SCACR2019 – International Short Course/Conference on Applied Coastal Research
Engineering, Geology, Ecology & Management
9th – 11th September 2019 – Bari, Italy

AN ASSESSMENT OF BEACH NOURISHMENT LIFETIMES ON SYLT IN GERMANY

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1. Introduction

To mitigate effects of coastal erosion along sandy shorelines, beach nourishments have become a popular engineering solution. A beach nourishment either refills sand on the emerged part of the beach profile, or creates a sand buffer to proactively counteract subsequent erosion (Stive et al., 2013). In Northern Europe, coastal authorities typically decide on a beach nourishment strategy, which is currently often the 'hold the line' strategy to preserve the shoreline volume of a certain reference year (e.g. 1984 on Sylt in Germany). Subsequently, coastal authorities determine when and where a beach nourishment is required based on a (series of) recent measurement(s). Thereafter, in line with the beach nourishment strategy, each beach nourishment needs to be designed, i.e. determined e.g. the amount and exact location of the to-be-placed sand.

To transfer the beach nourishment strategy towards a specific design target for a beach nourishment, an often-used term is the beach nourishment lifetime. The nourishment lifetime indicates a period of time in which the placed nourishment should lead to an above-reference sand volume (Stive et al., 2013), or an above pre-nourishment sand volume when no reference is present (Dette et al., 1994). Nourishment strategies, and hence aimed lifetimes, may differ, partly based on the still unknown long-term ecological impacts of beach nourishment placement. These impacts are either larger for larger quantities of sand (necessary for longer lifetimes), or more frequent. Furthermore, the large uncertainties involved in nourishment planning may affect the nourishment strategy. These uncertainties increase with increasing nourishment lifetime.

Present design guidelines to assess the lifetime of beach nourishments focus specifically on the nourished volume and the (pre-nourishment) local erosion rates, including a certain reference or buffer volume. Either pre-nourishment erosion rates are estimated with an amplification factor (Verhagen, 1992; Van der Spek et al., 2007) or initial erosion rates are assumed to increase with increasing nourishment volume (Dette et al., 1994). Nourishment lifetimes are also typically alongshore-averaged, while differences in intra-nourishment lifetime may be present that affect the nourishment performance (Dean, 2002). Partly due to the significant uncertainties in nourishment lifetime assessments, present guidelines focus on a few design parameters only (Verhagen, 1992). Another factor has been the lack of field observations to do a systematic study on beach nourishment lifetimes, aiming at generally applicable relations. While the uncertainties remain, data sets of long-term monitoring efforts nowadays provide the opportunity to perform a study of this type.

An example of such a data set was collected for the frequently-nourished sandy shoreline of Sylt in Germany. Its 34 km long west coast suffers from severe erosion. Since 1972, 147 beach nourishments have therefore been placed on the beach, with a total volume of approximately 44 Mm^3. The behaviour of these nourishments has been monitored with bi-annual measurements (on average). This has resulted in a data set of coastal profiles of over 40 years.

In this study, we analysed the data set of coastal profiles of the island of Sylt to systematically identify i) beach nourishment lifetimes and ii) relations between these lifetimes and the design of the beach nourishments. In this way, we aim for an increased general understanding of (intra-) beach nourishment lifetimes to support in the design process of beach nourishments. The outline of

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this paper is as follows: section 2 describes the analysed data set, the lifetime computations and how they are related to the nourishment design. Thereafter, in section 3, the calculated lifetimes and relations are presented. Section 4 discusses and concludes the findings.

2. Methodology

Sylt is the northernmost island of Germany and separates the North Sea from the Wadden Sea. Its sandy west coast consists of medium sand (D_{50} = ~350 μm) (AWI, 2017). The shoreline has a north-south orientation (Fig 1b) and has a convex curve with an orientation difference of 20 degrees between the northern and the southern half. In combination with the westerly wave climate (median wave direction is 273 degrees), this has resulted in southward (northward) time-averaged longshore sediment transport on the southern (northern) half, and loss rates have been approximately 0.5 Mm^3 (southern half) and 1 Mm^3 (northern half) per year (Ahrendt, 2001). In front of Westerland, a wave gauge of the coastal authority of Schleswig-Holstein (LKN.SH) measured significant wave heights (H_{m0}) of 0.83 (50th percentile) and 1.91 m (90th percentile), and relative peak wave periods (T_p) were 6.1 s (50th percentile) and 10.8 s (90th percentile). Mean tidal ranges were around 1.9 m (Ahrendt and Koster, 1996).

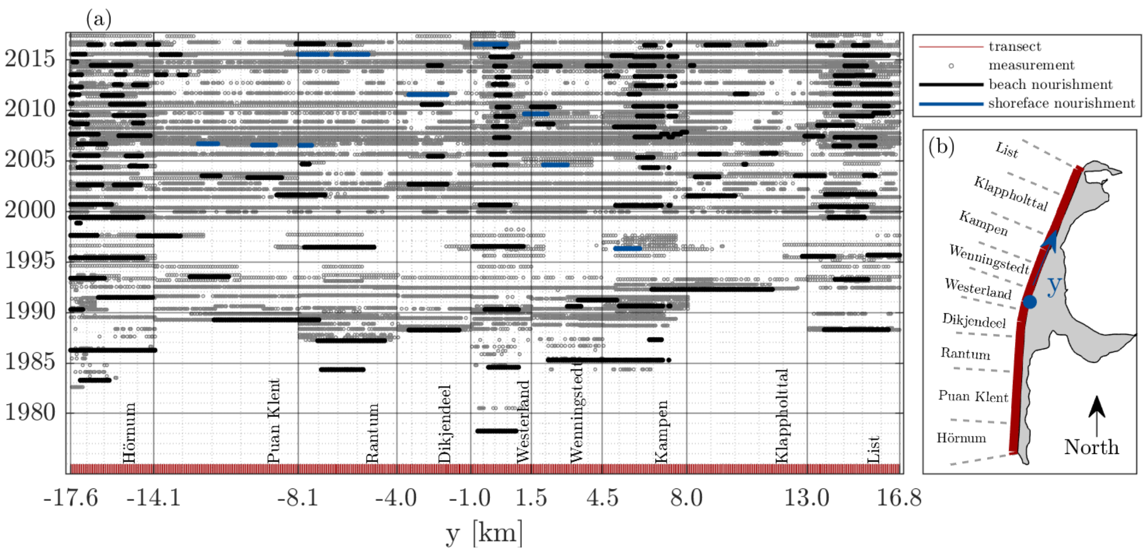

Figure 1: (a) The spatiotemporal distribution of the beach profile measurements (grey circles) and nourishments (black/blue lines) along the coastal transects (red lines) of Sylt. (b) the coastal transects and sections along Sylt.

Sylt has been divided into 9 coastal sections by the LKN.SH (Fig 1b). Each coastal section consists of coastal transects with alongshore spacing (∂y) of 50 m. Although coastal erosion was observed along the complete shoreline, especially Westerland (centre of the island), Kampen (on the northern half), Hörnum (at the southern end) and List (at the northern end) showed severe erosion. The focus of the nourishment campaigns therefore has been on these coastal sections, see also Fig 1a. This study considers the in total 147 beach nourishments that were placed on the emerged beach until 2017. An additional 9 were placed in the nearshore (i.e. shoreface nourishments). Fig. 1a also shows the spatial and temporal distribution of the performed beach profile measurements. The timing of the measurements has been strongly related to the nourishments. Typically, each transect was measured after the winter season (i.e. in March-April) to evaluate on the lost sand volumes. A second and/or a third measurement were/was collected during summer (i.e. in June-July) and/or autumn (i.e. September-October) along the nourished transects.

Measured coastal profiles along each of the 691 coastal transects were linearly interpolated and included in the analysis if their cross-shore spatial interval (∂x) was smaller than 20 m on the emerged beach part of the profile. The emerged beach part of the profile was defined based on the vertical elevation, namely between z=0 m and z=4 m of the time-averaged profile. Sand volumes of each measured profile were then computed between the related cross-shore locations $x_{z=0m}$ and $x_{z=4m}$, with an artificial lower limit of z = -10 m, see Fig 2a. Thereafter, the computed volumes were linearly spatiotemporally interpolated on a grid with longshore resolution (∂y) of 50 m and temporal resolution (∂t) of 7 d. This resulted in a weekly varying beach volume along each coastal transect, as shown in the example of Fig. 2b.

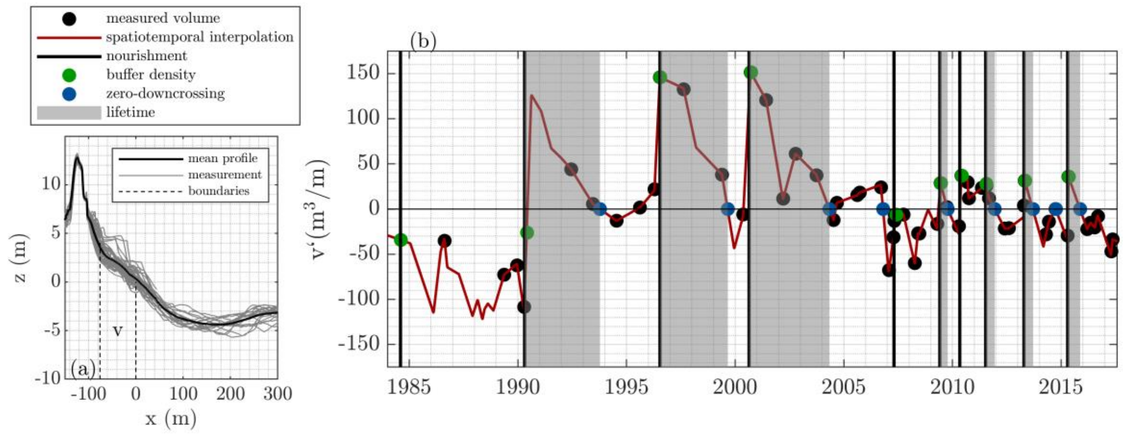

Figure 2: Lifetime calculation for transect y = 600 m. (a) the beach volume calculation and (b) the variability in beach volume from the mean, indicating measurements (black dots), the spatiotemporally interpolated weekly variation of the beach volume (red line), the zero-down crossing (blue dots), the created sand buffer (green dots), the nourishments (black vertical lines) and the nourishment lifetimes (grey areas).

The lifetime was defined as the period between the nourishment placement and the subsequent zero-down crossing of the time-averaged beach volume ($\overline{v}$) by the beach volume deviation (v`). No lifetime was allocated to nourishments for which no down-crossing occurred between 1 month and 4 years after the nourishment, or when another nourishment was placed during the nourishment lifetime. In case no above-average beach volume was measured in the 4 months after the nourishment, the nourishment was disregarded (e.g. the 1984, 1990 and 2007 nourishment in Fig. 2b). Finally, beach nourishments that eroded with averaged rates larger than 150 m^3/m/year were omitted.

The calculated nourishment lifetimes, in days (d), were thereafter projected with a linear system of the nourishments (i) density volume (c_n) in m^3/m, (ii), alongshore length (y_n) in m, (iii) created above-reference sand buffer (z_n) in m^3/m and (iv) relative alongshore location (rl_n), thereby following an approach as presented by Gijsman et al., (2018), see Eq. 1.

$$L_n = k_1 \cdot c_n + k_2 \cdot y_n + k_3 \cdot z_n + k_4 \cdot rl_n \quad (1)$$

The first two nourishment design parameters in Eq. 1 were provided by the LKN.SH (LKN.SH, 2016) and the third parameter was computed from the data record (see Fig. 2b). The fourth parameter was implemented to identify intra-nourishment lifetime variations. The relative alongshore location indicated the location of the nourishment – transect combination relative to the alongshore nourishment length and ranged from 0 (the most upstream location of the nourishment) to 1 (the most downstream location of the nourishment). The direction was defined based on the direction of time-averaged longshore sediment transport. Please note that this direction was southward on the southern half of Sylt, and northward on the northern half. In the Westerland coastal section, northward transport was assumed for the definition of the relative longshore nourishment location.

3. Results

Out of the 3290 nourishment–transect interactions, 899 met the set requirements and their nourishment lifetimes were computed. The 10th, 50th and 90th percentile of the computed lifetimes were 105 d, 287 d and 1036 d (i.e. 3.5 months, 9.5 months and 34 months), respectively (see Fig. 3a). Fig 3b-e show the ranges, distribution and the 10th, 50th and 90th percentile of the design parameters of these nourishments.

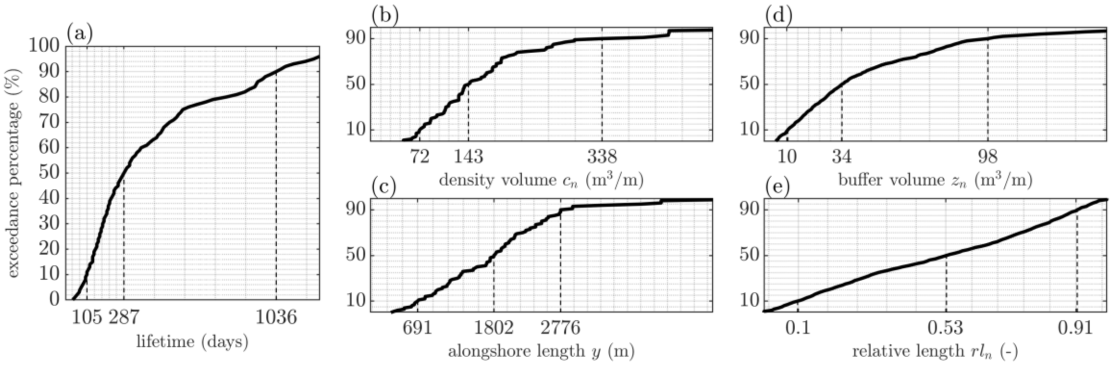

Figure 3: The probability density function of (a) the computed lifetimes, (b) the nourished density, (c) the alongshore nourishment length, (d) the created maximum sand buffer and (e) the alongshore relative location

The root-mean-squared-error (rmse) value of 271 d (i.e. 9 months) of the projection of the 899 nourishment lifetimes shows that the linear system (Eq. 1) was unable to quantify the nourishment lifetimes accurately. However, the system was able to project 45% of the variability in nourishment lifetimes, and may present qualitative relations. Furthermore, after excluding the morphological variation along the island by considering the nourishment lifetimes in each of the coastal section alone, the goodness-of-fit between the computed and the projected lifetimes increased up to r^2=0.70 for the Westerland coastal section (see Fig. 4). The rmse in Westerland decreased to 196 d (i.e. 5 months). One of the reasons that the nourishments in Westerland could be better projected was the high spatiotemporal density of both nourishments and measurements. Moreover, the long-term morphological behaviour of the coastal sections in the centre of the island was the most stable, see also Dikjendeel. In other coastal sections, especially at both ends of the island, trends in the long-term beach volume evolution affected the nourishment lifetime computation (i.e. which is based on a long-term reference beach volume).

Considering the coefficients of the linear system, it was found that only the k_3 value was consistently positive with approximately 3-4 d/m^3. The positive contribution of the created sand buffer was the most significant in comparison to the other parameters. In Westerland, a positively contributing nourishment density (0.58 d/m^3) and alongshore length (0.17 d/m) were identified. However, this may be the result of the correlation between the parameters for the studied nourishments, which was r^2 = 0.62 between c_n and y_n, r^2 = 0.31 between c_n and z_n and r^2 = 0.74 between y_n and z_n. In terms of the alongshore relative location, in Westerland, the lifetime decreased in the alongshore direction with a maximum of 139 d. This suggests a decrease in nourishment lifetime in the alongshore direction. However, this contribution was inconsistent and showed large variability between the different coastal areas. Hence, no general relation between the nourishment density, the alongshore length or the intra-nourishment location and the nourishment lifetime could be quantified.

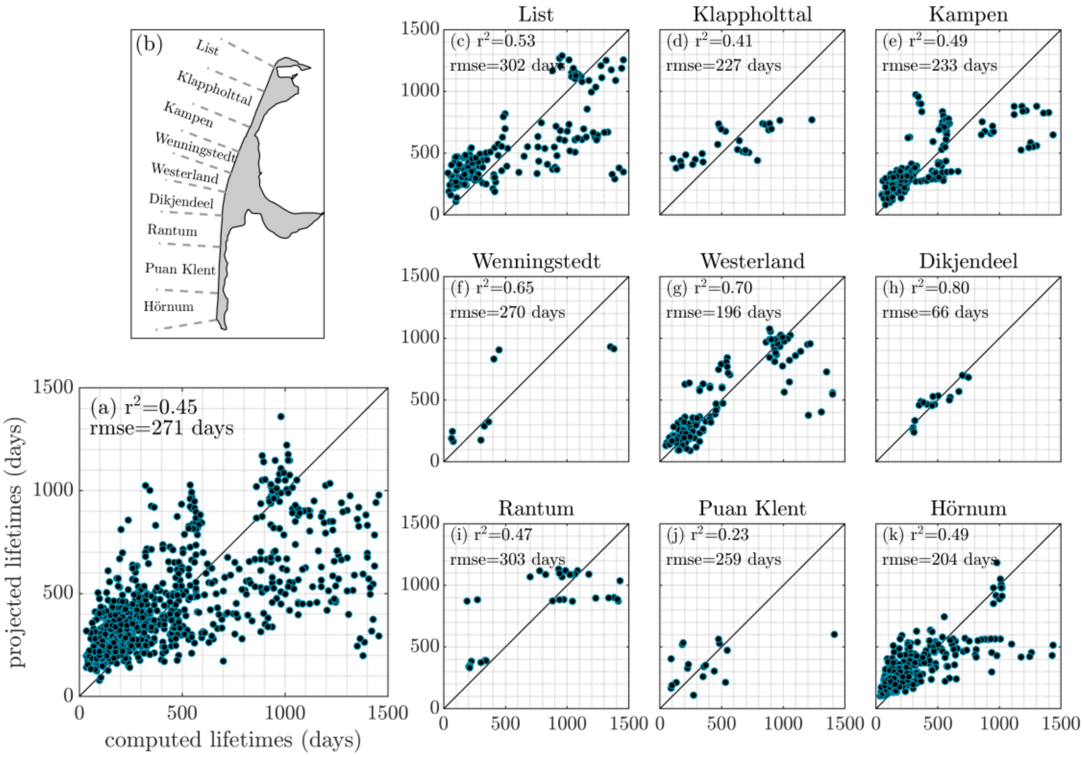

Figure 4: Performance of the linear system for the nourishment on (a) the complete island of Sylt and the individual coastal sections (c-k). The coastal sections are presented in (b).

4. Discussion and Conclusion

899 nourishment lifetimes were computed from a data set of coastal profiles of 40 years of a shoreline of 34 km, measured at alongshore intervals of 50 m. Computed mean nourishment lifetimes were 436 d and approximated the present nourishment strategy, which started with larger nourishments and nowadays aims at nourishment intervals of 1 year. The earlier placed nourishments with longer lifetimes (see Fig 2) were also captured (90^{th} percentile was 34 months). Important factors in the calculation were the definition of the nourishment lifetime and the present spatiotemporal variability of the measurements, in combination with the linear spatiotemporal interpolation. Many nourishments did not create above-average beach volumes, or they were not measured. The same holds for below-average volumes before nourishment placement.

A projection with a linear system could not quantify the large variability in the computed nourishment lifetimes. The linear system, only including nourishment design parameters, could qualitatively describe most of the variability in the nourishment lifetimes, locally with goodness-of-fit (r^2) up to 0.80. In general, it was found that the created buffer density was the only consistent parameter to increase the nourishment lifetime with approximately 3-4 d/m^3. For future nourishment lifetime predictions, it is therefore advised to (keep the) focus on the resulting created sand buffer above the reference volume, rather than on the nourishment density. Effects of the alongshore nourishment length and the alongshore relative location were present and confirmed previous findings for the Westerland coastal section (Gijsman et al., 2018). They were, however, not consistent for all coastal sections and therefore not generally applicable. A main limitation of the present approach was the correlation between the studied parameters. Since these parameters were not statistically independent in the data set, relations with individual parameters were biased.

Mean erosion rates of the nourishments during their lifetime were with 50 m^3/m/year in the same order of magnitude, but slightly larger than previously reported (Verhagen, 1996). However, the cross-shore loss of sand from the beach to the nearshore was included in the rates of the present study. Furthermore, it was found that for an increasing sand buffer the minimum erosion rates seemed to increase, thereby confirming the assumption of an exponential decay in (nourished) beach volume (Dette et al., 1994). The variability in the erosion rates (σ=32 m^3/m/year) did exceed the observed trend and may be explained by other effects (e.g. the variability in the wave climate).

The large variability in the nourishment lifetimes results from their physical design, the local hydrodynamic and morphological processes as well as the morphological evolution of the beach. Although qualitatively, a significant part of the variability could be related to the nourishment design. Variations in and interaction with hydrodynamic forces were disregarded and may explain additional variability in nourishment lifetimes and erosion rates. The morphological processes and evolution are challenging to include in a quantified assessment, also since the nourishment lifetime definition was based on a time-averaged beach volume. It therefore remains challenging to project the variability in nourishment lifetimes, even in the presence of long-term monitoring data sets, and no additional generally applicable relations with the nourishment design were found. An individual and local assessment of single nourishments therefore remains necessary to understand and predict their detailed morphological behaviour.

Table 1: The number of computed nourishment lifetimes for Sylt and the Westerland coastal section, in combination with the fitted values of the linear system (Eq. 1).

	Linear system characteristics				
	Nr.	k_1 [d/m^3]	k_2 [d/m]	k_3 [d/m^3]	k_4 [d]
Sylt	899	1.05	0.0673	3.57	-69.4
Westerland	153	0.58	0.171	2.72	-139

Acknowledgements

The study was funded by the German Federal Ministry of Education and Research (BMBF) via research project STENCIL (contract no. 03F0761). The authors acknowledge the coastal authority of Schleswig-Holstein (LKN.SH) for sharing the measurement of Sylt.

References

Ahrendt K., 2001. Expected effect of climate change on Sylt island: results from a multidisciplinary German project. *Climate Research* 18 (1), pp. 141-146

Ahrend K., and Köster R., 1996. An artificial longshore bar at the West coast of the island of Sylt/German Bight: first experiences. *Journal of Coastal Research* 12 (1), pp. 354-369.

AWI., 2017. Westerland_2017.xlsx. *Data file*, Alfred-Wegener-Institute

Dean R. G., 2002. Beach nourishment: theory and practice (18). World Scientific Publishing.

Dette H., Fuehrboeter A., Raudkivi A., 1994. Interdependence of Beach Fill Volumes and Repetition Intervals. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 120 (6), pp. 580-593.

Gijsman R., Visscher J., and Schlurmann T., 2018. A method to systematically classify the design characteristics of sand nourishments. In P. Lynett (Ed.), *Proceedings of the 36th International Conference on Coastal Engineering* 36. American Society of Civil Engineers.

LKN.SH, 2016. Fachplan küstenschutz Sylt – bisheriger küstenschutz – sandersatzmaßnahmen (in German).

Stive M., de Schipper M., Luijendijk A., Aarninkhof S., van Gelder-Maas C., van Thiel de Vries J., 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)*, pp. 1001-1008

Van der Spek A., De Kruif A., and Spanhoff R., 2007. Richtlijnen onderwatersuppleties (in Dutch). *Technical Report*, RIKZ rapport 2007.012

Verhagen H. J., 1992. Method for artificial beach nourishment. *Coastal Engineering*, pp. 2474-2485

Verhagen H. J., 1996. Analysis of beach nourishment schemes. *Journal of Coastal Research*, pp. 179-185