

## ADVECTION AND DIFFUSION OF SHORE-ATTACHED SAND NOURISHMENTS

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### Abstract

Understanding of the behaviour of coastline perturbations at soft-coastlines is essential for modelling coastal evolution at decadal time scales. Many coastline models do, for example, implicitly assume dominant diffusive behaviour of coastline features. The validity of this assumption is investigated for the Dutch coast on the basis of data on coastline perturbations. Bathymetrical data for a number of nourishments were used to assess the relative importance of diffusion with respect to advection of the sediment along the coast. For this purpose, the volume of sediment is computed for cross-shore transects along the coast. The alongshore distribution of this sediment over time (as a result of dispersion by waves and currents) is then analysed by means of simple shape parameters: a mean alongshore position and standard deviation of the nourishment sand from the centre. Next, the nourishments were also characterized with an advective and diffusive parameter by fitting of an advection-diffusion equation. These parameters then give a classification of the nourishment behaviour. It was found that the behaviour of nourishments at the Dutch coast is dominated by diffusive processes, while advective processes have some influence on the alongshore transport in the shallow part of the surfzone for smaller nourishments.

**Key words:** Coastal morphology, Non-linear coastline response, Advection-Diffusion, Nourishments

### 1. Introduction

A variety of coastline models is available to assess coastline evolution (e.g. Genesis or UNIBEST-CL+). These models do, however, implicitly assume that coastal evolution as a result of wave-driven transport can be described as a diffusive process. These models are not fundamentally different than the diffusion equation that was used by Pelnard-Considere (1956) to model coastline evolution. Standard coastline models can therefore not resolve more complex coastline responses like net alongshore migration, as this requires insight in both the advection and diffusion of the coastline perturbation (Falques, 2003). It is expected that advection can be triggered by specific hydrodynamic conditions, for example, as a result of wind driven currents, asymmetry of the tidal flow and high-angle waves or by feedback between the morphology of the coastline perturbation and hydrodynamics (Ashton & Murray, 2001). Numerical modelling with coastline models has been used in recent years to investigate these effects for flying spits and alongshore sand waves (e.g. Ashton & Murray, 2006, Van den Berg, 2012). Larson & Kraus (1991) applied a more simple approach towards the modelling of the migration of sediment along the coast by means of adding an advective term to the diffusion equation of Pelnard-Considere. Besides the modelling work, Bruun (1954) investigated observations of alongshore sand waves along the Danish coast. While other studies investigated the alongshore sand waves along the Dutch coast (Bakker, 1968, Verhagen, 1989, Ashton et al., 2003, Falques, 2005, Kærgaard & Fredsøe, 2013).

The relative importance of advection and diffusion at coastline perturbations has not been studied in great detail yet. An investigation is therefore started to isolate the advective and diffusive components as found

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in observed coastline evolution of nourishments in field surveys. Artificial nourishments with varying characteristics are investigated for this purpose.

Both advection (i.e. net-alongshore movement) and diffusion are thought to occur at large sand nourishments such as the ‘Sand Motor’ (~ 7,000 to 10,000 m<sup>3</sup>/m; Mulder & Tonnon, 2010). The evolution of smaller nourishments (~ 400 to 1,000 m<sup>3</sup>/m; Van Duin et al., 2004) is thought to be dominated by diffusion. This research aims at investigating this phenomenon using field data of nourishments along the Dutch coast. A characterisation of their behaviour is provided in this paper, which is considered an essential starting point for investigating the processes behind advection and diffusion of nourishments.



Figure 1. Examples of nourishments along the Dutch coast. Left : ‘Sand Motor’ between Monster and Kijkduin in July 2012 ; Right : ‘Sand groynes’ at Monster in October 2009 (Hoekstra et al., 2012)

## 2. Approach

In this study it is hypothesized that the relative importance of advection and diffusion is correlated with the local hydrodynamic forcing conditions as well as the volume and shape of the coastline perturbation. Measured bathymetrical changes were analysed in order to distinguish advection and diffusion in field situations. The advection is quantified on the basis of the alongshore migration (i.e. bias) of the nourishments and diffusion on the basis of the spreading of the sediment relative to the centre of gravity (i.e. standard deviation). For this purpose, the advection and diffusion coefficients (respectively the  $K$  and  $V_s$  parameter) of a modified version of the Pelnard-Consideré equation (eq. 1) are fitted such that observed coastline evolution as a result of the considered nourishment is best represented. Alongshore migration of the nourishment and spreading should be similar for the modelled and observed situations.

$$\frac{\partial y}{\partial t} = K \frac{\partial^2 y}{\partial x^2} - V_s \frac{\partial y}{\partial x} \quad (1)$$

With  $y = \text{cross-shore coastline position [m]}$ ,  
 $x = \text{alongshore position [m]}$ ,  
 $t = \text{time [yr]}$ ,  
 $K = \text{diffusion parameter [m}^2/\text{yr]}$   
 $V_s = \text{advection parameter [m/yr]}$

A number of steps were performed to come to the above described characterisation of the nourishment behaviour.

1. Collection of bathymetrical data of the nourishments
2. Determination of volumes of sediment in cross-shore transects
3. Assess observed nourishment characteristics (i.e. mean alongshore location and standard deviation).
4. Evaluate the diffusion and advection parameters with the modified Pelnard-Consideré equation.
5. Relate the observed nourishment behaviour to the observed conditions.

### 3. Data

The bathymetrical data used in this study concerns information for seven nourishment locations along the Dutch coast. Figure 2 shows the locations of the considered nourishments on a map of the Netherlands.



Figure 2. Overview of locations of considered nourishments along the Dutch coast

The considered nourishments were constructed between 1999 and 2011. The specifications differ considerably with respect to the nourishment shape, sand volumes and position of the nourishment in the cross-shore profile. The data set includes four very different nourishment types along the Delfland coast and four more similar (shoreface) nourishments at other locations along the coast. At the Delfland coast a beach, shoreface, concentrated local nourishment and a mega nourishment were selected (Figure 3). The beach and shoreface nourishment are common nourishment designs for the Dutch coast, while the Sand Groynes and Sand Motor are special nourishments with respect to their volume and shape. The Sand Groynes are three very concentrated nourishments with a very small alongshore footprint compared to regular nourishments (Hoekstra et al., 2012). The Sand Motor is a large spit-like mega nourishment with a size of  $\sim 21$  million  $m^3$  (Mulder & Tonnon, 2010) and an average alongshore sediment volume density of  $8,400 m^3/m$ .

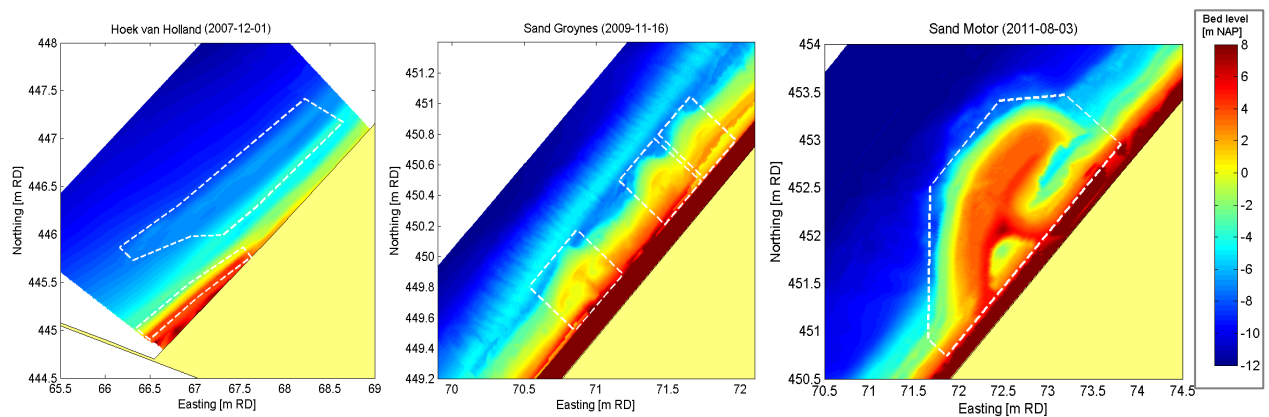


Figure 3. Delfland coast with the bathymetries after construction of the Hoek van Holland nourishments (left panel), the Sand Groynes (middle panel) and the Sand Motor (right panel). The dashed line shows the nourishment area. The locations of these nourishments are shown in Figure 2.

Data of combined shoreface and beach nourishments at the North-Holland and Ameland coast are also used in this study (see Figure 4). The Egmond and Bergen shoreface nourishments are considerably smaller (i.e.  $\sim 900,000 \text{ m}^3$ ) than the nourishments at Ameland and Julianadorp (respectively about 3 and 6 million  $\text{m}^3$ ). The nourishments at Egmond, Bergen and Ameland were placed at a depth of approximately NAP -5 m. The nourishment at Julianadorp extends from the edge of the tidal channel to the dunes. Only about half of this nourishment is located in the part of the profile that is dominated by wave-driven alongshore sediment transport (i.e. estimated to be between NAP-8m and NAP+5m).

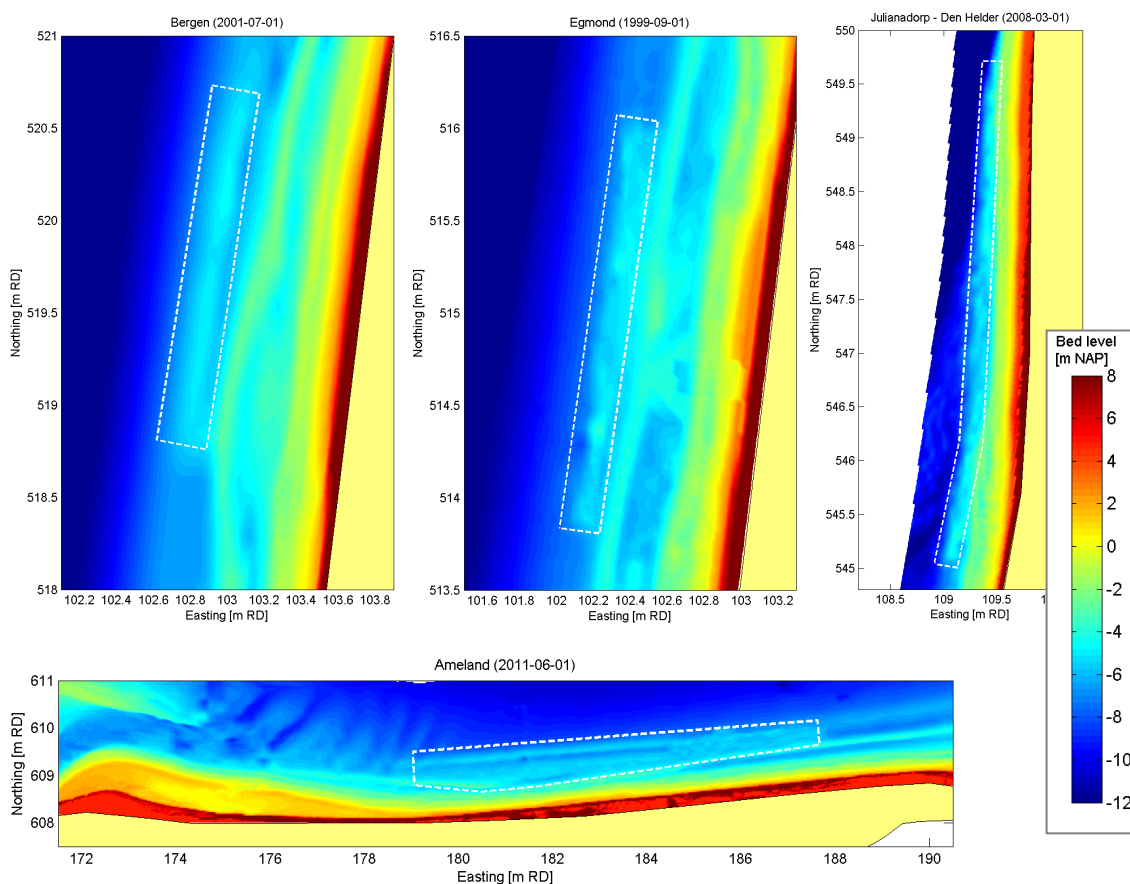


Figure 4. Nourishments along the North-Holland coast (at Egmond, Bergen Julianadorp) and Ameland coast. The dashed line shows the nourishment area.

In-situ multibeam data are the primary source of bathymetrical information in this study. For most locations these are available before and after the construction of the nourishment. Availability of data differs per nourishment. Monthly in-situ bathymetrical data is available for the Sand Motor, but for other nourishments only a limited number of bathymetrical surveys were available. Therefore, the bathymetrical data from annual transect measurements along the Dutch coast (Jarkus data) are used in addition to available surveys. These Jarkus data are used to obtain the reference situation before the nourishments for some of the nourishments (i.e. the Sand Motor, Sand Groynes, Egmond and Hoek van Holland) and for filling gaps in the data. It is noted that the time span of the bathymetrical data for the Sand groynes is very short (i.e. about a month), as other nourishments impacted later measurement data. Table 1 provides an overview of the characteristics of the nourishments and the survey periods. The available bathymetric surveys are referred to in Table 1 as 'reference' survey (before the nourishment), 'initial' survey (directly after the nourishment) and 'final' survey (latest useable survey after the nourishment construction).

Table 1. Overview of nourishment data.

Nourishment name / location	Nourishment type	Construction date	Volume [m <sup>3</sup> ]	Length [m]	Density [m <sup>3</sup> /m]	Bathymetry		
						Reference	Initial	Final
Sand Motor	Large scale	Mar – Aug 2011	21.000.000	2400	8400	Jun 2010	Aug 2011	Dec 2012
Sand Groynes	Local extensions	Oct – Nov 2009	532.000 *	3x 300	600	Jun 2009	Nov 2009	Dec 2009
Hoek van Holland	Beach	Apr – May 2007	744.000	1700	440	Apr 2007	Jun 2007	Oct 2008
Hoek van Holland	Shoreface	Oct – Nov 2007	753.000	3000	250	Oct 2007	Dec 2007	Oct 2008
Egmond	Shoreface	Jun – Sep 1999	880.000	2000	440	Jun 1999	Sep 1999	May 2003
Bergen aan Zee	Shoreface	Apr – Aug 2000	994.000	2000	500	Jul 1999	Jul 2001	Jul 2004
Ameland	Shoreface	May – Oct 2010	3.065.000	6000	500	May 2010	Jun 2011	Apr 2012
Julianadorp (Den Helder)	Beach, Shoreface and Tidal channel	Aug – Dec 2007	6.372.000*	9000	700	Apr 2007	Mar 2008	Apr 2010

\* The first Sand Groyne (~ 137,000 m<sup>3</sup>) was constructed between 15<sup>th</sup> and 20<sup>th</sup> of October 2009. The second Sand Groyne (~ 194,000 m<sup>3</sup>) was constructed between 31<sup>st</sup> and 6<sup>th</sup> of November and the third Sand Groyne (~ 201,000 m<sup>3</sup>) from the 7<sup>th</sup> to the 9<sup>th</sup> of November.

\*\* The nourished sediment at Julianadorp was distributed between the beach (~ 1.4 million m<sup>3</sup>), shoreface area (~ 3.2 million m<sup>3</sup>) and the edge of the tidal channel (~ 1.8 million m<sup>3</sup>). Only about 3 million is located in the active area of the coast that is studied (i.e. between NAP-8m and NAP+5m).

#### 4. Observed nourishment behaviour

The coastal evolution at the nourishments is evaluated on the basis of computed volumes of sediment in the cross-shore transects (at every 10 to 30 m in alongshore direction). The volumes are computed for the full profile as well as for separate horizontal layers which are restricted by pre-defined vertical levels (MSL -8 m, MSL -4 m, MSL and MSL +5 m), which were chosen as they are assumed to represent areas with different processes and response time scales. The dry beach (NAP to NAP +5 m) is dominated by swash and aeolian transport, the shallow water (NAP to NAP -4 m) by quick response time scales due the wave-driven alongshore transport and the deeper layer (NAP -8m to NAP -4m) with similar processes but with a larger response time scale. Morphological changes in deeper water (beyond NAP -8m) are expected to have very long time scales which are not covered by the data. From these volumes a mean averaged cross-shore position can be computed for each layer (or the full profile). Van Koningsveld & Mulder (2004) show the definition of a momentary coastline position which is computed in a similar way. The impact of the nourishment was then determined from the difference between the bathymetry survey before (i.e. 'reference') and after the nourishment ('initial'). Furthermore, a mean alongshore position of the nourished sediment (i.e. additional sediment compared to reference situation before nourishment) is determined for each layer. The spreading is analysed by computing the standard deviation around the mean coastline position (see Table 2).

Table 2. Overview of characteristics of the observed nourishment behaviour.

	Volume change*		Mean position change*		Standard deviation**		
	(NAP-8m to NAP+5m)		(NAP-8m to NAP+5m)		(NAP-8m to NAP+5m)		
	[10 <sup>6</sup> m <sup>3</sup> ]	[% V <sub>ini</sub> /yr]	[m]	[m/yr]	STD(t0) [m]	STD(t1) [m]	[m/yr]
Sand Motor	-0.67	-3%	6	4	658	756	71
Sand Groynes	0.11	+6%	40	487	831	799	-389
HvH beach***	-0.08	-10%	285	219	463	507	34
HvH shoreface****	-0.06	-28%	67	152	646	650	9
Egmond****	-0.30	-10%	354	97	873	619	-69
Bergen****	-0.28	-17%	-449	-150	971	583	-129
Ameland	0.24	+5%	512	613	2370	3008	764
Julianadorp	-0.78	-12%	27	13	1421	1482	29

\* Difference between ‘initial’ and ‘final’ survey (see Table 1)

\*\* Standard deviation of the alongshore distance of the nourished sediment from the centre of mass. Standard deviation is presented for the ‘initial’ situation after construction (t0) and the ‘final’ situation (t1).

\*\*\* Properties of the beach nourishment were determined for the layer from NAP to NAP +5m.

\*\*\*\* Properties of the shoreface nourishments were determined for the layer from NAP -8m to NAP.

Figure 5 shows the aggregated coastal evolution for the Sand Motor and Sand Groynes. The three layers in the plot indicate the alongshore distribution of sediment for the considered three vertical layers (with vertical levels at NAP-8m, NAP-4m, NAP and NAP+5m) at some time after the nourishment construction (i.e. ‘t1’ in Table 2).

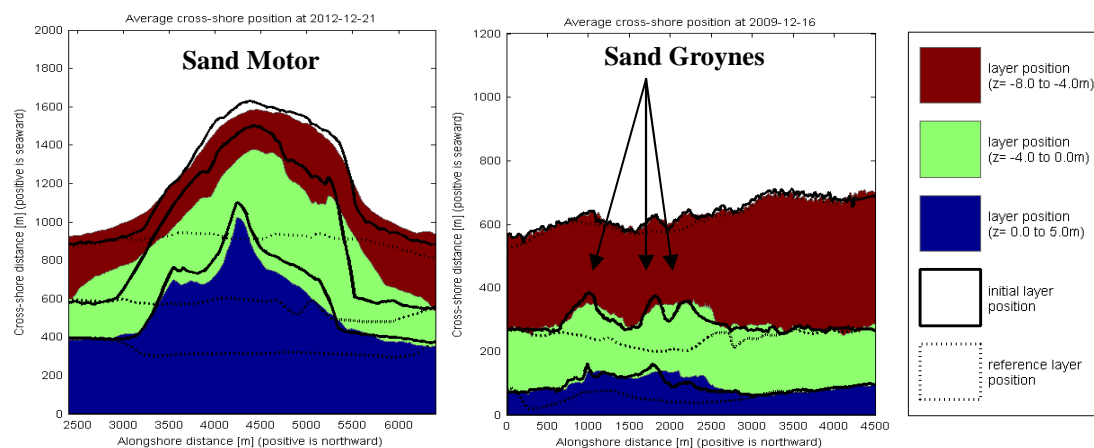


Figure 5. Time evolution of averaged coastline positions in cross-shore profile sections at the Sand Motor (left panel) and the Sand Groynes (right panel) for three depth layers (NAP-8m to NAP-4m, NAP-4m to NAP and NAP to NAP+5m). The ‘initial’ morphology after construction is indicated with the black lines and ‘final’ bathymetry as the stacked coloured bars.

Sand motor data show that the sediment has diffused from the centre to both sides of the nourishments. A small net migration of some metres is observed for the Sand motor (see 4 m/yr migration in Table 2). In contrast the Sand Groynes were somewhat closer to each other after the considered month (see negative change in standard deviation in Table 2) and alongshore migration was very strong (about 40 meter in the first days). It is therefore hypothesized that volume and shape of the nourishment may seriously affect the alongshore migration rate (i.e. advection) of nourishments. Furthermore, the life time of the nourishment may play a role, as temporary conditions from one direction may more strongly affect nourishment advection on shorter time scales and be compensated by other conditions on the longer term. Furthermore, some of the adjustments may be considered as initial adjustments of the nourishment morphology to the local conditions.

The conclusions for the Sand Motor should be somewhat nuanced if the behaviour of the separate layers of the Sand Motor is considered. This shows that little alongshore migration is observed on the dry beach (above NAP) and quite some in the shallow water (below NAP). The shallow water (‘green layer’) shows a large sediment accumulation on the right (i.e. northern side) side of the Sand Motor and a net migration rate of about 25 m/yr, which is expected to be for a large part due to net alongshore transport mechanisms in the surfzone and the smaller response time scales in this zone. A part of this sediment may, however, come from the dry beach which was somewhat eroded at the north-western side (about 700,000 m<sup>3</sup>) of the Sand Motor.

The evolution of the beach and shoreface nourishment at Hoek van Holland (Figure 6) indicates that a shift in alongshore position may also take place for regular nourishments (respectively about 219 and 152 m/yr) as the change in the standard deviation of the nourishment was relatively small (see Table 2). For the beach

nourishment it is, however, unclear to what extent this alongshore migration is the result of advective or diffusive processes. The reason for this is that the Rotterdam harbour moles block southward sediment transport, which hinders the isolation of the advective and diffusive processes.

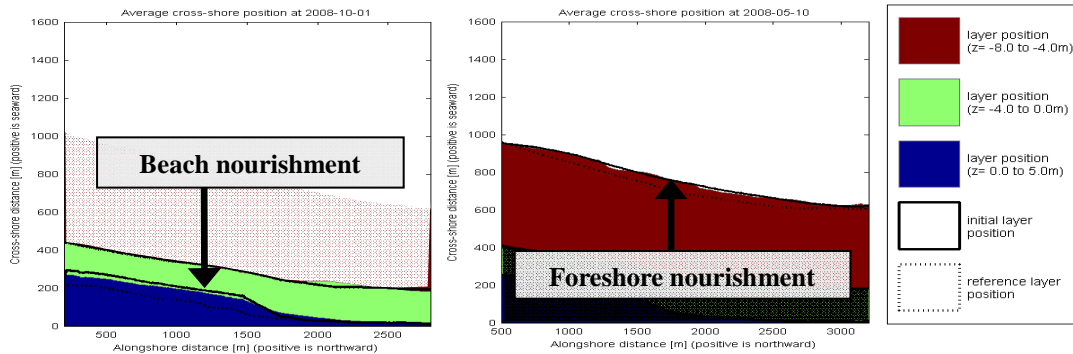


Figure 6. Time evolution of averaged coastline positions in cross-shore profile sections at Hoek van Holland for the shoreface and beach nourishment. The ‘initial’ morphology after construction is indicated with the black lines and ‘final’ bathymetry as the stacked coloured bars.

The shoreface nourishments at Egmond and Bergen aan Zee show a considerable decrease in volume over the considered period (Figure 7). This results in a reduction of the spreading of the nourishment sediment (i.e. negative change in standard deviation) as the remaining nourishment is less elongated. The alongshore migration of these nourishments is opposite to each other, as the Bergen aan Zee nourishment migrated southward (about 150 m/yr) and the Egmond nourishment to the northward (about 100 m/yr). The reason for this difference is not known. It is hypothesised that the regular pattern of alternating sand humps in the surfzone that are present at this stretch of coast may have affected the nourishment behaviour. Furthermore, this may also be related to the variability in the wave climate conditions, as it is for example not known to what extent a single storm can impact the coast here.

The Julianadorp nourishment is also expected to be influenced considerably by erosion (i.e. observed 25% reduction in volume). This erosion takes place along the whole nourishment, but is somewhat larger at the southern end (i.e. left side) due to landward migration of a local tidal channel. The observed net shift in coastline position is therefore not expected to be the result of alongshore sediment transport processes, but due to erosion of the coast. The shoreface nourishment at Ameland has migrated considerably during the monitoring period (about 600 m/yr) and was also spread considerably along the coast (about 760 m/yr difference in standard deviation). Part of the migration may relate to larger erosion on the western side of the coastal section (i.e. left side in the figure). However, the changes are much larger than for the other shoreface nourishments at the Dutch coast. It is therefore likely that the local (hydrodynamic) conditions affected the behaviour of this nourishment. The obliqueness of the incoming waves may play a role.

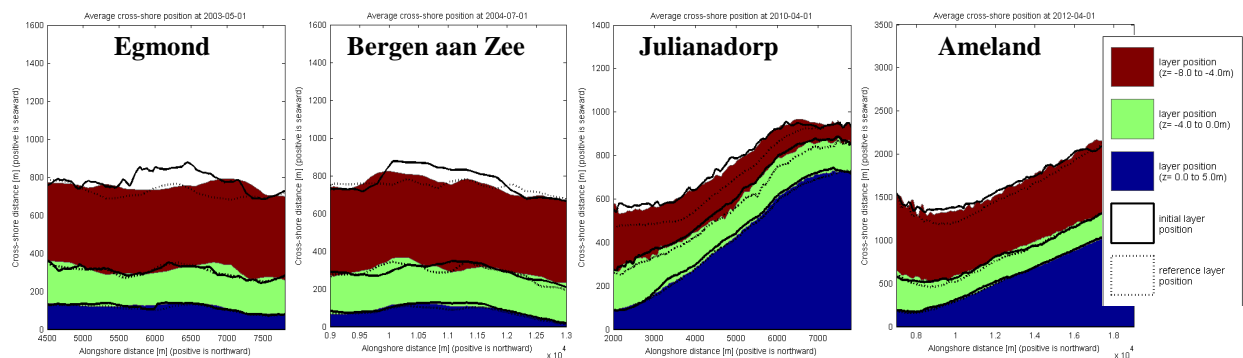


Figure 7. Time evolution of averaged coastline positions in cross-shore profile sections at Egmond, Bergen aan Zee, Julianadorp and Ameland (from left to right panel). The ‘initial’ morphology after construction is indicated with the

black lines and ‘final’ bathymetry as the stacked coloured bars.

On the basis of the observations it is hypothesised that alongshore migration depends on (1) the local hydrodynamic conditions on a stretch of coast which determine the transport capacity, (2) the nourishment volume which determines the inertia of the nourishment and (3) local bathymetrical features.

## 5. Characterisation of nourishment behaviour

A more objective description of the behaviour of the nourishments can be obtained by means of a characterisation with typical advection and diffusion coefficients  $K$  and  $V_s$  (eq. 1). The coefficients in equation 1 are calibrated for this purpose on the available information on the ‘coastline impact’ of the nourishments. The diffusion coefficient ( $K$ ) can be considered a proxy for the alongshore spreading and severity of the local wave climate and the advection coefficient ( $V_s$ ) is a proxy for the alongshore migration rate and net bias of the wave climate.

### 5.1. Methodology

The following steps are performed to come to obtain the characteristic diffusion and advection parameters of the nourishments:

1. The coastline impacts of nourishments are determined from bathymetrical data for a number of moments in time (i.e. at least for the ‘initial’ and ‘final’ survey). For this purpose, the averaged coastline positions from the analyses in Section 4 are used, which are referred to as ‘observed coastlines’.
2. The advection-diffusion model (eq. 1) is then used to assess the coastal evolution for all of the nourishments. The situation directly after construction of the nourishments is used as the ‘initial coastline’. The model uses a grid with a spatial step of 200 meter and a time step of 0.04 year. The active height of the profile corresponds to the height of the considered layer (i.e. 5 meter for the beach nourishment), 8 meter for the shoreface nourishments and 13 meter for the other nourishments for which the whole profile is expected to be impacted.
3. The advection and diffusion coefficient of the model are then calibrated in such a way that the ‘observed coastlines’ are best hindcasted. The gradient descent method (Cauchy, 1847) is used to minimise the squared error between the model prediction and the observed coastline behaviour for all available time instances. For this purpose, two additional runs with slightly modified advection or diffusion parameters are used besides the basic model settings.

### 5.2. Characterisation of coastal evolution at nourishments by advection and diffusion coefficients

The hindcasts of coastal evolution with the optimised advection-diffusion model represent the general behaviour of the coastline evolution as a result of the nourishments quite well (see Figure 8 to 15). The nourishments at the Delfland coast (i.e. Sand Motor, Sand Groynes, Hoek van Holland nourishments) are, however, better represented by the model than the other nourishments. The Delfland coast is therefore expected to be dominated by wave and tide driven alongshore transport processes which can be described with a combination of alongshore advection and diffusion.

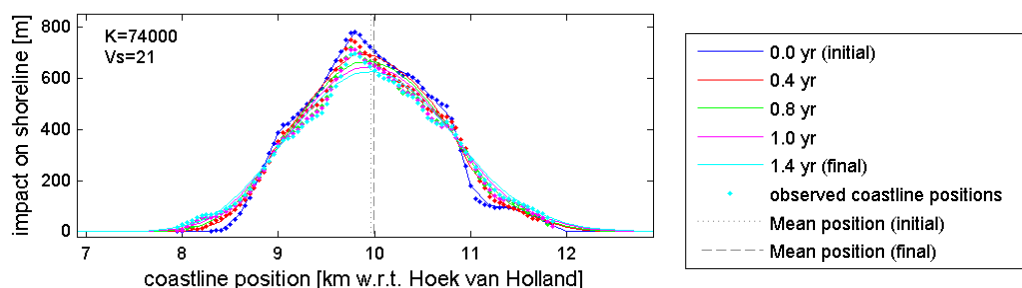




Figure 8. Modelled and observed coastline position at the Sand Motor with optimised coefficients

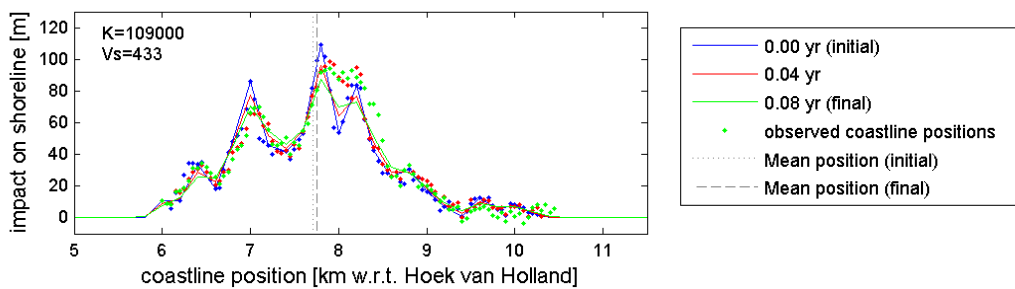


Figure 9. Modelled and observed coastline position at the Sand Groyne with optimised coefficients

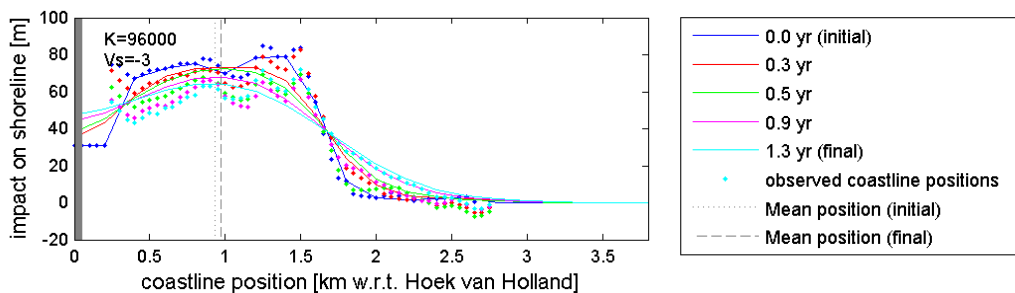


Figure 10. Modelled and observed coastline position of the beach nourishment at Hoek van Holland with optimised coefficients

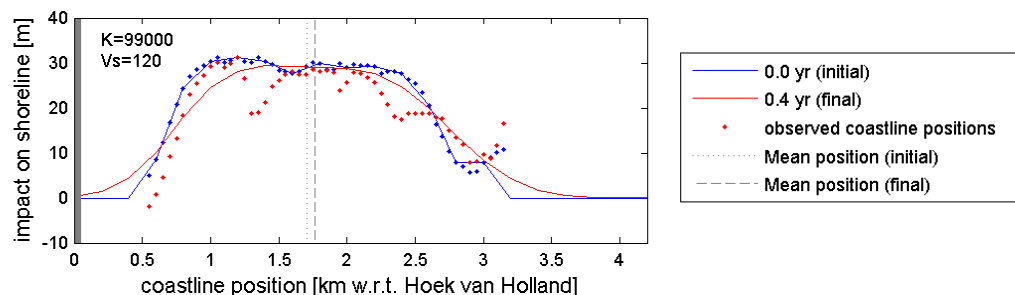


Figure 11. Modelled and observed coastline position of the shoreface nourishment at Hoek van Holland with optimised coefficients

More variability is observed at Egmond and Bergen aan Zee. The Egmond and Bergen aan Zee nourishments migrated about 5% of their alongshore length per year. However, the local coastline development here seems to be influenced by more than the combination of advection and diffusion, as it shows a very strong depression in the middle of the nourishment. It is therefore expected that (among others) cross-shore transport processes contributed to the local coastal evolution at these nourishments. Furthermore, it is noticeable that the coast at Egmond and Bergen aan Zee is characterised by a regular pattern of alternating sand humps which migrate along the coast. It is therefore also hypothesised that these local bathymetrical features significantly affect the behaviour of the nourishment. The alongshore migration of the nourishments at Egmond and Bergen aan Zee is larger than the migration of the shoreface nourishment at the Delfland coast. Furthermore, it is noticeable that the Egmond and Bergen aan Zee nourishments migrate in opposite directions, which is not likely due to the wave climate (which is similar). It is therefore hypothesised that this is the result of cross-shore transport processes or an adaptation of the nourishments to local bathymetrical features (like alongshore sand waves).

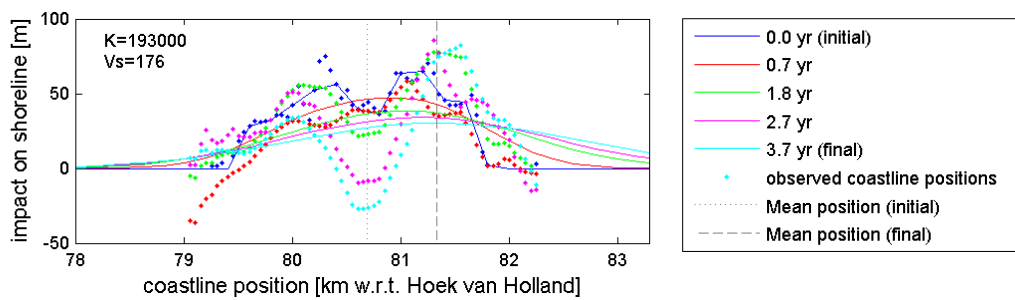


Figure 12. Modelled and observed coastline position at the Egmond shoreface nourishment with optimised coefficients

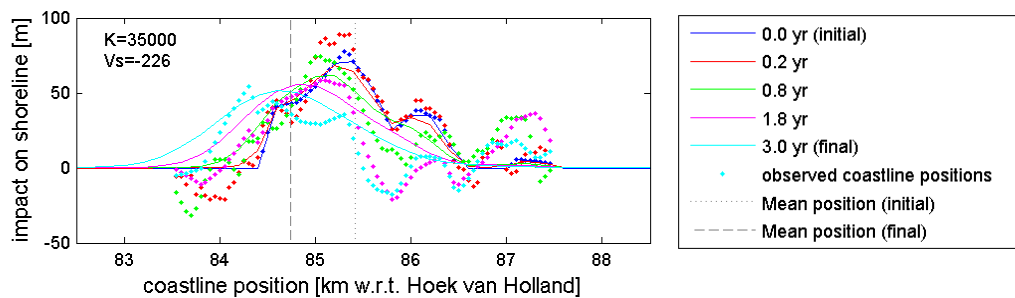


Figure 13. Modelled and observed coastline position at the Bergen aan Zee shoreface nourishment with optimised coefficients

The coastline development at Ameland and Julianadorp generally is represented quite well with the calibrated advection-diffusion model. It does, however, show some locations where the coastline regression is larger than at other parts of the nourishment. A regular pattern with a length scale of 2 to 3 kilometres may be distinguished here (e.g. for  $x=112$  and  $114$  km at Julianadorp). It is hypothesized that cross-shore transport towards a nearby tidal channel plays a role at the Julianadorp nourishment. Furthermore, regular coastline humps can be observed at the western end of the Ameland nourishment in the final situation (at  $x=7$  to  $9$  km). These coastline features are expected to be related the result of the landing of the ebb-tidal shoal of the Amelander Zeegat on the coast of Ameland and subsequent local spit development. Furthermore, it is noted that the observed coastline development at Ameland shows that additional sediment was nourished at the eastern side during the observation period. This hindcast is, however, still considered valuable for the western part.

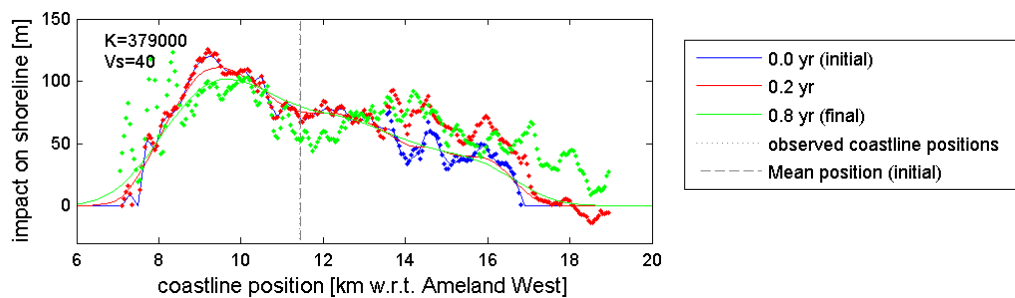


Figure 14. Modelled and observed coastline position at the Ameland nourishment with optimised coefficients

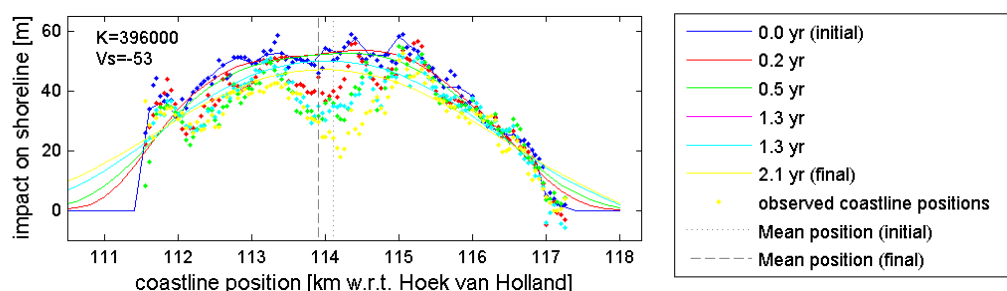


Figure 15. Modelled and observed coastline position at the Julianadorp nourishment with optimised coefficients

An overview of the calibrated coefficients of the advection-diffusion model that best represent the observed coastline development are presented in Table 3.

Table 3. Overview of optimal advection and diffusion parameters.

Location	Model settings			Measured		Modelled	
	Hactive [m]	K [m <sup>2</sup> /yr]	V <sub>s</sub> [m/yr]	dμ [m/yr]	dSTD [m/yr]	dμ [m/yr]	dSTD [m/yr]
Sand Motor	13	74000	21	6	71	9	77
Sand Groynes	13	109000	433	40 *	-389 *	393	72
HvH beach	5	96000	-3	285	34	156	17
HvH shoreface	8	99000	120	67	9	106	17
Egmond	8	193000	176	354 **	-69 **	70	60
Bergen aan Zee	8	35000	-226	-449 **	-129 **	-210	38
Ameland	8	379000	40	512 ***	764 ***	99	112
Julianadorp	13	396000	-53	27	29	32	21

\* The Sand Groynes get more compact initially resulting in a negative change in standard deviation

\*\* Expected to be influenced by cross-shore transport processes resulting in a negative change in standard deviation

\*\*\* Influenced by a smaller nourishment at the eastern side of Ameland within the considered timeframe

The magnitude of the diffusion of the sediment at the Delfland coast is found to be quite constant (order  $7 \cdot 10^4$  to  $10^5$  m<sup>2</sup>/yr). This gives an indication that the severity of the climate determines the local diffusion of the nourishments, as the wave climate is more or less similar for these nourishments. This is in line with Larson & Kraus (1991) who show that the diffusion coefficient is related to the transport capacity. The smaller diffusion coefficient at the Sand Motor is expected to be related to a physical restriction in the maximum transports as they are limited by the local sediment transport capacity. The diffusion at Egmond and Bergen aan Zee is considered not very representative, as other processes are expected to influence it considerably (e.g. cross-shore transport processes and local bathymetrical features). At Ameland and Julianadorp the diffusion coefficient was higher than at the Delfland coast, which can be explained by the more severe wave climate at these locations. It is noted that modelled and computed standard deviation differ considerably for the nourishments at the Sand Groynes, Egmond and Bergen aan Zee. This means that the nourishments initially get more compact (i.e. negative change in the standard deviation), which can not be modelled with the advection-diffusion equation. While the observed coastline development at Ameland differs from the computed development as sediment was nourished at the eastern side of Ameland during the observation period.

The alongshore migration rate was found to be larger for smaller nourishments, nourishments that are placed in the middle of the surfzone and for nourishments in the northern part of the Netherlands. Furthermore, temporary conditions (e.g. south-westerly storms) are expected to influence the migration rate of smaller nourishments. A smaller relative influence of advection is expected if the nourishment is placed on the dry beach or in great volumes (e.g. 'Sand Motor'). This influence of the nourishment volume seems

to be logical as a very large nourishment has more inertia than a small one.

The advection of nourishments is therefore assumed to be an independent absolute process which is not influenced a lot by the nourishment. Consequently, the relative influence on small features is bigger than on very big features. Next to this, it is noted that the Hoek van Holland beach nourishment is not influenced as much by advection as the other nourishments. The 'migration rate' is considered a less suitable parameter for this beach nourishment, as it is enclosed on one side by a breakwater. Due to this enclosure the net diffusion to one side is blocked, which results in a 'migration rate' that partly consists of diffusive processes (i.e. normal spreading of the nourishment to one side). The advection coefficient is therefore expected to be a better means of assessing the coastline behaviour for the beach nourishments.

## 6. Conclusions on advection and diffusion of nourishments along the Dutch coast

This paper investigates the coastal evolution at eight artificial nourishments with varying characteristics on the basis of bathymetrical field surveys. The aim of the analyses is to isolate the advective and diffusive components as found in the observed coastline evolution. A number of conclusions come forward from the analyses in this paper:

- The evolution of coastline perturbations along the Dutch coast is dominated by diffusion. Advection of nourished sediment, however, does contribute to local coastline evolution for some of the nourishments. This holds especially for small to moderately large nourishments in the active part of the surfzone (e.g. shoreface nourishments). For example, the Egmond and Bergen aan Zee nourishments migrated about 5% of their initial alongshore length per year. It is, however, noted that it is expected that the Egmond and Bergen nourishments are influenced by cross-shore sediment transport processes and local bathymetrical features (i.e. regular sand humps with a length scale of some kilometres).
- Diffusion of nourishments is expected to be related to the severity of the local hydrodynamic climate rather than to the properties of the nourishments, as the diffusion was more or less similar for all of the nourishments along the Delfland coast. Only for a mega nourishment (i.e. 'Sand Motor') the diffusion coefficient is somewhat lower, which is expected to be due to the large net transports that are limited by the local transport capacity.
- The advection of nourishments is expected to be correlated to the specifications of the nourishment. Aspects like the position in the profile, the size of the nourishment and the local hydrodynamic conditions affect the relative contribution of advection (or alongshore migration). The advection of nourished sediment was observed more strongly in the shallow part of the surfzone (NAP-4m to NAP) than in the other layers (e.g. for Sand Motor). Furthermore, temporary hydrodynamic conditions (e.g. south-westerly storms) have a larger impact on the initial development of small nourishments.

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