Evolution of alongshore bathymetric variability around a mega-scale beach nourishment

Radermacher, Max; Geerlof, Wessel; de Schipper, Matthieu; Huisman, Bas; Aarninkhof, Stefan; Reniers, Ad

Publication date
2017

Document Version
Final published version

Published in
Proceedings of Coastal Dynamics 2017

Citation (APA)
Radermacher, M., Geerlof, W., de Schipper, M., Huisman, B., Aarninkhof, S., & Reniers, A. (2017). Evolution of alongshore bathymetric variability around a mega-scale beach nourishment. In T. Aagaard, R. Deigaard, & D. Fuhrman (Eds.), *Proceedings of Coastal Dynamics 2017: Helsingør, Denmark* (pp. 1370-1375)

Paper No. 079 in Proceedings of Coastal Dynamics 2017, 12-16 June 2017 Helsingør, Denmark
ed. Troels Aagaard, Rolf Deigaard, David Fuhrman

EVOLUTION OF ALONGSHORE BATHYMETRIC VARIABILITY AROUND A MEGA-SCALE BEACH NOURISHMENT

Max Radermacher[1,2], Wessel Geerlof[1], Matthieu de Schipper[1,3], Bas Huisman[1,4], Stefan Aarninkhof[1] and Ad Reniers[1]

Abstract

The presence of complex nearshore sand bar patterns (i.e. alongshore bathymetric variability) has an impact on local currents, affecting recreational safety and nearshore mixing processes. This study assesses the evolution of alongshore bathymetric variability along the Delfland coast in The Netherlands, over the first 5 years after construction of a mega-scale beach nourishment (the Sand Motor) in the central part of the coastal cell. A total of 38 bathymetric surveys was conducted over this period. Alongshore variability was quantified by subtracting an alongshore averaged bathymetry from the actual surveyed bed levels for both the intertidal and subtidal zone. From 2 years after construction onwards, the subtidal nearshore bathymetry at the Sand Motor is considerably more alongshore variable than the adjacent parts of the Delfland coast. Intertidal variability tends to be high in areas where beach groynes are present.

Key words: nearshore bathymetry, alongshore variability, rip currents, nourishments, Sand Motor

1. Introduction

Nearshore sand bars can take many different shapes, varying from alongshore uniform ridges to highly complex spatial patterns (Hino, 1974; Lippmann and Holman, 1990). If alongshore variability in nearshore bars is present, this will result in alongshore variability in the hydrodynamic forcing. In extreme cases, alongshore variable hydrodynamic forcing leads to the generation of rip currents, which are associated with considerable risks regarding recreational safety at the beach (Dalrymple et al., 2011; Brighton et al., 2013).

While alongshore variable nearshore bar patterns are commonly observed along natural (Ranasinghe et al., 2004; Price and Ruessink, 2011) as well as engineered beaches (Grunnet et al., 2005; De Schipper et al., 2013), the latter case raises the question if and how anthropogenic modifications can affect the alongshore bathymetric variability of a beach. An assessment of this influence is of great importance, as safe recreation is a necessary constraint for any human intervention along recreational beaches (Van den Hoek et al., 2014). In particular, the impact of very large beach nourishments on alongshore bathymetric variability remains yet unclear. Coastal cells with mega-nourishments are associated with large erosive (at the nourishment itself) and accretionary (around the nourishment) trends, while the presence of a nourishment also modifies large-scale geometric properties of the beach, such as the cross-shore profile slope and the coastline orientation (De Schipper et al., 2016).

This study aims to quantify the spatio-temporal evolution of alongshore bathymetric variability in a coastal cell after construction of a mega nourishment. The results will contribute to assessing the influence of the Sand Motor on recreational safety, as well as on nearshore hydrodynamic mixing processes.

2. Field site and bathymetric surveys

The Sand Motor mega-nourishment (Stive et al., 2013; also referred to as Sand Engine) was constructed in 2011 as a hook-shaped peninsula, consisting of 17.5 Mm^3 of sand. It is a mitigation measure for the

---

[1] Department of Hydraulic Engineering, Delft University of Technology, Delft, Netherlands. m.radermacher@tudelft.nl
[2] WaveDroid, Rijswijk, Netherlands
[3] Shore Monitoring & Research, Den Haag, Netherlands
[4] Deltares, Delft, Netherlands

structural beach erosion problems at the 17 km long Delfland coastal cell, which stretches from the harbour breakwaters of Rotterdam in the South to the harbour breakwaters of The Hague in the North (Figure 1). Throughout the coming decades, the Sand Motor is expected to provide the Delfland coastal cell with a steady supply of sand through natural sediment transport processes.

Over the first 5 years of its development, the nourishment was spread out in alongshore direction and attained a more or less Gaussian shape. The initial, relatively steep cross-shore profile was reworked by hydrodynamic processes and obtained a milder, single-barred profile (De Schipper et al., 2016). The bathymetric evolution of the Sand Motor and the Delfland coast was captured by regular topographic surveys at approximately two-monthly intervals. Sub-tidal bed levels were measured with a single-beam echo sounder and RTK-DGPS mounted on a personal watercraft, while sub-aerial bed levels were measured with RTK-DGPS mounted on an all-terrain vehicle. Bed levels were sampled along fixed cross-shore transects of approximately 30 m alongshore spacing, ranging approximately between the -6 m bed level contour and the base of the first dune row. At the Sand Motor, locally a refined transect spacing was applied.

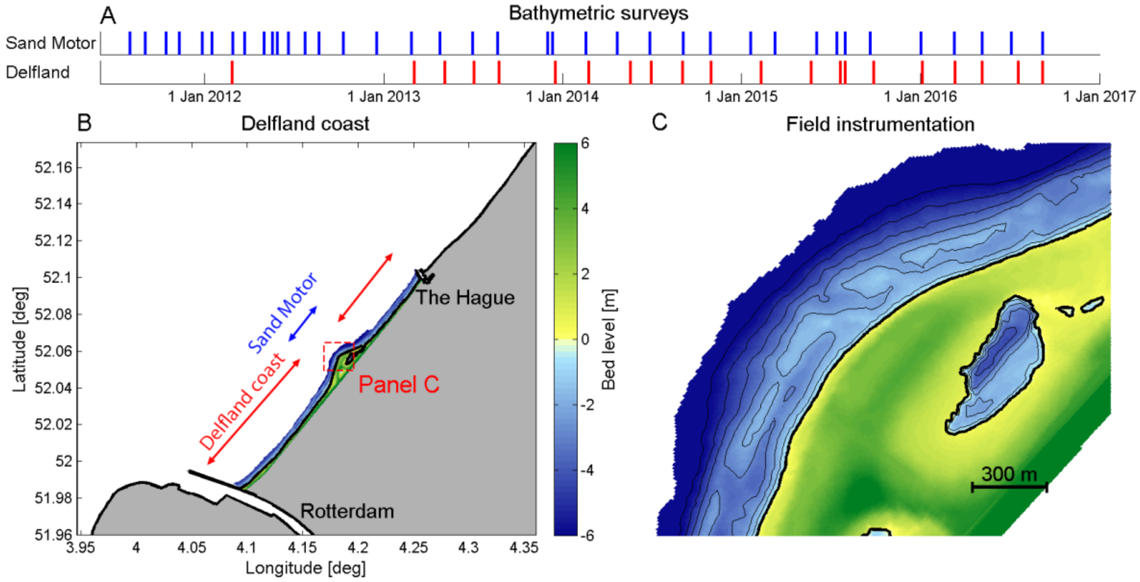

Figure 1. Overview of bathymetric surveys in time for the Sand Motor and the full Delfland coast (panel A), position of the Delfland coast between Rotterdam and The Hague (panel B) and a close-up of nearshore bar patterns around the tip of the Sand Motor in July 2014, including bed contour levels between -6 m and 0 m (panel C). All bed levels in this study are given with respect to the Dutch reference level (N.A.P.).

3. Quantification of alongshore bathymetric variability

Alongshore bathymetric variability is defined here as the deviation of bed levels with respect to the alongshore averaged bathymetry (De Schipper et al., 2013). Hence, the alongshore bathymetric variability $z_{v,a}$ is quantified according to Equation (1).

$$z_{v,a}(x,y) = \left| z(x,y) - \frac{1}{L} \int_{y-L/2}^{y+L/2} z(x,y)dy \right| \tag{1}$$

Here, $z_{v,a}$ is the alongshore bathymetric variability, x and y are the cross-shore and alongshore grid coordinates respectively, z is the vertical level of the bed and L is the length scale used for alongshore averaging. While De Schipper et al. (2013) computed the alongshore averaged bathymetry over the full width of their experimental site, averaging length scale L is introduced here to account for large-scale variations in cross-shore beach slope. Using an alongshore averaged bathymetry over the full length of the

Delfland coastal cell would introduce an artificial signal as a result of bathymetric variations at a much larger scale than the investigated nearshore bar patterns.

The presence of the Sand Motor in the analysis domain introduces local variations in coastline orientation. As the spatial scale of these variations (of O(1 km)) is far larger than the spatial scale of bar pattern variability (O(100 m)), the local coastline orientation should be compensated for when calculating $z_{v,a}$. Therefore, topographic survey data in real-world coordinates (x_r, y_r) were interpolated to a curvi-linear nearshore grid to maintain a strictly alongshore (y) and cross-shore (x) coordinate system (Figure 2). The grid is aligned with a smoothed version of the -1 m bed level contour. The alongshore grid spacing is 10 m at the -1 m contour and may vary slightly in cross-shore direction due to the curvi-linear character of the grid. The cross-shore grid spacing is 2 m. L was chosen to be 600 m for the subtidal part of the profile and 200 m for the intertidal part of the profile, which is sufficient to average out the typical length scales of nearshore bars found in both regions.

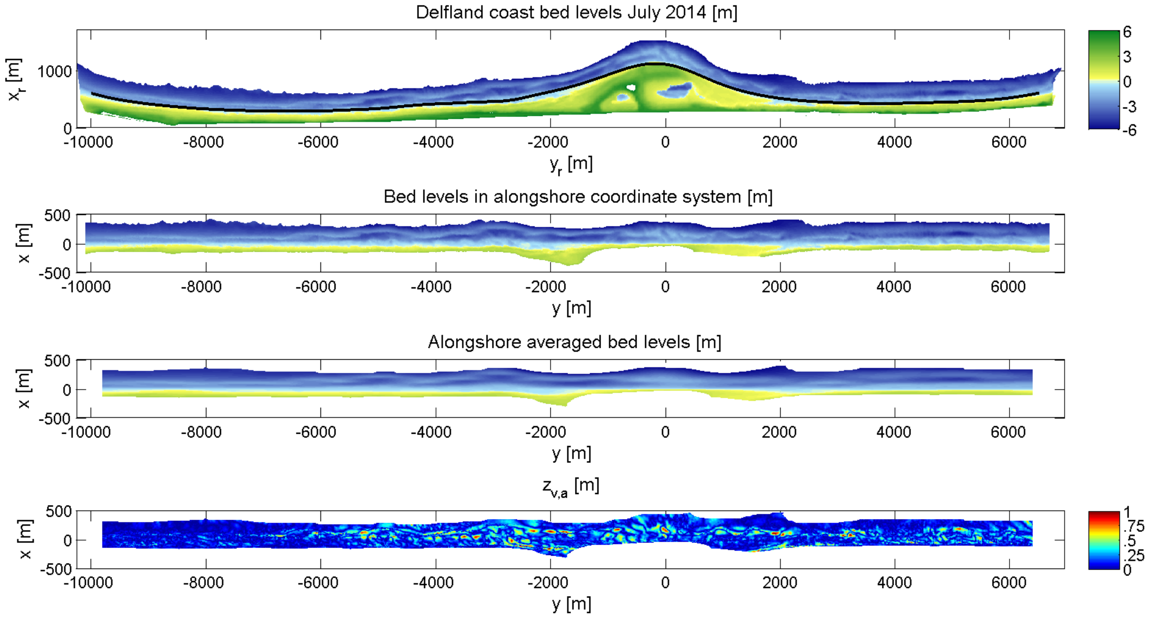

Figure 2. Step-wise calculation of alongshore bathymetric variability with L = 600 m. The July 2014 bathymetric survey is used here as an example. The solid line in the upper panel marks the smoothed -1 m bed level contour. The y-axis runs along this contour.

Calculated fields of $z_{v,a}$ were averaged over blocks spanning an alongshore distance of 30 m, which was approximately equal to the survey transect spacing. A differentiation was made between $z_{v,a}$ for the subtidal and intertidal parts of the bathymetry. The boundary between these subdomains was drawn at 60 m offshore of the smoothed -1 m bed level contour, which is situated landward of the subtidal bars and seaward of the intertidal bars.

4. Results

The analysis method for the assessment of $z_{v,a}$ was applied to all 38 bathymetric surveys of the Sand Motor and Delfland coast, ranging in time from August 2011 to September 2016. Clear spatio-temporal patterns of subtidal alongshore bathymetric variability can be observed at the Delfland coast (Figure 3, middle panel). As time progresses, the Sand Motor becomes more and more alongshore variable, while this trend is less obvious at the adjacent coastline. Late 2013, values of alongshore variability start increasing. A very sudden increase takes place in early 2015 between y = -3000 and 0 m. Along the northern edge of the Sand Motor, a more gradual increase takes place over the course of 2015 and 2016. Throughout the analysis period, the locations where the Sand Motor attaches to the adjacent coastline (i.e. entrance of the lagoon in the North and the strongly curved stretch of coastline on the southern side) show considerable subtidal alongshore bathymetric variability.

In order to determine whether the subtidal alongshore bathymetric variability at the Sand Motor is significantly larger than along the adjacent parts of the Delfland coast, significance testing is performed. Values of data points falling in between the dashed lines in the middle panel of Figure 3 were compared to those in the outer parts of the domain. The issue of dependence of adjacent data points was resolved by subsampling in alongshore direction with a step size of 180 m, which was chosen based on autocorrelation analysis. The zero hypothesis H_0 stated that the average subtidal alongshore bathymetric variability was not larger at the Sand Motor than at the remaining part of the Delfland coast. Significance testing with Welch's t-test (Welch, 1947) on every individual survey (i.e. every row in the timestack of Figure 3) shows that H_0 can be rejected at the 95% confidence level from late 2013 onwards. Hence, the subtidal alongshore bathymetric variability is significantly larger at the Sand Motor than at the adjacent coastline as of 2.5 years after construction of the nourishment.

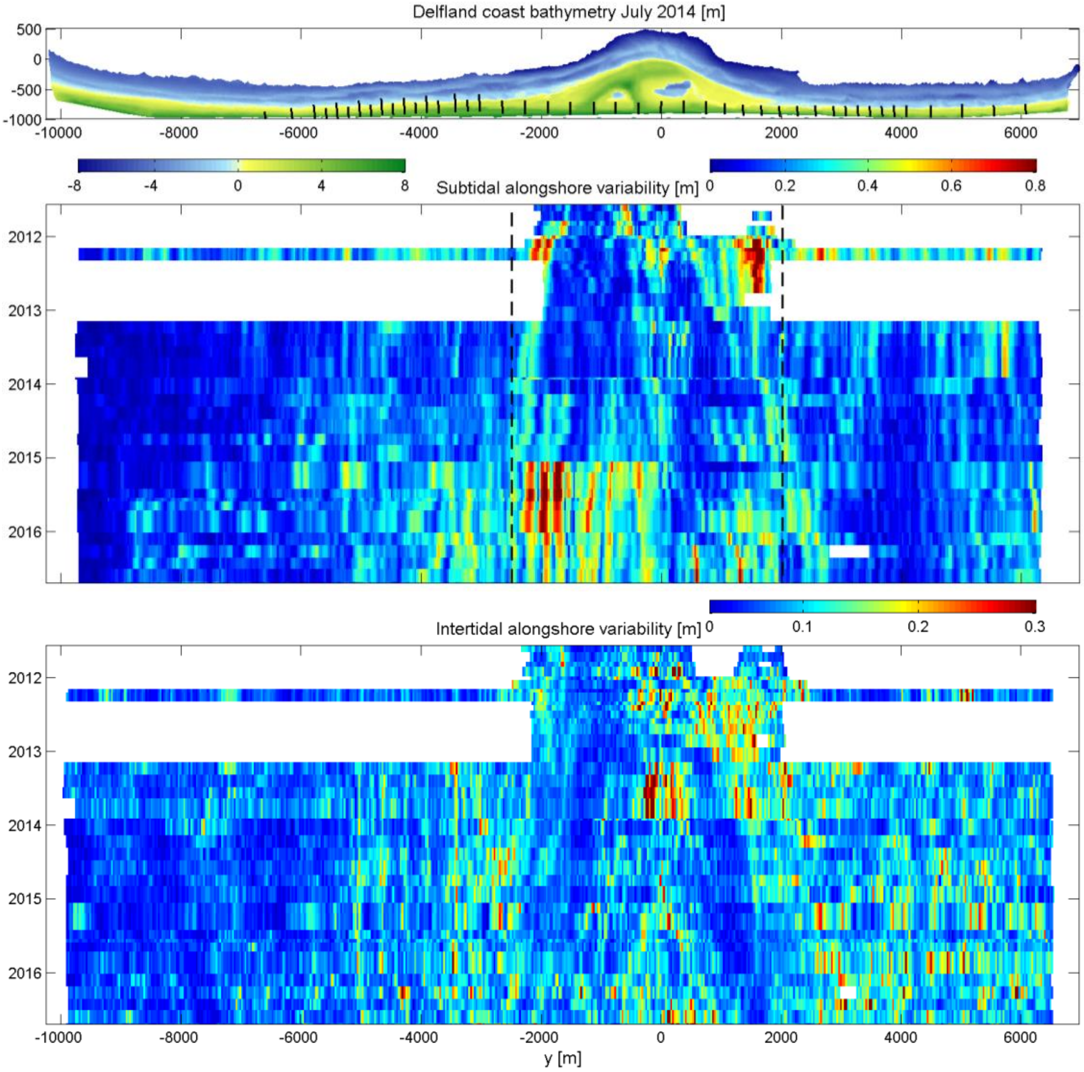

Figure 3. Timestack of subtidal (middle panel) and intertidal (lower panel) alongshore bathymetric variability over the first 5 years after construction of the Sand Motor. Values of $z_{v,a}$ were averaged over blocks of 30 meters in alongshore direction in the subtidal and intertidal part of the domain respectively. Dashed black lines in the middle panel indicate the approximate extent of the Sand Motor. Black lines in the upper panel indicate the locations of rubble-mound groynes.

The evolution of intertidal alongshore variability (lower panel of Figure 3) shows completely different patterns. This is confirmed by the very low r^2 of 0.05 between the subtidal and intertidal variability (again, after subsampling to 180 m in alongshore direction). Large intertidal variability is observed between -5000 m < y < -2000 m and 2000 m < y < 6000 m, which coincides with the stretches of coastline where groynes are present and exposed (crest levels approximately at 0 m). Around every groyne, a pattern of small channels forms, which is reflected in the values of $z_{v,a}$. Furthermore, specific areas at the Sand motor exhibit relatively high intertidal alongshore variability over short periods of time. It is hypothesised that these events of high intertidal variability are related to the presence of shore-connected subtidal bars, which generate relatively large bed level differences in the intertidal zone.

5. Discussion

Observed spatio-temporal trends in alongshore bathymetric variability are typically generated by morphodynamic interaction of the bathymetry and the incoming wave field. While the speed and predictability of changes in alongshore variability are relatively large at open ocean beaches (e.g. Lippmann and Holman, 1990; Price and Ruessink, 2011), the evolution is found to be much slower at beaches along marginal seas, such as the Dutch North Sea coast (e.g. Van Enckevort et al., 2004; De Schipper et al., 2014). The absence of frequent, abrupt decreases of alongshore bathymetric variability over a long stretch of coastline in Figure 3 indicates that morphologic reset events have not taken place over the entire analysis period.

The alongshore bathymetric variability at the Sand Motor was found to be higher than at the adjacent coastline after two years of morphologic development of the nourishment. Factors that may account for the larger alongshore variability at the Sand Motor are the local shoreline orientation with respect to the wave climate, the cross-shore beach slope and spatial gradients in wave conditions along the Delfland coast (e.g. due to wave focusing at the Sand Motor or sheltering by the harbour breakwaters of the port of Rotterdam, see Figure 1 panel B). Additionally, persistent erosive (at the Sand Motor) and accretionary trends (along the adjacent coastline) might lead to spatial differences in alongshore variability. Many of these variables are influenced by the presence of the Sand Motor itself, suggesting an impact of large-scale beach nourishments. The effects of beach slope and shoreline orientation are not yet fully understood, although it is hypothesised that alongshore variability is reduced for beaches with steeper slopes or with more oblique wave incidence angle.

The calculation of $z_{v,a}$ in Equation (1) depends on the alongshore averaging length scale L. The values of L chosen in this study (200 m and 600 m for the intertidal and subtidal beach respectively) were chosen to be larger than the typical alongshore length scales of nearshore bathymetric features observed in the bathymetric surveys. It was confirmed that variations in L up to a factor 2 only altered the magnitude, but not the spatio-temporal patterns of alongshore variability presented in Figure 3. Hence the findings of this study are insensitive to reasonable changes in L.

Although three-dimensional bar patterns are associated with the generation of rip currents, this does not mean that a direct relation between $z_{v,a}$ and recreational safety exists. Hazardous hydrodynamics can only influence recreational safety if they coincide with the presence of beach users (e.g. Houser et al., 2015). A large recreational use of the beach at the Dutch coast is not associated with high wave conditions which can generate strong rip currents over a variable subtidal bathymetry. Wave conditions are typically locally generated, and do often coincide with windy, clouded or even stormy weather conditions with a low number of beach users. Therefore, intertidal bathymetric variability may be of greater relevance for swimmer safety at the Delfland coast. It should be noted that this relation will be different at open ocean beaches that receive energetic, distant swells.

6. Conclusions

The spatio-temporal evolution of alongshore bathymetric variability along the Delfland coast was assessed in this study. Subtidal alongshore variability was found to be significantly larger at the Sand Motor than at the adjacent coastline after 2 years of morphologic development of the mega-nourishment. The locations where the Sand Motor attaches to the surrounding coastline are particularly alongshore variable in the subtidal part of the profile. The intertidal alongshore variability developed independently of the subtidal variability and showed less clear temporal trends. Intertidal alongshore variability is highest at parts of the Delfland coast where groynes are present.

The observations presented here are relevant when assessing the impact of human interventions in the coastal zone on recreational safety and nearshore mixing processes. The forcing behind the observed spatio-temporal evolution of alongshore bathymetric variability will be addressed in future research.

Acknowledgements

MR was supported by STW Grant 12686: Nature-driven Nourishments of Coastal Systems (NatureCoast), S1: Coastal safety. BH was supported by the ERC-Advanced Grant 291206 - Nearshore Monitoring and Modeling (NEMO). Yeow Chong Tan is acknowledged for his exploratory work on alongshore variability at the Sand Motor.

References

Brighton, B., Sherker, S., Brander, R., Thompson, M. and Bradstreet, A., 2013. Rip current related drowning deaths and rescues in Australia 2004-2011. *Natural Hazards and Earth System Sciences*, 13: 1069-1075.

De Schipper, M., De Vries, S., Ranasinghe, R., Reniers, A. and Stive, M., 2013. Alongshore topographic variability at a nourished beach. *Proceedings of Coastal Dynamics 2013, Arcachon, France.*

De Schipper, M.A., Reniers, A.J.H.M., Ranasinghe, R. and Stive, M.J.F., 2014. The influence of sea state on formation speed of alongshore variability in surfzone sand bars. *Coastal Engineering*, 91: 45-59.

De Schipper, M.A., De Vries, S., Ruessink, G., De Zeeuw, R.C., Rutten, J., Van Gelder-Maas, C. and Stive, M.J.F., 2016. Initial spreading of a mega feeder nourishment: Observations of the Sand Engine pilot project. *Coastal Engineering*, 111: 23-38.

Grunnet. N.M., Ruessink, B.G. and Walstra, D.J.R., 2005. The influence of tides, wind and waves on the redistribution of nourished sediment at Terschelling, The Netherlands. *Coastal Engineering*, 52: 617-631.

Hino, M., 1974. Theory on formation of rip-current and cuspidal coast. *Proceedings of the 14th Conference on Coastal Engineering, Copenhagen, Denmark*.

Houser, C., Murphy, T. and Labude, D., 2015. Alongshore Corrspondence of beach users and rip channels at Pensacola Beach, Florida. *Natural Hazards*, 78: 2175-2183.

Lippmann, T.C. and Holman, R.A., 1990. The spatial and temporal variability of sand bar morphology. *Journal of Geophysical Research*, 95(C7): 11757-11590.

Dalrymple, R.A., MacMahan, J.H., Reniers, A.J.H.M. and Nelko, V., 2011. Rip currents. *Annual Review of Fluid Mechanics*, 43: 511-81.

Price, T.D. and Ruessink, B.G., 2011. State dynamics of a double sandbar system. *Continental Shelf Research*, 31: 659-674.

Ranasinghe, R., Symonds, G., Black, K. and Holman, R., 2004. Morphodynamics of intermediate beaches: a video imaging and numerical modelling study. *Coastal Engineering*, 51: 629-655.

Stive, M.J.F., De Schipper, M.A., Luijendijk, A.P., Aarninkhof, S.G.J., Van Gelder-Maas, C., Van Thiel de Vries, J.S.M., De Vries, S., Henriquez, M., Marx, S. and Ranasinghe, R., 2013. A new alternative to saving our beaches from sea-level rise: The Sand Engine. *Journal of Coastal Research,* 29(5): 1001-1008.

Van den Hoek, R.E., Brugnach, M., Mulder, J.P.M. and Hoekstra, A.Y., 2014. Analysing the cascades of uncertainty in flood defence projects: How “not knowing enough” is related to “knowing differently”. *Global Environmental Change*, 24: 373-388.

Van Enckevort, I.M.J., Ruessink, B.G., Coco, G., Suzuki, K., Turner, I.L., Plant, N.G. and Holman, R.A., 2004. Observations of nearshore crescentic bars. *Journal of Geophysical Research*, 109 (C06028), doi:10.1029/2003JC002214.

Welch, B.A., 1947. The generalization of ‘student’s’ problem when several different population variances are involved. *Biometrika*, 34(1-2): 28-35.