A METHOD TO SYSTEMATICALLY CLASSIFY DESIGN CHARACTERISTICS OF SAND NOURISHMENTS

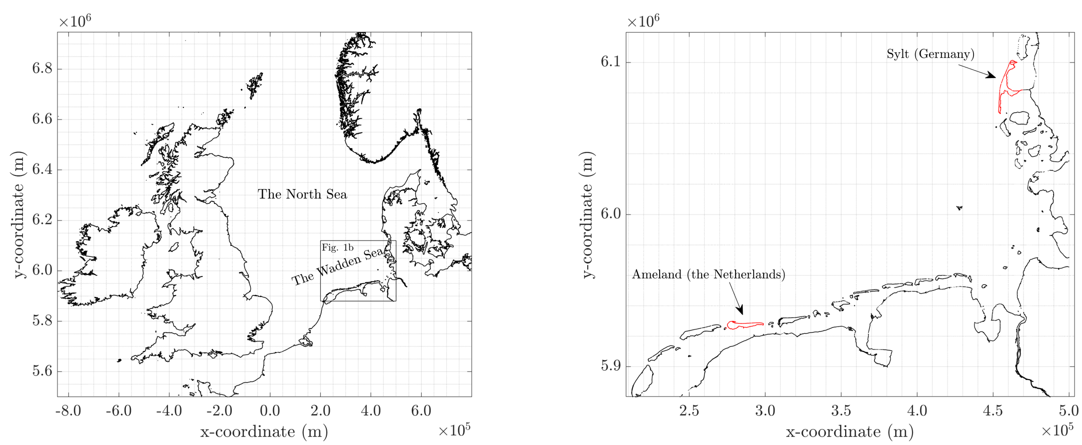
Rik Gijsman*,[1], Jan Visscher[1], Torsten Schlurmann[1]

The decades of collected monitoring data of coastal profiles in combination with the decades of experience with sand nourishments in the Wadden Sea, forms an invaluable basis to study the inter-site efficiency of sand nourishment design. However, a systematic data-driven study of this type needs to be applicable for the inter-site varying (i) nourishment design strategies, (ii) coastal monitoring data sets and (iii) natural morphodynamics of the shorelines, respectively. This study introduces a four-step method able to systematically classify the influence of individual nourishment design parameters on the nourishment lifetime (i.e. the period of influence on the natural dynamics of a coastal profile). With the non-linear and adaptive principle component analysis (PCA) method, nourishment lifetimes of beach- and shoreface nourishments are extracted from data sets that describe different natural morphodynamics. Based on an application of the method to a limited number of nourishments placed in two coastal areas in the Netherlands (Ameland) and Germany (Sylt), increasing nourishment concentration, alongshore nourishment length and absolute nourishment peak elevation seem to increase the lifetime of beach- and shoreface nourishments. Nourishment lifetimes at profile more downstream seem to decrease for beach nourishments, but increase for shoreface nourishments. The method supports inclusion of additional coastal profiles and parameters related to the nourishment design, natural morphodynamics of the coastal profile and hydrodynamic forcing, to quantify nourishment design influences on nourishment lifetimes at different locations.

Keywords: Coastal monitoring; Nourishment design; Nourishment lifetime; Principle component analysis

INTRODUCTION

Sand nourishments have become a routine coastal protection measure to mitigate the effects of coastal erosion along many sandy shorelines in Europe (Hamm et al., 2002; Hanson et al., 2002). Seaward of the Wadden Sea barrier islands, nourishments have replaced the previously used coastal infrastructure (e.g. groins) in the 1950's already. In the same period, coastal monitoring programs have initiated in this area. Since then, cross-shore coastal profiles are measured at certain alongshore locations, cross-shore locations and temporal intervals. The Wadden Sea covers the south-eastern part of the North Sea in northern Europe, see Fig. 1a. This study will specifically focus on two data sets of frequently nourished and measured coastlines in the Wadden Sea: the central parts of (1) Ameland (the Netherlands) and Sylt (Germany), see Fig. 1b.



(a) The North Sea **(b)** The Wadden Sea

Figure 1: The field study sites in the Wadden Sea (coordinates in UTM32)

Both the nourishment and monitoring strategies, applied by the coastal authorities of the two coastlines, do differ significantly (Wilmink et al., 2017). In the Netherlands, the reference sand volume of the coastal profiles of 1990 is maintained proactively by *Rijkswaterstaat* (RWS) with sand nourishments each 4-5 years

[1]Ludwig Franzius Institute of Hydraulic, Estuarine and Coastal Engineering, Leibniz University Hannover, Germany

(Mulder and Tonnon, 2011). Primary objective of their coastal monitoring strategy is to detect and project trends in these volumes, by sampling regularly in space and time. In Germany (i.e. the state of Schleswig-Holstein), however, coastal erosion is mitigated by the *Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig Holstein* (LKN.SH) with relatively frequent nourishment campaigns. Most of the monitoring is adapted to these nourishment events (LKN.SH, 2016). As a result, their data sets consist of irregular spatial- and temporal intervals. Tab. 1 provides more details on the temporal characteristics of the two nourishment and monitoring strategies, respectively.

	monitoring start	monitoring interval	nourishment start	nourishment interval
		year		*year*
Ameland	1965	≈ 1	1990	$\approx 4-5$
Sylt	1972	$\approx 0.25-1$	1972	≈ 1

Table 1: Typical temporal characteristics of monitoring- and nourishment history

The combination of long-term monitoring data sets and experience with nourishments forms an invaluable basis to study the inter-site efficiency of individual nourishment designs. A generally applicable methodology to perform a systematic study of this type, however, lacks. This study introduces a four-step methodology to relate nourishment design with nourishment lifetime. The lifetime of an individual nourishment is defined as a characteristic period of influence on the local natural morphodynamics of a coastal profile. The methodology provides a tool to support understanding of design influences on nourishment efficiency inside and outside the Wadden Sea.

This paper is outlined as follows: section 2 describes the different conditions for the two field sites. In Section 3 the methodology is introduced. Thereafter section 4 presents the results of the application of the methodology to the data sets of the field sites. Finally, the discussion and conclusion are presented in section 5.

DESCRIPTION OF THE FIELD STUDY SITES

A key challenge in the development of a systematic methodology is its general applicability, since distinct differences are present in the inter-site local conditions. This is illustrated with the two field study sites. The differences are categorised by variability in terms of:

1. applied nourishment design
2. collected monitoring data set
3. natural morphodynamic behaviour of the coastal profile

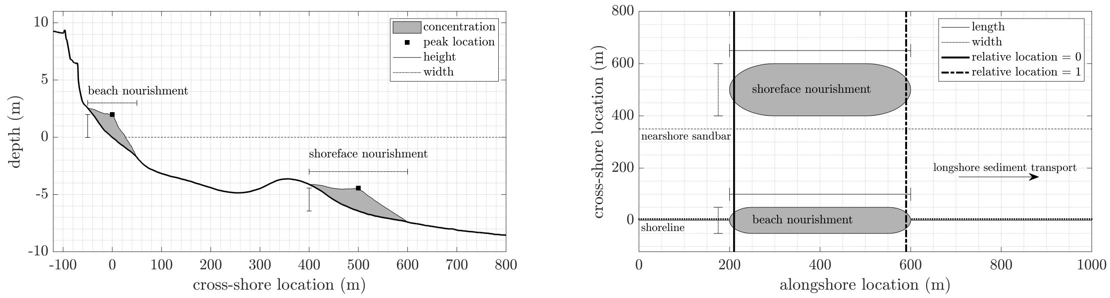
Both the nourishments are caried out by, as well as the monitoring data sets are collectd by RWS, for Ameland and LKN.SH for Sylt (Wilmink et al., 2017).

Variability in nourishment design

Firstly, the strategic nourishment decisions as well as nourishment design decisions for the two study sites deviate. In terms of strategic nourishment decisions, typically the nourishment location in cross-shore direction x_n and the nourishment volume V_n are selected (Stive et al., 2013). Generally two nourishment types are distinguished with reference to cross-shore location: (1) beach nourishments, placed on the elevated beach, and (2) shoreface nourishments, placed on the submerged beach (i.e. the nearshore). Nourishment volumes are related to the expected nourishment lifetime L_n, and are therefore based on the chosen nourishment frequency f_n (Dette, 1977; Rijkswaterstaat, 2007).

In terms of nourishment design, further considerations are for instance the alongshore length y_n (determines the alongshore averaged concentration $c_n = \frac{v_n}{y_n}$) and the alongshore location relative to a single coastal profile $y_{r,n}$. $y_{r,n}$ is defined along the nourishment from upstream to downstream in the direction of alongshore sediment transport, and ranges from 0 to 1 for the initial location of construction. Additionally, the location of the nourishment peak p_n, the nourishment width w_n and the nourishment height h_n are parameters to consider in the design of nourishments.

The discussed nourishment parameters are presented in Fig. 2. Tab. 2 summarises the deviation in numbers and nourishment design parameters applied at the study sites between 1990 and 2016.



(a) Cross-shore dimension **(b)** Longshore dimension

Figure 2: Considered parameters with regard to the nourishment design

	beach nourishments				shoreface nourishments			
	nr.	L_n	c_n	y_n	nr.	L_n	c_n	y_n
		year	$\frac{m^3}{m}$	*km*		*year*	$\frac{m^3}{m}$	*km*
Ameland	5	4-5	180-240	4-8	7	3-5	250-560	2-8
Sylt	20	1	50-675	0.2-5	2	1-2	150-450	0.5-2

Table 2: Variability in nourishment numbers and design parameters

Variability in monitoring data set

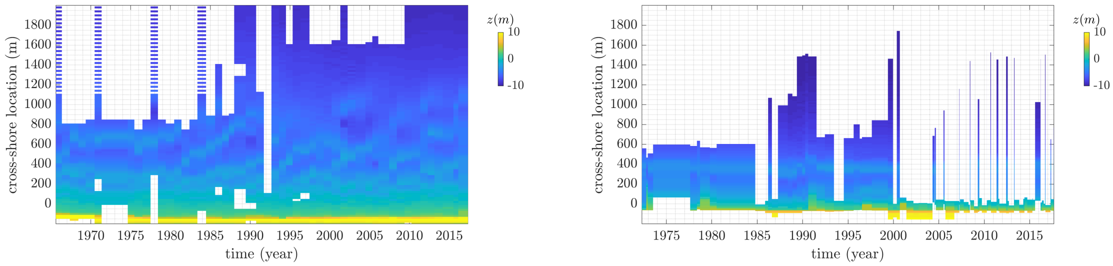
Secondly, distinct differences are present in the characteristics of the monitoring data sets of two study sites. The data sets contain bathymetric measurements z_b of cross-shore profiles at alongshore locations y, measured on alongshore intervals Δy. In time, each location in every cross-shore profiles consists of a mean value $\overline{z_b}$, and a fluctuation around this mean z_b'. x represents the cross-shore location, where x is equal to zero at mean sea level in the averaged-profile, and positive in the offshore direction. The part of the cross-shore profile that is measured is indicated with δx. Measurements are performed at certain times t, with temporal sampling intervals f_s.

Tab. 3 presents the deviations between the monitoring strategies applied at the two field sites. In Ameland, measurements are collected regularly in space and time, on average with a smaller sampling frequency. In Sylt, measurements are collected irregularly in space and time, with a higher sampling frequency on average.

	δy	δx	f_s
	m	m	p.a.
Ameland	regular (250)	regular (-200<x<3000)	regular (1)
Sylt	irregular (50<δy<100)	irregular (-100<x<1500)	irregular (1<f_s<4)

Table 3: Variability in monitoring strategy

In Fig. 3 the measurements collected in one of the coastal profiles are shown (i.e. profile 1600 for Ameland and profile 0+205 for Sylt). The characteristics of the data sets represent the main patterns of the profiles at the central parts of the islands. The smaller sampling frequency of the Ameland data sets limits the focus to study nourishments with multi-annual lifetimes alone. The larger coverage of the nearshore provides the opportunity to study nearshore dynamics and the effects of shoreface nourishments. Since the measurements in Sylt focus on individual nourishment campaigns, before- and after nourishment measurements are included. In contrast to the Ameland case study, these measurements provide the opportunity to study the behaviour of individual beach nourishments with lifetimes shorter than 1 year, since initial intra-annual profile changes of the nourishment are captured.



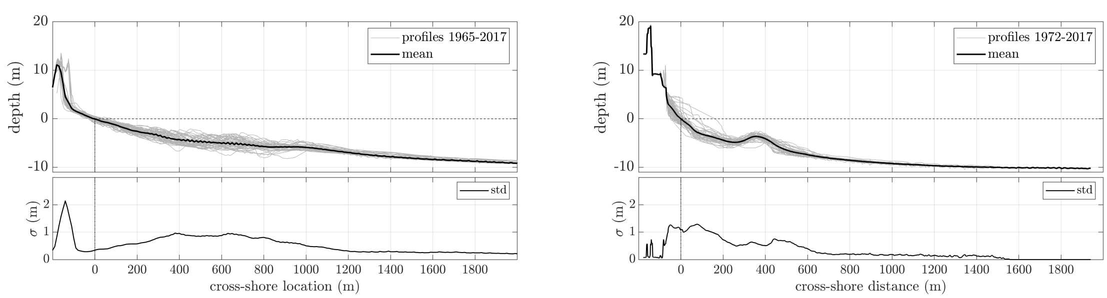
(a) Ameland profile 1600 **(b)** Sylt profile 0+205

Figure 3: Typical spatiotemporal data set coverage

Variability in natural morphodynamics

Thirdly, the natural morphodynamics of the coastal profiles are different. Inter-site differences in coastal profiles and coastal profile dynamics are often related to the beach profile slope i_b and the presence of nearshore sandbars (Wright and Short, 1984). The temporal standard deviation of the cross-shore locations in profiles $\sigma_{z_b'}$ is a commonly used indicator to compare profile dynamics (Larson et al., 2003).

Fig. 4 presents the variability in coastal profile and coastal profile dynamics between Ameland and Sylt. The Ameland profile has a more gentle slope compared to the Sylt profile ((±1:50 and ±1:17.5 between the 0m and 2m depth contours respectively). Furthermore, 2-3 consectutive sandbars are present in the Ameland profile. In the Sylt profile, only 1 sandbar is typically present. In terms of standard deviations, the Ameland profile is characterised by an increasing standard deviation in the nearshore. This increase is the result of inter-annual sandbar migration in the nearshore of Ameland (Ruessink et al., 2003). Sylt's profiles' standard deviaton decreases in the nearshore as no migration of the sandbar is observed. Please note that the Ameland profiles are typically measured in the summer season, and Sylt profiles are measured in both summer and winter season. Following the descriptive beach state model of Wright and Short (1984), the Ameland and Sylt profiles can be classified as more reflective and more dissipative, respectively.



(a) Ameland profile 1600 **(b)** Sylt profile 0+205

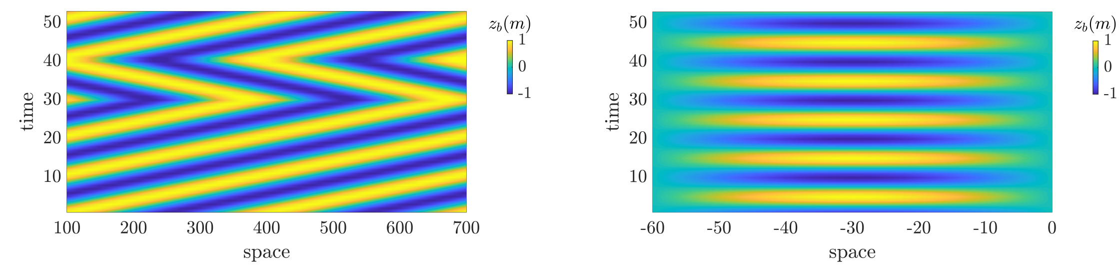
Figure 4: Typical long-term morphodynamic behaviour

Due to the larger number of shoreface nourishments included in the Ameland profile dynamics, in combination with the long-term regular measurements of the nearshore, the focus of this study is on the shoreface nourishments implemented along Ameland ($100 < x < 700$). Since the studied Sylt profile dynamics are mainly interupted by beach nourishments, which are measured individually, the beach nourishments implemented in the Sylt profile are focussed on ($-60 < x < 0$).

METHODOLOGY

To relate nourishment design and nourishment lifetime, the lifetime of individual nourishments is extracted from the data sets. Since different types of morphodynamic behaviour are present at different locations in long and cross-shore direction, and the interest is in the non-stationary effects of the nourishments, the adaptive and non-stationary principle component analysis (PCA) method is applied (also known as Empirical Orthogonal Function (EOF) method (Jolliffe, 2002)).

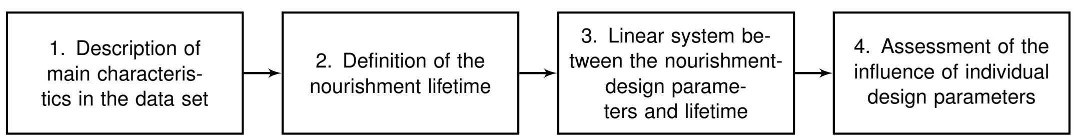
The proposed methodology consists of four steps and is introduced by an application to two artificial data sets. Analogous to the morphodynamic behaviour of the Ameland nearshore and the Sylt beach, these artificial data sets describe a non-stationary migrating wave and a stationary standing wave in time (see Fig. 1a and b). Both waves have an amplitude of 1m and a 10 timesteps period, the migrating wave length is 300m and the standing wave length 120m.



(a) Migrating wave **(b)** Standing wave

Figure 5: Artificial data sets based on the Ameland nearshore (a) and Sylt beach (b)

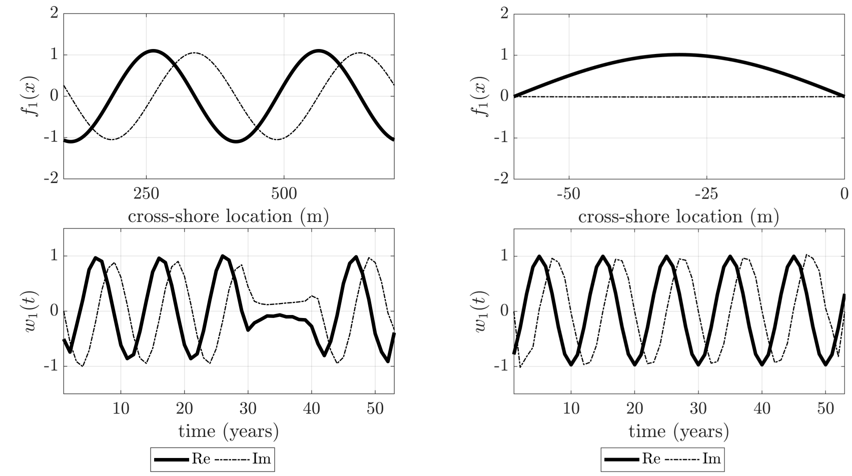
The methodology consists of the following four steps:



Step 1

In step 1, the PCA method is applied to the complete spatial and temporal data sets. The PCA method aims to describe most of the variance in the data sets with individual components, containing a spatial function f_k with temporal weights w_k. The spatial functions $f_{1,2,3...}$ consecutively aim to describe most of the (remaining) variance in the data set. Their temporal weights $w_{1,2,3...}$ indicate how the specific spatial component is fit to the data set in time. A multiplication of the spatial function with a specific temporal weight results in the best-fit profile for the specific time step. In this way, the PCA method adapts to the most present coherent patterns in the data sets (Aubrey, 1979; Wijnberg and Terwindt, 1995). Since both standing and migrating wave patterns are analysed, the complex PCA method (CPCA) is applied to the two individual data sets, which is able to describe migrating patterns in data sets (Ruessink et al., 2003; Larson et al., 2003; Kroon et al., 2008). The CPCA method is the PCA method applied to the temporal Hilbert Transform of the original data set. Accordingly, the real part of the data sets describes the original data set, and the imaginary part a 90 degrees phase shift of the original data. The resulting spatial functions and temporal weight are also complex. Since the imaginary part of the temporal weights is equal to the Hilbert Transform of their real part, the imaginary part can be disregarded.

Fig. 6a and b present the resulting first spatial function and temporal weights of an application of the CPCA method to the artifical datasets. For the migrating wave example, 80% of the variance is described by the first component, 100% of the standing wave variance is described. For the migrating wave, the quarter-wavelength phase delay of the imaginary part on the real part of f_1 indicates that the rightward migrating wave signal is described. w_1 presents the stationary migration during the first 30 and last 12 time steps, as well as the interruption in between. The absence of the imaginary part for f_1 of the standing wave example indicates the standing wave nature (i.e. no phase difference between the real and the imaginary). Since w_1 are normalised, f_1 indicates the absolute maximum elevated beach profile. w_1 presents the stationary migration of the standing wave in time, and simultaneously indicate positive, negative and average beach profile elevations.



(a) Migrating wave **(b)** Standing wave

Figure 6: First components, with spatial functions (top) and temporal weights (bottom).

Step 2

Step 2 aims to determine the lifetime of individual nourishments. The lifetime of a nourishment is defined as a characteristic period of influence on the local natural morphodynamics. The beach volumes is the normally-used indicator to determine the lifetime of beach nourishments (Hanson et al., 2002; Stive et al., 2013). Here, the beach profile elevation is used, which is directly related to the beach volume. The period between the beach nourishment and the following long-term averaged beach profile is defined as the lifetime of beach nourishments. This approach is applicable to beach nourishments that elevated the beach profile from below average to above average. Since shoreface nourishments in fields with nearshore sandbar migration do not elevate the profile in this way, these type of nourishments require a different definition. Therefore, the period of interruption in the migration of the nearshore sandbars is defined as the lifetime of shoreface nourishments (Van Duin et al., 2004; Grunnet and Ruessink, 2005; Ojeda et al., 2008).

Due to the adaptive nature of the PCA method, lifetimes of both types of nourishment can be derived from the temporal weights of the first components. As indicated for the artificial data sets, interruptions in a migrating wave can be detected to identify the lifetime of shoreface nourishments. Profile elevations can be derived from a standing wave to estimate the lifetime of beach nourishments, see Fig. 6a and b.

The following definitions of nourishment lifetimes are used in this study:

Lifetime of beach nourishments in a standing wave profile:
the period the nourishment results in an above-average beach profile elevation

Lifetime of shoreface nourishments in a migrating sandbar profile:
the period the nourishment interrupts the stationary migration of the sandbars

Step 3

As a third step, the derived nourishment lifetimes are related to their design parameters. In order to analyse the direct influence of the individual design parameters, a system of linear equations between the nourishment lifetime and the nourishment design parameters is assumed. In this way, it is assumed that the lifetime of nourishments linearly increases with an increase in the design parameter, and non-linear effects are disregarded. Furthermore, influences of the natural profile dynamics and hydrodynamic forcing on the nourishment lifetime are disregarded here. However, the structure of the methodology allows to include parameters related to profile dynamics and/or hydrodynamics. Eq. 1 presents the linear system that is used here:

$$\begin{bmatrix} c_{n,1} & Z_{n,1} & y_{n,1} & y_{r,n,1} \\ c_{n,2} & Z_{n,2} & y_{n,2} & y_{r,n,2} \\ \dots & \dots & \dots & \dots \\ c_{n,m} & Z_{n,m} & y_{n,m} & y_{r,n,m} \end{bmatrix} \cdot \begin{bmatrix} i_1 \\ i_2 \\ \dots \\ i_k \end{bmatrix} = \begin{bmatrix} L_1 \\ L_2 \\ \dots \\ L_m \end{bmatrix} \tag{1}$$

in which c_n is the alongshore averaged concentration, z_n is the nourishment peak elevation, y_n is the alongshore length and $y_{r,n}$ is the alongshore relative location of the analysed transect relative to the initial nourishment location. The lifetime of the nourishments is indicated with L in *days*. i are the linear coefficients of influence for the design parameters, where k is the number of included design parameters. The number of investigated nourishments is indicated with m and should be larger than k.

Step 4

Finally, in step 4, the derived coefficients of influence i_j are analysed. Goodness-of-fit values between found lifetimes and the predicted lifetimes by the linear system are used to indicate the validity of the linear system assumption. In case of high goodness-of-fit values, the best-fit equation gives an estimate of the nourishment lifetime based on its design parameters as presented hereafter:

$$L_n, j = \sum c_j \cdot P_j \tag{2}$$

RESULTS

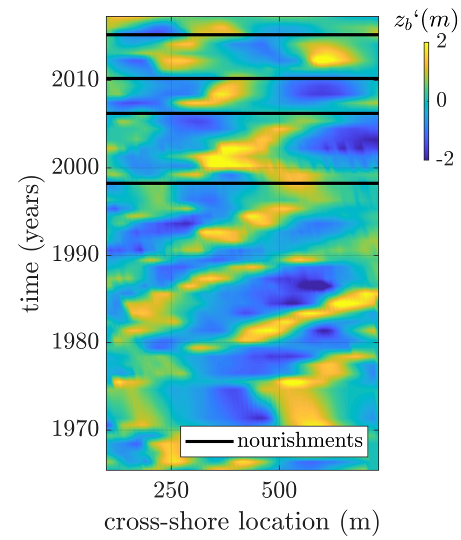
The methodology is applied to data sets of the Ameland nearshore and the Sylt beach. Since the mean profiles dominate the variance in the data sets, the fluctuating depth values z'_b are used as input. The fluctuating data sets of the previously introduced coastal profiles are presented in Fig. 7a and c.

Shoreface nourishments on Ameland

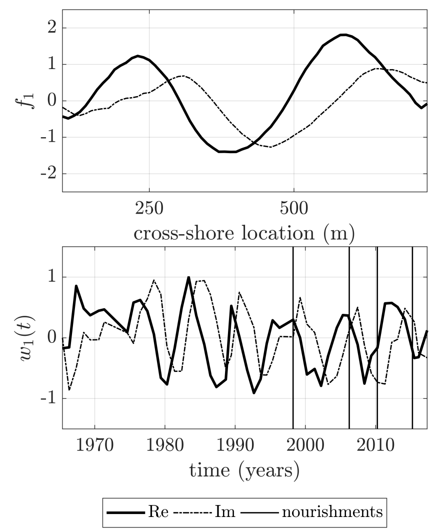
Fig. 7b presents the first component of the Ameland data set. 47% of the variance in the data set is described with this component that, similar to the artificial example, has the characteristics of an offshore migrating wave. The remaining components described interruptions in the sandbar migration as well as longer-term morphodynamics and noise. Hence, the main variance in the data set is the result of an offshore migrating sandbar. The analysis reveals that the shoreface nourishments have an interrupting effect on the offshore sandbar migration and hence, on the temporal weights. A more detailed analysis is required to quantify the periods of these effects. Therefore, this study uses the results of a systematic application of this method to the data set of Ameland (Gijsman et al., in review). Fig. 8a presents the in that study used approach, in which the lifetime is determined based on the correlation between the first component and the original data set. A threshold correlation is used to identify the periods of interruption in the migration of the nearshore sandbars (i.e. lifetime, grey areas in Fig. 8a). For the shoreface nourishments in 1998, 2003, 2006, 2010, 2011 and 2015, the profile on which the specific nourishment had the longest effect (i.e. the maximum lifetime) is used in the analysis. As a result, 6 nourishment lifetimes were determined.

Beach nourishments on Sylt

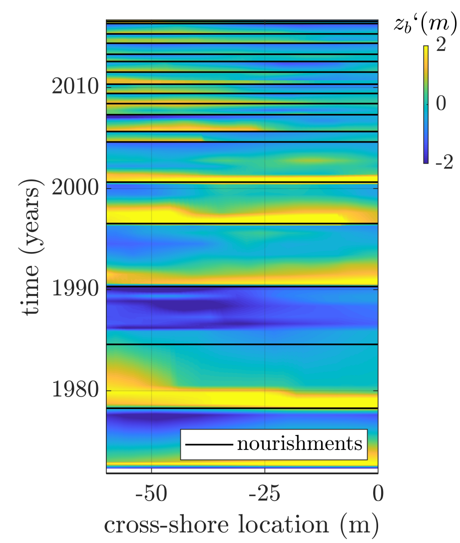
The first component of the Sylt data set describes 88 % of the variance. Similar to the artificial example, the component represents a standing wave, see Fig. 7d. The remaining components described seasonal changes of the beach profile as well as noise. In time, the standing wave is migrating non-stationary, that is abrupt increases as a result of nourishments are followed by gradual beach erosion. Fig. 8b presents the zero-downcrossing times of the temporal weights (i.e. mean profiles). These times give an estimation of the nourishment lifetime (grey areas in Fig. 8b). For the beach nourishments in 1990, 1996, 2000, 2004, 2005, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, the nourishment effect on profile 0+205 is used in the analysis. Due to the insufficient temporal resolution of the measurements before and after, the nourishments in 1972, 1978 and 1984 are disregarded in the analysis. The same hold for the nourishment in 2016, because the next averaged beach profile has not been reached in the data set. Hence, the lifetimes of 14 beach nourishments are determined. The LKN.SH provided the nourishment design parameters (pers. comm).



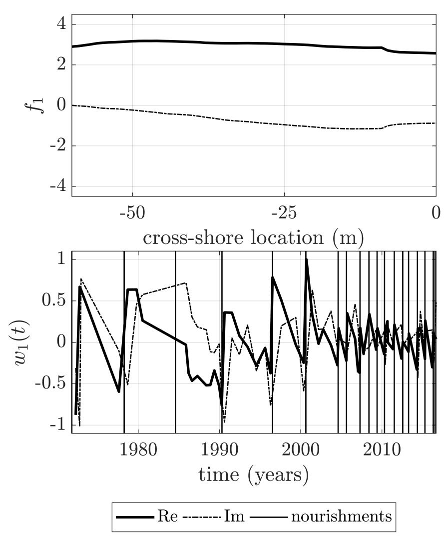
(a) Demeand data set Ameland nearshore



(b) Migrating behaviour of the first component of the Ameland nearshore

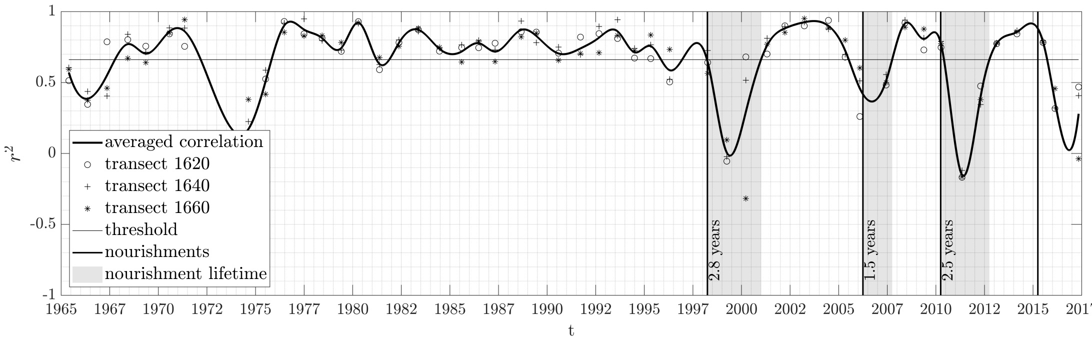


(c) Demeaned data set Sylt beach

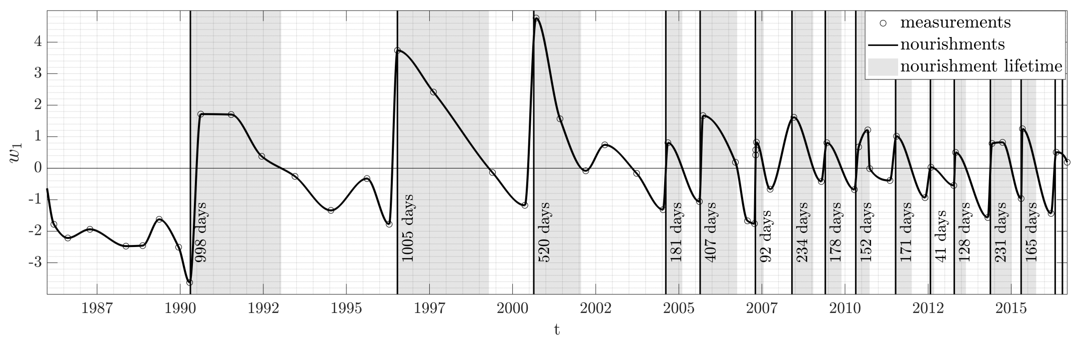


(d) Standing behaviour of the first component of the Sylt beach

Figure 7: CPCA method application to two characteristic coastal profiles



(a) Shoreface nourishments on Ameland (after Gijsman et al., in review)



(b) Beach nourishments on Sylt

Figure 8: Lifetime determination of nourishments placed in two characteristic profiles

The found goodness-of-fit values of the linear system of equations (i.e. 0.79 for the shoreface nourishments and 0.89 for the beach nourishments) are sufficient to draw general conclusions about the influence of the individual parameters. Due to the limited number of nourishments here, the numbers are interpreted qualitatively rather than quantitatively. The coefficients of influence are presented in Tab. 4, and indicate that nourishments with increasing concentration, length and absolute peak elevation increased the nourishment lifetime. A relative location increase (i.e. a more-downstream profile along the nourishment) results in a shorter lifetime for beach nourishments, but a longer lifetime for shoreface nourishments.

	Ameland	Sylt
	Shoreface nourishments	Beach nourishments
Goodness-of-fit	0.79	0.89
Number	6	14
Concentration	+ 3.5 days/m^3	+ 0.7 days/m^3
Length	+ 0.4 days/m	+ 0.2 days/m
Peak elevation	- 4.7 days/m	+ 95 days/m
Relative location	+ 514 days/−	-335 days/−

Table 4: Results of the linear system

DISCUSSION AND CONCLUSION

This study introduces a method that can be used to systematically analyse the influence of nourishment design parameters on the nourishment lifetime. Since the adaptive and non-stationary CPCA method is used to determine periods of influence of the nourishments on the longer-term morphodynamics, the methodology is applicable to shoreface nourishments in fields with nearshore sandbar migration and beach nourishments on an eroding beach. The statistical nature of the method requires a high quality data set, both spatially and temporally. Furthermore, the nourishment effects on the coastal profile dynamics should be sufficiently present in the data set in order to be seperated by the CPCA method. A first application to two high quality data sets in the Netherlands (Ameland) and Germany (Sylt) resulted in the following qualitatively found relations between nourishment design and lifetime at these two locations:

- A linear system with nourishment design parameters (1) concentration, (2) length, (3) peak elevation and (4) relative location can describe most of the variability in the lifetimes of shoreface nourishments (r^2 = 0.79) and beach nourishments (r^2 = 0.89).
- Increasing nourishment concentration, length and absolute peak elevation increase the lifetime of shoreface and beach nourishments.
- In the alongshore downstream direction, the lifetime of beach nourishments decreases and the lifetime of shoreface nourishment increases.

As expected, the concentration is found to have a positive effect on the lifetime of shoreface and beach nourishments. The alongshore length has a positive, but smaller, effect as well. For shoreface nourishments, this relation was discussed by Spanhoff et al. (2006), who argued that this is the result of a larger breaker effect for longer shoreface nourishments. Nourishments that increased the beach profile to a higher elevation resulted in a longer lifetime, as is found for deeper constructed shoreface nourishments. Although Gijsman et al. (in review) found the same relation on a larger scale, it must be noted that the range of this parameter is small for the studied shoreface nourishments here. Finally, a contradicting effect of for locations in the alongshore downstream direction on the lifetime of beach and shoreface nourishments is identified. The lifetime of beach nourishments seems to decrease in the alongshore downstream direction, although the linear relation is questionable in this case. The found increase in shoreface nourishment lifetime in the downstream direction can be attributed to i) the alongshore migration of the shoreface nourishment and/ or ii) the previously mentioned increased breaker effect.

These findings are based on an application to a limited number of nourishments at specific locations for shoreface and beach nourishments. Another limitation of the presented results is the correlation between the design parameters of the nourishments in the data sets. However, a first qualitative insight in the effect of the nourishment design on its efficiency is found for the study areas specifically. Although effects of the natural profile dynamics and hydrodynamic forcing on the nourishment lifetime are neglected in this study, the presented method is able to include additional design parameters as well as parameters related to original profile dynamics and hydrodynamic forcing (up to a number of the studied nourishments) to arrive at nourishment design recommendations for coastal authorities.

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