion factor from free-flow wind velocity to shear
477 velocity $\alpha = 0.058$, the air density $\rho_a = 1.25$ kg/m³, the particle density ρ_p
478 $= 2650.0$ kg/m³, the gravitational constant $g = 9.81$ m/s², the nominal grain
479 size $d_n = 335$ μ m and a reference grain size $D_n = 250$ μ m.

480 The cumulative theoretical sediment transport volumes in onshore (Q_{os}
481 [m³]) and alongshore (Q_{as} [m³]) direction are computed by time integration
482 and conversion from mass to volume following:

$$\begin{aligned} Q_{os} &= \sum q \cdot \frac{\Delta t \cdot \Delta y}{(1-p) \cdot \rho_p} \cdot f_{\theta_u, os} = 110 \cdot 10^4 \text{ m}^3 \\ Q_{as} &= \sum q \cdot \frac{\Delta t \cdot \Delta x}{(1-p) \cdot \rho_p} \cdot f_{\theta_u, as} = 3 \cdot 10^4 \text{ m}^3 \end{aligned} \quad (\text{A.2})$$

483 where the temporal resolution $\Delta t = 1$ h, the alongshore span of the mea-
484 surement domain $\Delta y = 4$ km, the approximate lateral beach width $\Delta x =$
485 100 m, the porosity $p = 0.4$ and $f_{\theta_u, os}$ and $f_{\theta_u, as}$ are factors to account for
486 respectively the onshore and alongshore wind directions only, defined as:

$$\begin{aligned} f_{\theta_u, os} &= \max(0 ; \cos(312^\circ - \theta_u)) \\ f_{\theta_u, as} &= \sin(312^\circ - \theta_u) \end{aligned} \quad (\text{A.3})$$

487 where θ_u [°] is the hourly averaged wind direction and 312° accounts for
488 orientation of the original coastline.

489 Note that the difference between the onshore and alongshore cumula-
490 tive theoretical sediment transport volumes (Equation A.2) of a factor 40
491 is determined solely by the difference between the onshore and alongshore
492 cross-sections of 4 km and 100 m respectively. The sediment transport vol-
493 umes per meter width in onshore and alongshore direction are of the same
494 order of magnitude (275 m³/m and 267 m³/m respectively).

495 References

- 496 Aagaard, T., Davidson-Arnott, R., Greenwood, B., and Nielsen, J. (2004).
497 Sediment supply from shoreface to dunes: linking sediment transport
498 measurements and long-term morphological evolution. *Geomorphology*,
499 60(1):205–224. doi:10.1016/j.geomorph.2003.08.002.
- 500 Anthony, E. J. (2013). Storms, shoreface morphodynamics, sand supply, and
501 the accretion and erosion of coastal dune barriers in the southern north
502 sea. *Geomorphology*, 199:8–21. doi:10.1016/j.geomorph.2012.06.007.

- 503 Bagnold, R. (1937). The transport of sand by wind. *Geographical journal*,
504 pages 409–438.
- 505 Borsje, B. W., van Wesenbeeck, B. K., Dekker, F., Paalvast, P., Bouma, T. J.,
506 van Katwijk, M. M., and de Vries, M. B. (2011). How ecological engineering
507 can serve in coastal protection. *Ecological Engineering*, 37(2):113–122.
508 doi:10.1016/j.ecoleng.2010.11.027.
- 509 Davidson-Arnott, R. G. and Law, M. N. (1990). *Seasonal patterns and con-*
510 *trols on sediment supply to coastal foredunes, Long Point, Lake Erie*, pages
511 177–200. Wiley Chichester.
- 512 De Schipper, M., De Vries, S., Ranasinghe, R., Reniers, A., and Stive, M.
513 (2013). Alongshore topographic variability at a nourished beach. In *Coastal*
514 *Dynamics 2013: 7th International Conference on Coastal Dynamics, Ar-*
515 *cachon, France, 24-28 June 2013*. Bordeaux University.
- 516 de Schipper, M. A., de Vries, S., Ruessink, G., de Zeeuw, R. C., Rutten, J.,
517 van Gelder-Maas, C., and Stive, M. J. (2016). Initial spreading of a mega
518 feeder nourishment: Observations of the sand engine pilot project. *Coastal*
519 *Engineering*, 111:23–38. doi:10.1016/j.coastaleng.2015.10.011.
- 520 de Vriend, H. J., van Koningsveld, M., Aarninkhof, S. G., de Vries, M. B., and
521 Baptist, M. J. (2015). Sustainable hydraulic engineering through build-
522 ing with nature. *Journal of Hydro-environment Research*, 9(2):159–171.
523 doi:10.1016/j.jher.2014.06.004.
- 524 de Vries, S., Arens, S. M., de Schipper, M. A., and Ranasinghe, R. (2014).
525 Aeolian sediment transport on a beach with a varying sediment supply.
526 *Aeolian Research*, 15:235–244. doi:10.1016/j.aeolia.2014.08.001.
- 527 de Vries, S., Radermacher, M., de Schipper, M., and Stive, M. (2015). Tidal
528 dynamics in the sand motor lagoon. In *E-proceedings of the 36th IAHR*
529 *World Congress*.
- 530 Delgado-Fernandez, I., Davidson-Arnott, R., Bauer, B. O., Walker, I. J.,
531 Ollerhead, J., and Rhew, H. (2012). Assessing aeolian beach-surface dy-
532 namics using a remote sensing approach. *Earth Surface Processes and*
533 *Landforms*, 37(15):1651–1660. doi:10.1002/esp.3301.

- 534 Donchyts, G., Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J., and
535 van de Giesen, N. (2016). Earth’s surface water change over the past 30
536 years. *Nature Climate Change*, 6(9):810–813. doi:10.1038/nclimate3111.
- 537 Edwards, B. L. and Namikas, S. L. (2009). Small-scale variability in sur-
538 face moisture on a fine-grained beach: implications for modeling aeo-
539 lian transport. *Earth Surface Processes and Landforms*, 34:1333–1338.
540 doi:10.1002/esp.1817.
- 541 Grunnet, N. M. and Ruessink, B. (2005). Morphodynamic response of
542 nearshore bars to a shoreface nourishment. *Coastal Engineering*, 52(2):119–
543 137. doi:10.1016/j.coastaleng.2004.09.006.
- 544 Hamm, L., Capobianco, M., Dette, H., Lechuga, A., Spanhoff, R., and Stive,
545 M. (2002). A summary of european experience with shore nourishment.
546 *Coastal engineering*, 47(2):237–264. doi:10.1016/S0378-3839(02)00127-8.
- 547 Houser, C. (2009). Synchronization of transport and supply in beach-
548 dune interaction. *Progress in Physical Geography*, 33(6):733–746.
549 doi:10.1177/0309133309350120.
- 550 Jackson, N. L. and Nordstrom, K. F. (2011). Aeolian sediment transport
551 and landforms in managed coastal systems: a review. *Aeolian research*,
552 3(2):181–196. doi:10.1016/j.aeolia.2011.03.011.
- 553 Jackson, N. L., Nordstrom, K. F., Saini, S., and Smith, D. R. (2010). Effects
554 of nourishment on the form and function of an estuarine beach. *Ecological*
555 *Engineering*, 36(12):1709–1718. doi:10.1016/j.ecoleng.2010.07.016.
- 556 Kocurek, G. and Lancaster, N. (1999). Aeolian system sediment state: theory
557 and mojave desert kelso dune field example. *Sedimentology*, 46(3):505–515.
558 doi:10.1046/j.1365-3091.1999.00227.x.
- 559 Lynch, K., Jackson, D. W., and Cooper, J. A. G. (2016). The fetch effect
560 on aeolian sediment transport on a sandy beach: a case study from mag-
561 illigan strand, northern ireland. *Earth Surface Processes and Landforms*.
562 doi:10.1002/esp.3930.
- 563 McKenna Neuman, C., Li, B., and Nash, D. (2012). Micro-
564 topographic analysis of shell pavements formed by aeolian transport in

- 565 a wind tunnel simulation. *Journal of Geophysical Research*, 117(F4).
 566 doi:10.1029/2012JF002381. F04003.
- 567 Namikas, S. L., Edwards, B. L., Bitton, M. C. A., Booth, J. L., and
 568 Zhu, Y. (2010). Temporal and spatial variabilities in the surface mois-
 569 ture content of a fine-grained beach. *Geomorphology*, 114:303–310.
 570 doi:10.1016/j.geomorph.2009.07.011.
- 571 Nickling, W. G. and Ecclestone, M. (1981). The effects of soluble salts on
 572 the threshold shear velocity of fine sand. *Sedimentology*, 28:505–510.
- 573 Ojeda, E., Ruessink, B., and Guillen, J. (2008). Morphodynamic response
 574 of a two-barred beach to a shoreface nourishment. *Coastal Engineering*,
 575 55(12):1185–1196. doi:10.1016/j.coastaleng.2008.05.006.
- 576 Sherman, D. J., Jackson, D. W., Namikas, S. L., and Wang, J. (1998).
 577 Wind-blown sand on beaches: an evaluation of models. *Geomorphology*,
 578 22(2):113–133. doi:10.1016/S0169-555X(97)00062-7.
- 579 Sherman, D. J. and Li, B. (2012). Predicting aeolian sand trans-
 580 port rates: a reevaluation of models. *Aeolian Research*, 3(4):371–378.
 581 doi:10.1016/j.aeolia.2011.06.002.
- 582 Stive, M. J. F., de Schipper, M. A., Luijendijk, A. P., Aarninkhof, S. G. J.,
 583 van Gelder-Maas, C., van Thiel de Vries, J. S. M., de Vries, S., Henriquez,
 584 M., Marx, S., and Ranasinghe, R. (2013). A new alternative to saving our
 585 beaches from sea-level rise: the Sand Engine. *Journal of Coastal Research*,
 586 29(5):1001–1008. doi:10.2112/JCOASTRES-D-13-00070.1.
- 587 Stockdon, H. F., Holman, R. A., Howd, P. A., and Sallenger, A. H. (2006).
 588 Empirical parameterization of setup, swash, and runup. *Coastal engineer-
 589 ing*, 53(7):573–588. doi:10.1016/j.coastaleng.2005.12.005.
- 590 van der Wal, D. (1998). The impact of the grain-size distribution of nourish-
 591 ment sand on aeolian sand transport. *Journal of Coastal Research*, pages
 592 620–631.
- 593 van der Wal, D. (2000). Grain-size-selective aeolian sand transport on a
 594 nourished beach. *Journal of Coastal Research*, pages 896–908.

- 595 Van Slobbe, E., De Vriend, H., Aarninkhof, S., Lulofs, K., De Vries, M., and
596 Dircke, P. (2013). Building with nature: in search of resilient storm surge
597 protection strategies. *Natural hazards*, 65(1):947–966. doi:10.1007/s11069-
598 012-0342-y.
- 599 Waterman, R. E. (2010). *Integrated coastal policy via Building with Nature*.
600 TU Delft, Delft University of Technology.
- 601 Wiggs, G. F. S., Baird, A. J., and Atherton, R. J. (2004). The dynamic
602 effects of moisture on the entrainment and transport of sand by wind.
603 *Geomorphology*, 59:13–30. doi:10.1016/j.geomorph.2003.09.002.