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DOI

[10.1016/j.geomorph.2020.107522](https://doi.org/10.1016/j.geomorph.2020.107522)

Publication date

2021

Document Version

Final published version

Published in

Geomorphology

Citation (APA)

Ton, A. M., Vuik, V., & Aarninkhof, S. G. J. (2021). Sandy beaches in low-energy, non-tidal environments: Linking morphological development to hydrodynamic forcing. *Geomorphology*, 374, 1-11. Article 107522. <https://doi.org/10.1016/j.geomorph.2020.107522>

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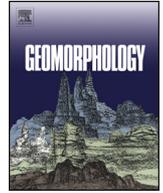
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Sandy beaches in low-energy, non-tidal environments: Linking morphological development to hydrodynamic forcing

Anne M. Ton^{a,*}, Vincent Vuik^{a,b}, Stefan G.J. Aarninkhof^a

^a Delft University of Technology, Civil Engineering and Geosciences, P.O. Box 5048, 2600 GA Delft, the Netherlands

^b HKV Consultants, P.O. Box 2120, 8203 AC Lelystad, the Netherlands

ARTICLE INFO

Article history:

Received 20 May 2020

Received in revised form 13 November 2020

Accepted 17 November 2020

Available online 20 November 2020

Keywords:

Low-energy

Sandy lake beach

Morphodynamics

Depth of closure

ABSTRACT

The morphodynamic behaviour of low-energy beaches is poorly understood, compared to that of exposed coasts. This study analyses the morphological development of sandy, low-energy beaches and the steering hydrodynamic processes. Four densely-monitored study sites in the non-tidal lake Markermeer in the Netherlands offered a unique opportunity to examine the relation between their hydraulic boundary conditions and morphodynamics. Regular bathymetric surveys were executed at all locations. Furthermore, the wave climate was monitored at one of these four sites. All four sites exhibit a commonly found low-energy beach morphology, with a narrow beach face and a low-gradient, subaqueous platform. This platform reaches an equilibrium depth quickly and then stays relatively stable. The stable elevation of the platform is located near Hallermeier's depth of closure. A sediment budget analysis over time demonstrates that the beach faces at all study sites have eroded during more energetic periods, and sediment accumulated offshore. During the monitoring periods of 2 to 4 years, the elevation of the platforms reached an equilibrium, but other morphological dimensions are still developing. The new insights gained from this study enable the prediction of platform elevations along sandy beaches in low-energy, non-tidal environments, and have contributed to our insight in the underlying processes driving the morphological evolution.

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1. Introduction

Coastal regions near open coasts, estuaries and lakes are some of the most densely populated regions of the world. Knowledge on morphodynamics is crucial for protecting and managing these areas. Most coastal research concerns high-energy or open coasts. Low-energy or sheltered beaches are expected to have similar, but less pronounced, morphodynamics compared to high-energy beaches. Therefore, only few studies have focussed on low-energy coasts (Lorang et al., 1993b; Nordstrom and Jackson, 2012; Eliot et al., 2006; Vila-Concejo et al., 2020), implying that the knowledge on physical processes and morphodynamics in this field lags behind that of exposed beaches. Despite the importance of low-energy beaches for coastal protection, recreation, and ecology, morphodynamics remain poorly understood.

The terms low-energy, fetch-limited and sheltered are often used alternately to describe similar environments, such as the beaches of estuaries-, lakes, and reservoirs (Jackson et al., 2002; Nordstrom and Jackson, 2012). The exact characteristics are poorly defined in the literature (Goodfellow and Stephenson, 2005; Nordstrom and Jackson, 2012). According to Jackson et al. (2002), definitions of low-energy vary from very small prevailing significant wave height, $H_s < 0.10$ m (Nordstrom et al., 1996), to limited storm wave height, $H_b < 1.0$ m

(Hegge et al., 1996). The influence of tides is not explicitly considered in the definitions. In all definitions, it is agreed that morphological changes are storm-driven, as prevailing wave conditions have limited reshaping capacity (Jackson et al., 2002; Nordstrom and Jackson, 2012).

Jackson et al. (2002) found that low-energy tidal sandy beaches often have a narrow, steep foreshore, with seaward a low gradient, subaqueous terrace. This terrace is often referred to as a "low tide terrace", "sub-tidal terrace" or "platform" and may be vegetated (Travers et al., 2010). Several sites with such low-energy conditions and morphology are described in the literature (Eliot et al., 2006; Goodfellow and Stephenson, 2005; Lorang et al., 1993b; Lowe and Kennedy, 2016; Mujal-Colilles et al., 2019; Nordstrom et al., 1996; Vila-Concejo et al., 2010).

Besides describing and analysing low-energy sites, several scholars have aimed to develop conceptual models describing the morphotype of these beaches. These descriptions range from beach states applicable to all energy levels (Wright and Short, 1984) to morphotypes for the low-energy beach face only (Makaske and Augustinus, 1998). Although all these models roughly point in the same direction, described in Section 2, the morphotypes are based on varying indicators. Some are based on wave energy and sediment characteristics, others just on one of both, or even just on the location of the beach (for a review, see Vila-Concejo et al. (2020)). Therefore, the morphodynamics of low-energy beaches as well as their most important drivers are largely unknown. Four study sites in lake Markermeer, the Netherlands, provide a unique opportunity to study the morphology of low-energy, non-tidal, sandy

* Corresponding author.

E-mail address: a.m.ton@tudelft.nl (A.M. Ton).

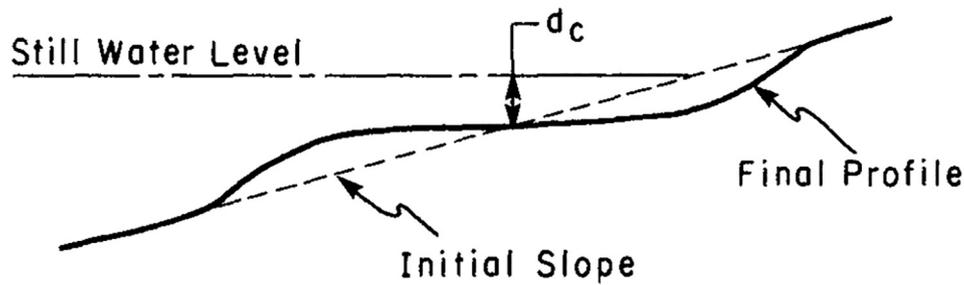


Fig. 1. Equilibrium profile with sub-marine cut or wave cut as found from laboratory experiments with constant waves on an initially plane slope (reused from Hallermeier, 1979).

beaches. These beaches are subject to low-energy waves and have the commonly found steep foreshore and low-gradient platform.

The general profile shape of low-energy beaches is similar to profiles found in laboratory experiments with constant waves on an initially plane slope of sediment (Hallermeier, 1979). From these laboratory results, Hallermeier (1979) concluded that under controlled wave conditions, commonly an equilibrium profile is reached with a platform, which he called the submarine cut or wave cut with water depth d_c (Fig. 1). According to Hallermeier (1979), the equilibrium depth of this platform is at the depth where the surface waves reach the limit of their erosive action.

Hallermeier (1980) developed a theoretical formulation to estimate the depth of closure, the depth at which wave action has negligible effect on sediment transport (d_s). It is calculated as follows:

$$d_s = 2.28H_{s,12h} - 68.5 \frac{H_{s,12h}^2}{gT_{p,12h}^2}, \tag{1}$$

where $H_{s,12h}$ (m) and $T_{p,12h}$ (s) are the nearshore significant wave height that is exceeded for 12 h per year and its associated wave period, and g is the gravitational acceleration (m/s^2). Hallermeier (1980) validated this formula with measured values for d_c from laboratory tests. The laboratory experiments are representative for the hydrodynamic conditions and morphological platform development at our study sites, as is confirmed in Section 4.1.

This study aims to analyse the morphological development of sandy, low-energy beaches and its relation to hydrodynamic forcing. Our central hypothesis is that the platform elevation at the study sites is governed by the depth of closure according to Hallermeier (1980).

The next section describes conceptual models regarding morphotypes of low-energy beaches. Section 3 describes the field sites and methods. Section 4 shows the bathymetric features of the study sites, a

quantification of hydrodynamic forcing and its relation to the cross-shore profile. In Section 5 these results are discussed and lastly, Section 6 gives the conclusions.

2. Low-energy beaches - morphotypes and classifications

Several researchers have pursued to classify the low-energy beach and describe its shape in different morphotypes. Wright and Short (1984) describe the beach state based on the dimensionless fall velocity, given by $\Omega = H_b/(w_s * T_p)$, where H_b is significant breaking wave height (m), w_s is fall velocity (m/s) and T_p is peak wave period (s). Beach states ranging from reflective ($\Omega < 2$) to intermediate ($2 < \Omega < 6$) to dissipative ($\Omega > 6$) are described and linked to wave steepness and sediment characteristics. A reflective morphology is expected for low-energy beaches. Features of a reflective beach according to Wright and Short (1984) are a steep, usually linear, beach face, with on the offshore side a pronounced step, after which the bed slope decreases considerably. Although beach states for a wide range of Ω (1 to >6) are described, the method is derived from high-energy beaches. Therefore doubts exist on whether low-energy beaches fall within the scope of this approach. Jackson et al. (2002) state that low-energy beaches can be classified as either reflective or dissipative if the nomenclature by Wright and Short (1984) is followed, since rips and other 3D bed forms are not observed at low-energy beaches. Hegge et al. (1996) consider low-energy beaches to be described by the reflective beach state. However, the single reflective beach state cannot adequately describe the wide range of profile slopes and concavities observed on low-energy beaches. Therefore they identified four classifications from 52 low-energy beach profiles, categorized by dimensions, slope curvature and grain size. The morphotypes for low-energy shores, ordered from less to more exposure are: (1) concave, (2) moderately concave, (3) moderately steep, and (4) stepped, with the latter as exception since this type does not fit in this order (Fig. 2). The beaches were ordered from fully

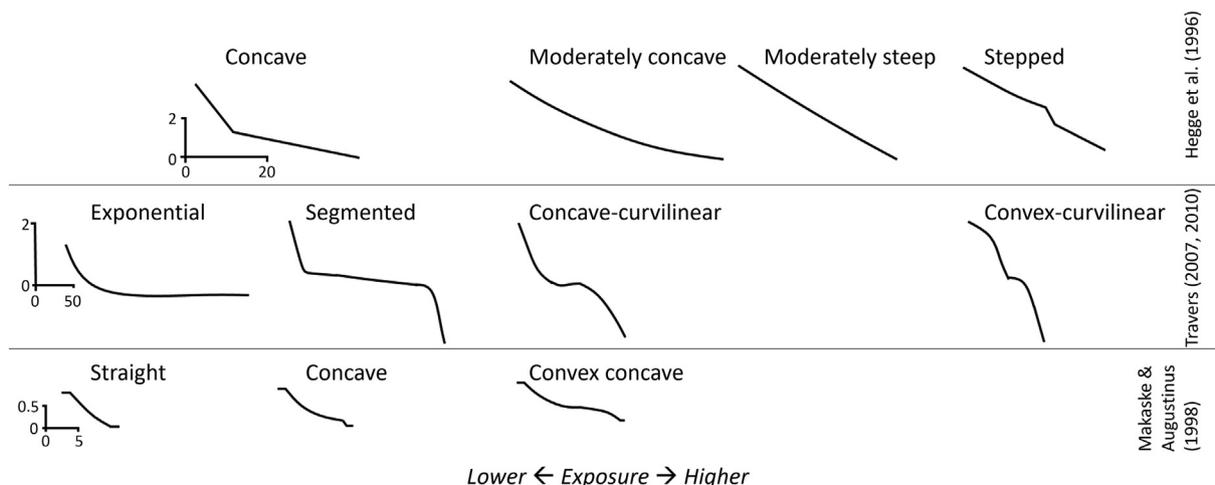


Fig. 2. Low-energy cross-shore beach morphotypes by and adjusted from Hegge et al. (1996), Travers (2007) and Makaske and Augustinus (1998).

protected to fully exposed based on hydrographic charts, leaving hydraulic conditions unquantified.

Similar to the analysis by Hegge et al. (1996), Travers (2007) identified four low-energy beach types. She quantified the exposure with the exposure factor $E_f = \log(FI/M_s)$, where FI is the direct fetch length and M_s is the marginal shoal width. The most protected sites have the lowest exposure factor. From least to most exposed, the beach types are: (1) exponential, (2) segmented, (3) concave-curvilinear and (4) convex-curvilinear (Fig. 2).

Although the shapes by Travers (2007) are different from Hegge et al. (1996), the general outline is quite similar. More sheltered beaches show a more pronounced terrace, while more exposed shores have a more or less plane slope.

Besides these state classifications, some conceptual models for the beach face of low-energy beaches have been developed. Based on field sites in estuaries in the U.S.A., Jackson and Nordstrom (1992) give a qualitative description of the morphodynamics. They found that sediment exchange is limited to a zone between the upper limit of swash at high water and the break in slope separating the foreshore from the low-tide terrace, since there is insufficient energy to mobilize sediment on the low-tide terrace. During a typical storm, the upper foreshore would erode and the sediment would be deposited on the lower foreshore. Parallel slope retreat of the foreshore can occur as a result of high-energy events or prolonged periods of unidirectional longshore currents.

A second low-energy beach face model is developed by Makaske and Augustinus (1998). They described the morphological changes of the micro-tidal, low-wave beach face of the Rhone Delta in France, to extend the study by Wright and Short (1984). Cross-shore profiles were measured during one spring-neap tide cycle, excluding storm conditions from the results. Three types of “base profiles” were defined, ordered from lower to higher wave energy: the straight profile (daily $H_b < 0.25$ m), the concave profile and the convex-concave profile (daily $H_b > 0.35$ m).

The different morphotype models coincide more than seems. Fig. 2 shows the conceptual models ordered from less (left) to more (right) exposure. Similar profile shapes from different sources are aligned vertically. For instance, the straight beach face coincides with the exponential/concave profile and a convex concave beach face is similar to the concave-curvilinear and moderately concave profile.

In summary, the least exposed sites generally have the steepest and narrowest beach face and the strongest breaks between the swash zone and the terrace. The different models all point towards wave energy and sediment characteristics as drivers for different morphotypes, but quantification is different per study or even absent. The physical relation between hydrodynamics and morphology has at most been described in general terms and morphological evolution over time has received even less attention.

3. Study sites & methods

3.1. Study sites

As mentioned above, the four study sites are artificial beaches located in lake Markermeer. Lake Markermeer is a shallow (~4 m deep) inland fresh-water lake without tide in the Netherlands (Fig. 3). The lake has regulated summer and winter water levels, respectively NAP -0.2 m and -0.4 m, where NAP is the vertical reference datum in the Netherlands, close to mean sea level. Since waves are fully determined by local wind in this area, on average coming from the southwest, there is a strong positive correlation between wave height and wind set-up (Steetzel et al., 2017). Since the lake is shallow, waves are depth-limited. The significant wave height does not exceed 1.5 m and the peak wave period is typically between 2.5 and 3.5 s during storms. Average and 95-percentile values of the significant wave height do not differ much between the study sites (Table 1). Lake Markermeer is separated from Lake IJsselmeer by a dam, the Houtribdijk, which is the

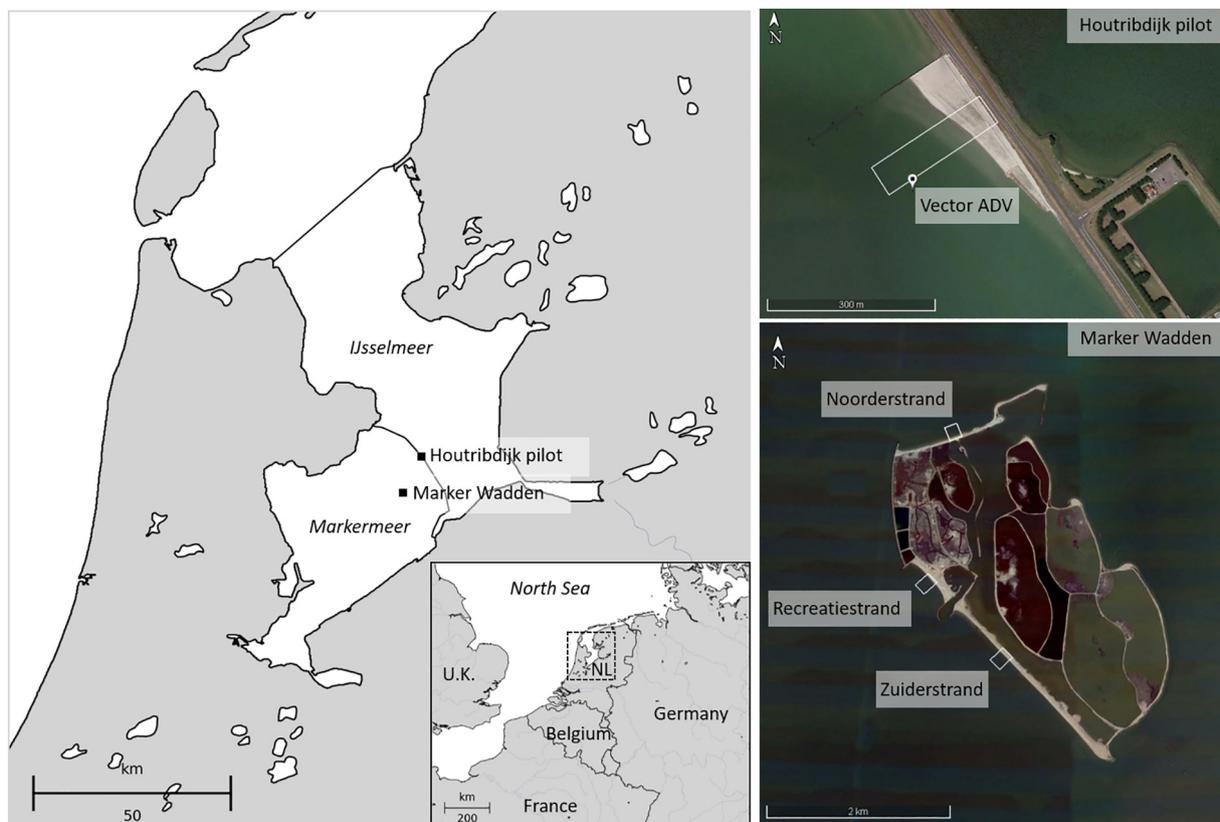


Fig. 3. Overview location of the study sites, Pilot Houtribdijk and Marker Wadden beaches, in the Netherlands (NL), with considered transects within the white boxes. Right images from Google Earth, Landsat/Copernicus.

Table 1
Significant wave height characteristics study sites.

	Mean H_{m0} [m]	95-percentile H_{m0} [m]	Period
Pilot Houtribdijk	0.20	0.54	Oct 2014 – Mar 2018
Noorderstrand	0.26	0.53	Apr 2019 – Sep 2019
Zuiderstrand/Recreatiestrand	0.27	0.63	Apr 2019 – Sep 2019

location of the first study site, the Pilot Houtribdijk (Fig. 3). This was a pilot study into dike reinforcement by sandy foreshores (Penning et al., 2015). The 300 m long beach, closed off by a sheet pile wall at the northwest side, was constructed and monitored from 2014 until it merged into the sandy dike reinforcement in 2018. The other three study sites are located at the Marker Wadden, constructed in 2016 (Fig. 3). This artificial archipelago consists of shallow marsh islands, protected by three stretches of sandy beaches and dunes and is meant to improve water quality and ecological habitats in this area. Pilot Houtribdijk was constructed of sand with a D_{50} of 270 μm and the Marker Wadden beaches of sand with a D_{50} of 350 μm .

3.2. Monitoring

At all sites, bathymetric data was collected using a singlebeam (Pilot Houtribdijk) or multibeam (Marker Wadden) echosounder, while shallow bathymetric data were measured by a moving RTK-GNSS-carrier (Rijkswaterstaat and Stichting EcoShape, 2018). The GNSS carrier was also used to monitor topography at Pilot Houtribdijk, while at the Marker Wadden, topographic data was collected by aerial mapping with a drone (structure-from-motion) (Natuurmonumenten, 2019). The singlebeam and multibeam have a typical vertical accuracy of respectively ± 0.1 and ± 0.2 m, while the RTK-GNSS and aerial mapping respectively have a typical vertical accuracy of ± 0.03 m and ± 0.05 m.

At Pilot Houtribdijk, 43 transects with a spacing of 15 m were monitored from September 2014 to March 2018 at 23 occasions, with intervals ranging from 1 to 6 months (Table 2, Fig. 4). The measurements from January 2018 onwards are not taken into account, since the Pilot was excavated for other research purposes at that time. Longshore transport was evident at this location, proven by the rotation of the beach face due to varying wave angles. The platform elevation is similar over all transects (Fig. 4), so to limit the effect of the rotation in the analysis, only the transects in the centre of the area (transect 10–14) are considered in this study. Morphological development of this 60 m wide area is studied by averaging these 5 profiles. At all three study sites on the Marker Wadden, 9 profiles with a spacing of 20 m were monitored every 3 months, from July 2018 to September 2019, and the same averaging method is followed (Fig. 4).

Incoming waves and flow velocities were recorded from October 2014 to March 2018 by an underwater frame with a Nortek Vector ADV (8 Hz, velocity measurement point NAP-1.64 m, pressure gauge NAP-1.44 m), 100 m offshore of Pilot Houtribdijk (Steetzel et al.,

2017). The measurements were done in bursts of 8 min per hour and corrected for atmospheric pressure and pressure attenuation.

3.3. Depth of closure

To confirm that the morphological evolution of lake Markermeer beaches aligns with the conditions considered by Hallermeier (1980), we predict the depth of closure for Pilot Houtribdijk with Eq. (1). We use the classic definition of the depth of closure, where wave induced sediment transport is negligible, which should therefore be a proxy for the platform elevation. To make an accurate approximation and analyse the development over time, we predict the depth of closure for each storm event. This classic approach is different from the method often used nowadays, where the depth of closure is used to find the deepest limit where sediment transport is negligible for (multi-year) time series of coastal profile evolution, as for instance done by Hinton and Nicholls (1998). Nicholls et al. (1998) demonstrated that Hallermeier's (1980) approach defines robust estimates for the depth of closure, particularly for individual erosional events.

The predicted depth of closure is compared to the level of the corresponding platform from the bathymetry (see Section 3.5). The depth of closure relative to datum (Z_{DoC}) is found by subtracting d_s from a representative water level applicable during said storm event (Fig. 6).

3.4. Hydrodynamic analysis

To predict the depth of closure per storm event, information on wave height, period and water level is needed. We executed a storm analysis on the wave data from the offshore Vector ADV at Pilot Houtribdijk. Storm events are determined through a peak analysis on the spectral significant wave height, H_{m0} , derived from the ADV data. For each peak, the height, prominence and duration are calculated. The peak prominence measures how much the peak stands out from the surrounding baseline of the signal and is defined as the vertical distance between the peak and its lowest contour line. A peak in H_{m0} is selected if it fulfils the following three conditions (Fig. 5):

1. The peak height is higher than the threshold significant wave height of 0.5 m;
2. The peak prominence is at least 0.3 m;
3. The peak duration at 45% (from the top) of the peak prominence is at least 5 h

After selecting the peaks, the 12-hour exceeded wave height $H_{m0,12h}$ is calculated with a rolling window of 12 h, listing the minimum H_{m0} . Subsequently, the maximum value of $H_{m0,12h}$ for the period from 6 h before to 6 h after each peak moment is selected as the $H_{m0,12h}$ for that storm. The 12-hour average peak wave period at the storm peak is used for $T_{p,12h}$.

For the representative water level needed to calculate Z_{DoC} , Nicholls et al. (1998) suggest to use the Low Water Level or Mean Low Water. But since the Lake Markermeer is non-tidal, we introduce another definition. We define the 12-hour exceeded water level during the storm, h_{12h} , as the vertical reference level to estimate the depth of closure (Fig. 5). The 12-hour exceeded water level is calculated with a rolling window of 12 h, listing the minimum water level. The maximum value of h_{12h} for the period from 6 h before to 6 h after each peak moment, as determined from H_{m0} , is the 12-hour exceeded water level for that storm. This calculation is identical to the method for $H_{m0,12h}$,

Table 2
Monitoring occasions Pilot Houtribdijk.

19-9-2014	27-5-2016
25-10-2014	23-8-2016
19-11-2014	23-11-2016
28-12-2014	6-3-2017
23-1-2015	17-5-2017
15-2-2015	1-9-2017
18-3-2015	19-10-2017
6-4-2015	1-12-2017
21-8-2015	22-12-2017
25-1-2016	6-1-2018
28-2-2016	20-2-2018
	20-3-2018

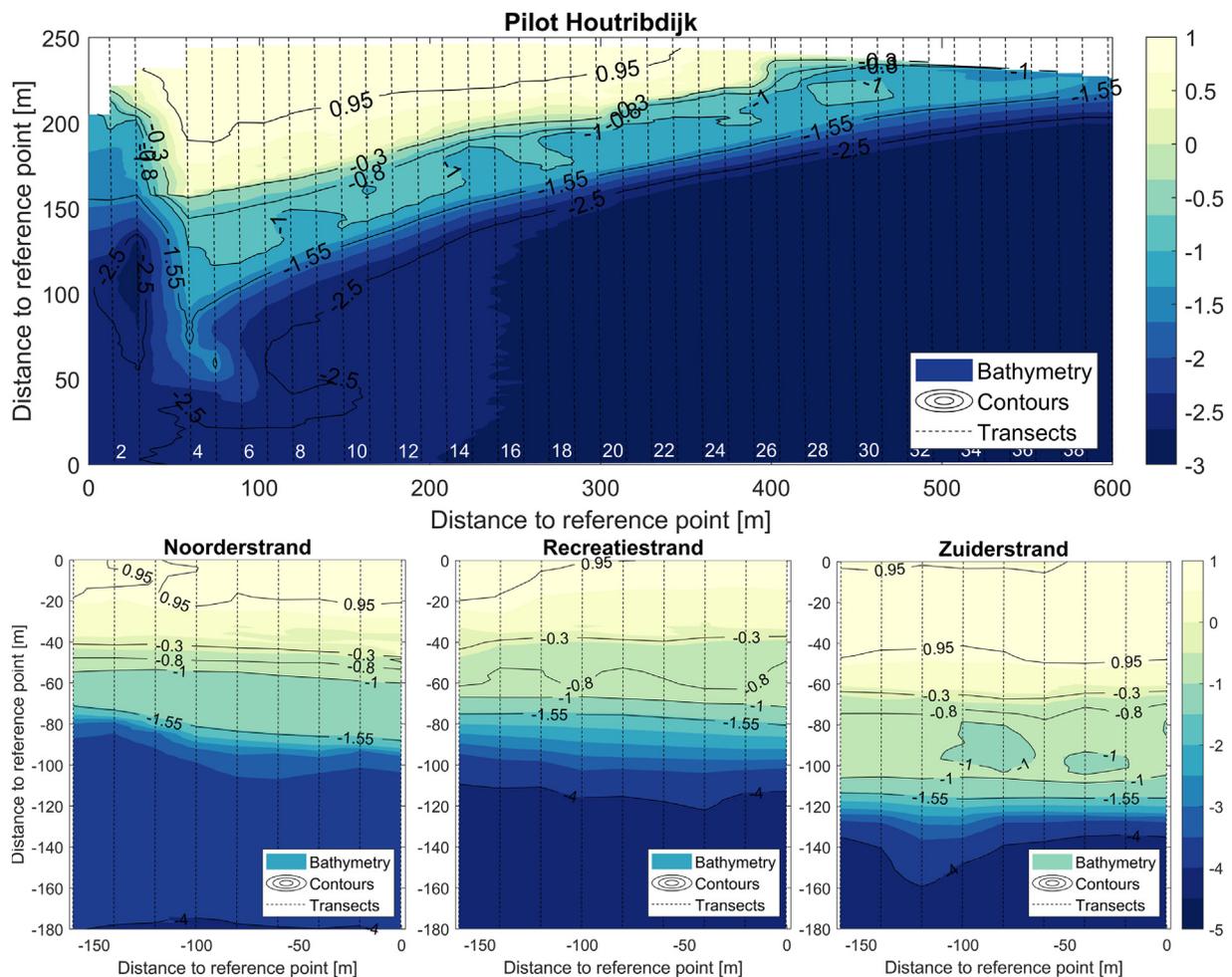


Fig. 4. Bathymetry of the four study sites, the white numbers in the Houtribdijk plot represent the numbers of the transects. Pilot Houtribdijk was surveyed in April 2015, and the Marker Wadden sites in July 2018.

but with the storm peak moments already determined from H_{m0} . The relative depth of closure is calculated as follows:

$$z_{Doc} = h_{12h} - d_s \tag{2}$$

To analyse the relation between hydrodynamics and morphological development, the storm analysis is extended to two-weekly characteristics, including cumulative wave energy. The wave energy is calculated, assuming a Rayleigh distribution, as $E = \frac{1}{16} \rho g H_{m0}^2$. The cumulative wave energy is equal to the sum of the wave energy at the peaks of all selected storms within the two weeks.

3.5. Morphological quantification

We divided the cross-shore profile in three vertical sections to include the following morphological regions (Fig. 7):

- I. the beach face above the yearly average water level (beach face section),
- II. the zone that includes the platform (platform section), and
- III. the deeper part of the profile (offshore section).

These sections are separated by four vertical levels:

- above the beach face (NAP+0.95 m),
- at the annual average lake level (NAP-0.3 m),
- at the submerged slope, just below the platform (NAP-1.55 m),

- just below the lake bottom (Pilot Houtribdijk: NAP-2.8 m, Marker Wadden: NAP-4.2 m).

The vertical limits of these sections are chosen starting from the yearly average water level (NAP-0.3 m). From that level a distance is found that upward includes the beach face and downward the platform for all four locations, 1.25 m. The lowest limit is just below the flat lake bottom, offshore from the submerged slope below the platform. For Pilot Houtribdijk all sections are of equal height, and for the Marker Wadden locations the section height ratio for I:II:III is approximately 1:1:2. The upper vertical limit at NAP+0.95 m is translated into a horizontal limit for the first measurement in time per transect, to create a fixed onshore boundary and more clearly demonstrate beach face erosion. The offshore boundary for Pilot Houtribdijk is at 250 m, after which no bathymetric data is available. For the Marker Wadden sites, this boundary lies at 150 m, since data availability is variable offshore from that point. This method of following volume change in vertical sections over time is similar to that of Steetzel et al. (2017), but with a slightly adjusted volume definition, for a longer time span and for more study sites.

The average platform height is the average height of the profile in the platform section. The slopes of the beach face and the slope in the offshore section are determined at respectively the yearly average water level (NAP-0.3 m) and the transition between the platform section and the offshore section (NAP-1.55 m). The local slope in each of these two points is estimated from a 2 meter profile section centered around these two locations of interest.

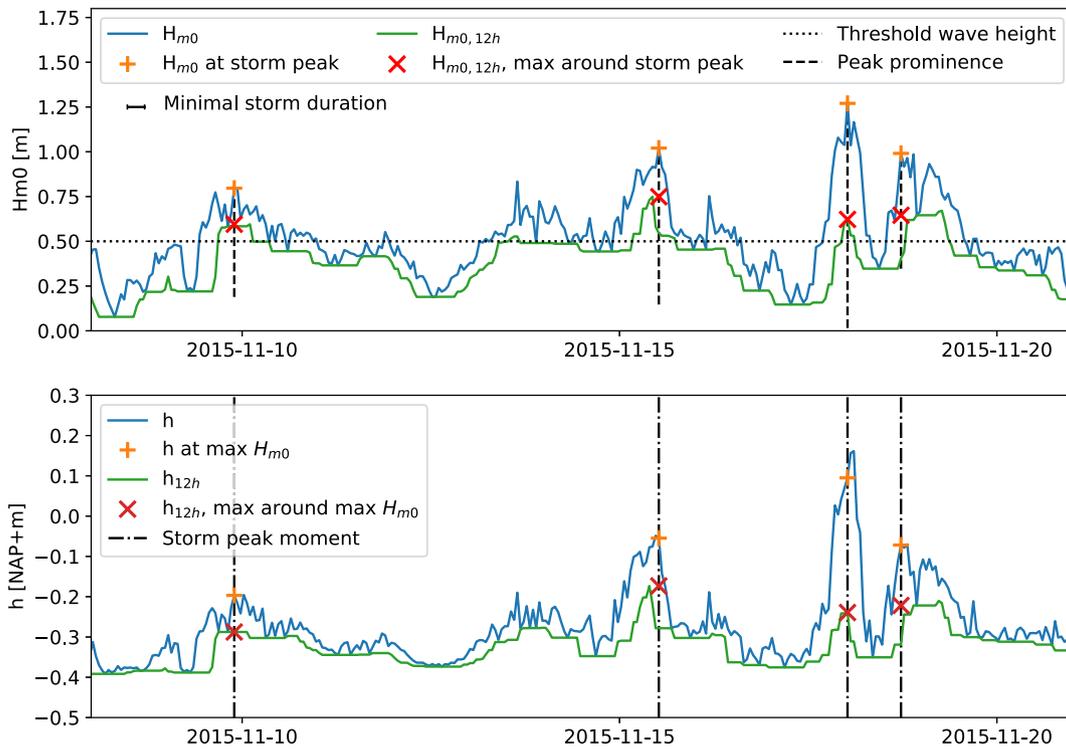


Fig. 5. Example from storm peak analysis of H_{m0} , Pilot Houtribdijk. The wave height (H_{m0}), with the identified storm peaks, and the corresponding 12-hour exceeded wave height ($H_{m0,12h}$), with its storm peak height. The water level (h) at the storm peak moment and the corresponding 12-hour exceeded water level (h_{12h}), with its storm peak height.

4. Results

4.1. Bathymetric features

All four study sites in lake Markermeer display a similar profile shape and a similar development over time (Fig. 8). At the Pilot Houtribdijk site, where morphological development has been monitored from construction onwards, a subaqueous platform evolved within the first months at NAP-1.0 m, on average at 0.7 m below water level (Fig. 8). The same is visible for the sites at the Marker Wadden. The beaches at Noorderstrand and Recreatistrand were constructed in late 2016, and reconstructed a few times between then and March 2018. The beach at Zuiderstrand was constructed and reconstructed between late 2017 and March 2018. Because of the number of human interventions, it is not possible to give an as-built situation, but below NAP+1 m the initial plane slope was approximately 1:20 for all the Marker Wadden beaches. At these sites, a platform is also visible at NAP-1.0 m, but the initial development took place before the first measurement (Fig. 8). The platforms vary in width from 30 to almost 60 m, depending on the location and the time. The profiles connect to the original lake bottom at NAP-2.8 m (Pilot Houtribdijk) and -4.2 m (Marker Wadden) with a steeper slope.

All locations have a steep beach face, although at Noorderstrand it has a slightly lower gradient (Table 3). Moreover, the Noorderstrand beach face slope varies substantially over time. The beach face slopes of the other three locations are very comparable. The average offshore slope is similar for all four locations.

The bathymetric data show a retreat around the water line at all sites. Because of erosion on the beach face, the platform widens over time, growing in both onshore and offshore direction for all sites, except for Recreatistrand. There the slope below NAP-1.55 m is more or less stable.

4.2. Depth of closure

The characteristic storm wave height $H_{m0,12h}$, wave period $T_{p,12h}$ and base water level h_b are derived from the hydraulic data (Fig. 9). The 12-hour exceeded H_{m0} varies around 0.5 m, while the maximum storm peak H_{m0} is around 1.3 m (Fig. 9). The maximum storm wave height is relatively stable, since the wave height is depth-limited in lake Markermeer.

Per period of two weeks, the average, minimum and maximum values of $H_{m0,12h}$ and $T_{p,12h}$ are used to calculate the average, minimum, and maximum depth of closure. At times with more than two different

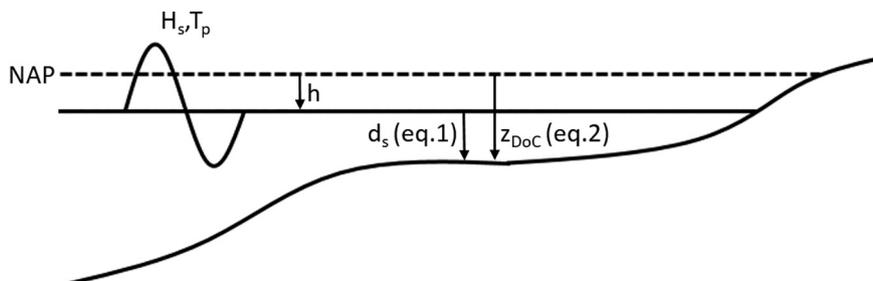


Fig. 6. Visualisation definitions depth of closure (d_s), depth of closure relative to datum (z_{Doc}).

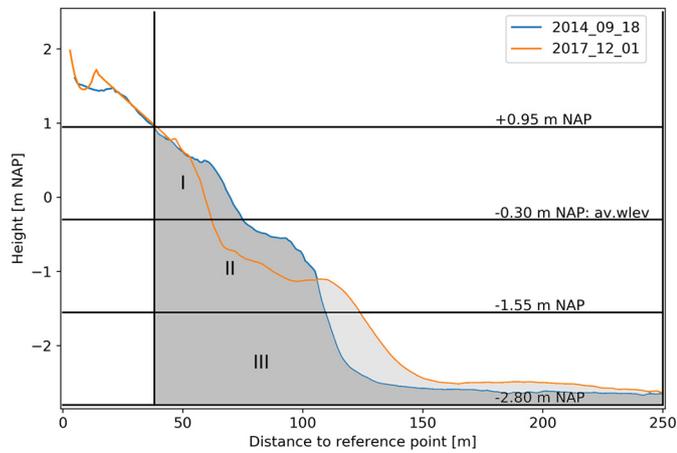


Fig. 7. Method of volume calculation at Pilot Houtribdijk, showing section I: beach face section, section II: platform section and section III: offshore section. In dark grey the volume corresponding to the profile at September 18, 2014.

storms per two weeks, the minimum and maximum depth of closure can differ up to almost a meter. The instantaneous Z_{DoC} per storm fluctuates between $Z_{DoC,min}$ and $Z_{DoC,max}$. Averaged over the whole period, $Z_{DoC,av}$, $Z_{DoC,min}$ and $Z_{DoC,max}$ differ -0.07 m, 0.03 m and -0.18 m respectively from the average platform height. For individual storms, $Z_{DoC,max}$

can be up to 0.42 m lower than the average platform height. However, the average Z_{DoC} (av. $h_b - av. d_s$) stays relatively stable over time, and varies around NAP-1.0 m (standard deviation over all transects: 0.23 m). This accurately corresponds to the actual average platform height at the Pilot Houtribdijk. At the study sites at the Marker Wadden the platform height is also situated around NAP-1.0 m (Fig. 8). Unfortunately no long time series of hydrodynamic data is available for these sites. Analysis of short time series shows that the wave climate at the Marker Wadden is similar to that of Pilot Houtribdijk (Table 1), as are the sediment characteristics. Therefore, we can assume that the depth of closure for the Marker Wadden sites is in the same order of magnitude. The platform at these locations is also situated around NAP-1.0 m (Fig. 8), which confirms the results at Pilot Houtribdijk.

4.3. Volume changes in time

To quantify morphological developments in time, cross-shore volume changes are calculated for different sections (Fig. 7). This analysis reveals that the volume of the beach face decreases over time for all four study sites (Figs. 10, 11). The volume around the platform steadily decreases at Pilot Houtribdijk, while for the sites at the Marker Wadden, the decrease in volume only occurs after a period of 6 months with stable or even increasing volumes. At Pilot Houtribdijk, Noorderstrand and Zuiderstrand, the beach face and platform per location develop at a comparable pace, while the offshore volume is gradually increasing. At Recreatiestrand, the offshore volume change fluctuates around zero,

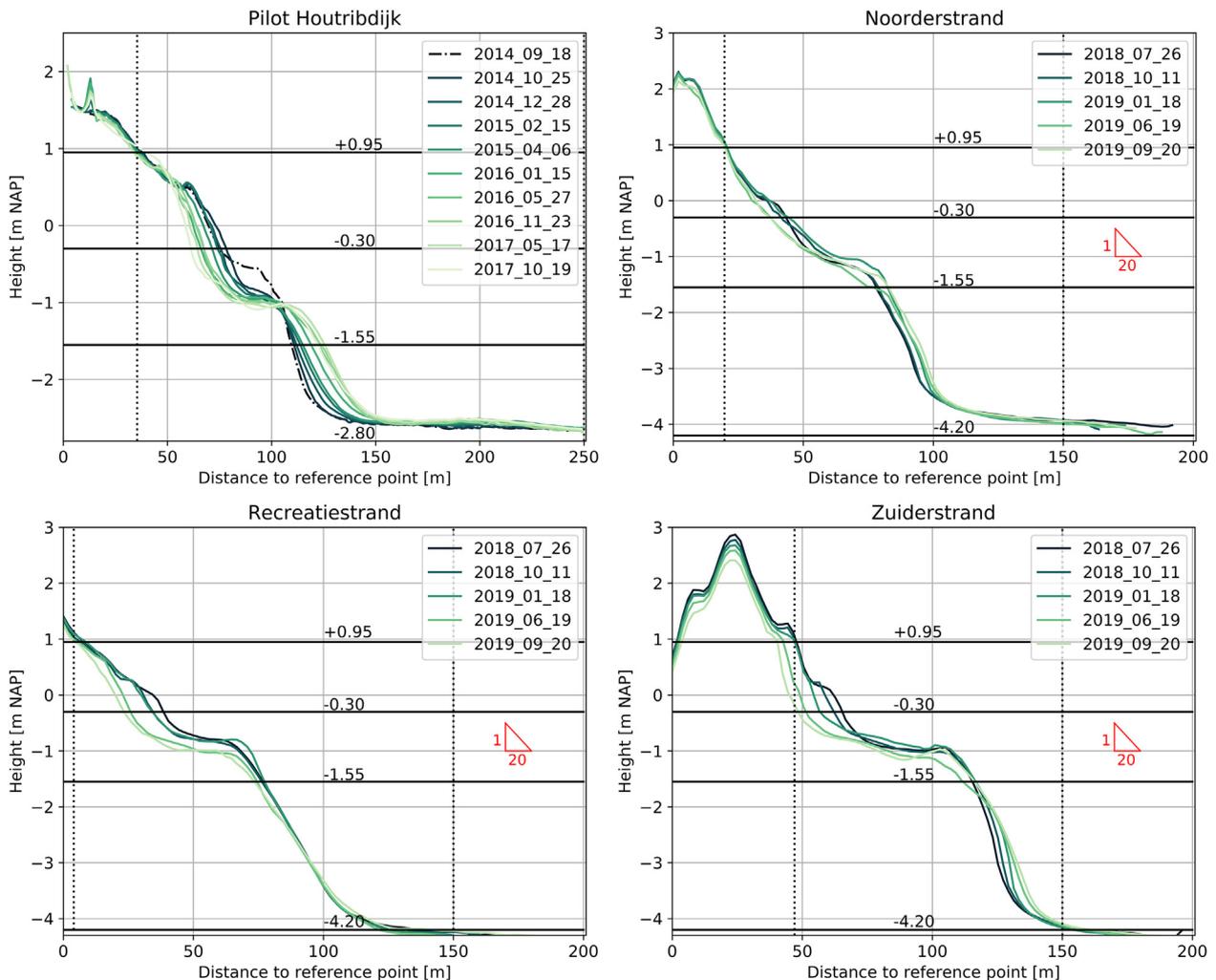


Fig. 8. Development of the average cross-shore profile at the four study sites, with the as built profile at Pilot Houtribdijk (dashed line) and the as built angle at the Marker Wadden locations (1:20) and the vertical section division for the morphological quantification.

Table 3
Bathymetric features, averaged over time and transects.

	Slope (1:x)		Platform elevation (m NAP)
	Beach face ($\mu \pm \sigma$)	Offshore ($\mu \pm \sigma$)	
Pilot Houtribdijk	9 ± 1	14 ± 2	-0.93
Noorderstrand	20 ± 7	14 ± 4	-1.11
Recreatiestrand	11 ± 3	13 ± 2	-0.89
Zuiderstrand	11 ± 2	14 ± 3	-1.00

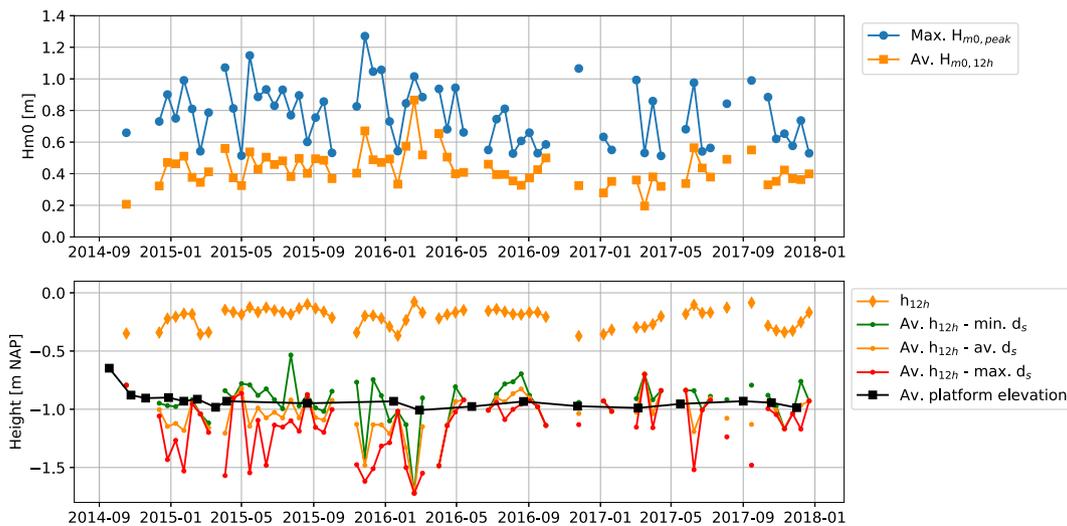


Fig. 9. Top frame: Maximum peak storm wave height per 14 days (Max. $H_{m0,peak}$) and average peak storm wave height per 14 days (Av. $H_{m0,12h}$). Bottom frame: 12-hour exceeded water level (h_{12h}), subtracted by minimum (min.), average and maximum depth of closure (d_s), compared to the average platform elevation.

and increases and decreases mostly simultaneously with the platform volume, thus all sections develop in the same manner. The total volume at the selected transects of Pilot Houtribdijk and Noorderstrand increased over time, while at Recreatiestrand and Zuiderstrand, a nett decrease took place.

4.4. Relation between volume changes and wave conditions

The wave climate in 2015 is quite energetic year-round, whereas and especially 2016 and 2017 are relatively more calm, as is visible in the cumulative wave energy (Fig. 12). In general, no seasonality in the wave climate is visible for these years, and both average wave height (0.6 to 0.9 m) and maximum peak storm wave height (0.8 to 1.2 m) are fairly constant throughout the year (Fig. 12).

The erosion or sedimentation rate varies over the period of observation, with slightly higher rates at the beginning of the monitoring period (grey highlight) and a distinct deviation in April 2015 (Fig. 12). The rapid changes in the first months after construction concern the initial profile development. The sedimentation peak of the offshore section in April 2015 does not coincide with a peak in wave energy event, the cause is unknown. Note that the rate of volume change (in $m^3/m/day$) in the lower panel is influenced by the interval between bathymetric surveys, with more frequent surveys, and therefore a more volatile rate of change in the first months after construction. The energetic periods between May 2015 and February 2016 and between February 2017 and September 2017 (red highlight) coincide with erosion of the beach face. Volume changes of the platform section do not strictly correspond with energetic periods, although erosion is slightly more common in periods with high wave energy. The offshore volume is growing in energetic periods, but not exclusively in these periods. During the energetic period between September and December 2017

(yellow highlight) the beach face volume is increasing, contradictory to the earlier trends. In this period, sedimentation on the top of the beach face is observed (Fig. 8).

5. Discussion

The shape of low-energy beach profiles in lake Markermeer corresponds to the general description by Jackson et al. (2002), with a steep beach face and low-gradient platform. From the four considered sites, only the relatively sheltered site Noorderstrand has a less steep beach face and shows a less distinct break between the swash zone and the platform, as would be expected from the conceptual models.

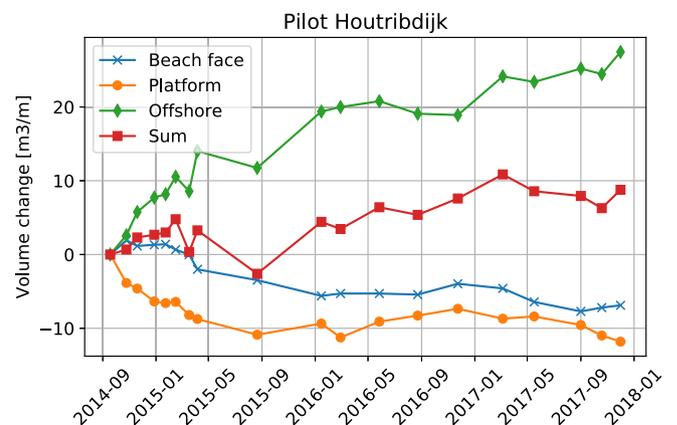


Fig. 10. Volume change per section since September 2014, at Pilot Houtribdijk.

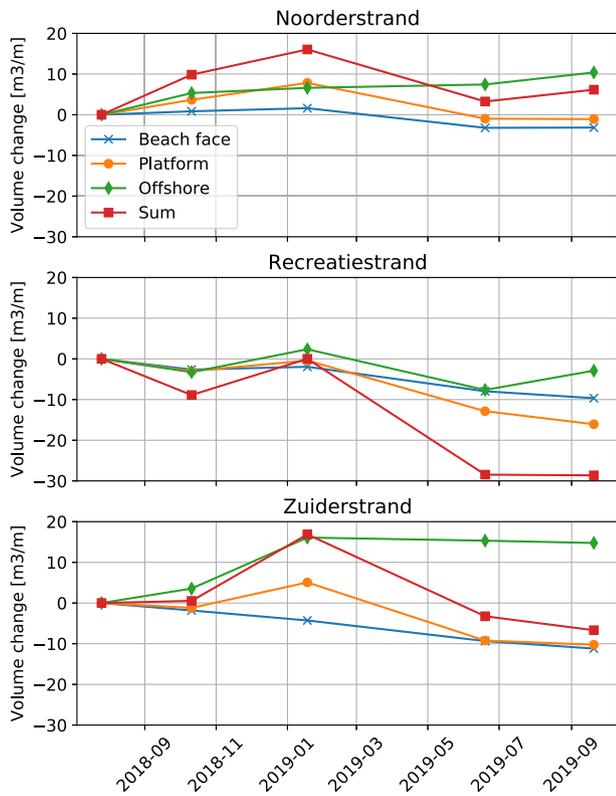


Fig. 11. Volume change per section since July 2018, at Marker Wadden.

The elevation of the characteristic platforms, at approximately NAP-1.0 m, might be explained by applying the depth of closure formula by Hallermeier (1980) (Eq. (1)). The laboratory conditions to which his formula was validated, constant waves at a constant water level onto an initially plane slope, correspond well to the conditions at the study sites. Despite these similarities, some assumptions in the calculation method are debatable. For non-stationary conditions, a time scale should be chosen for events that determine the equilibrium limit or potential depth of closure. In the analysis by Nicholls et al. (1998) for high-energy coasts, the 12-hour exceeded H_{m0} gave the best results for the event dependent depth of closure compared to 6 h and 18 h. This duration has also been applied in the current study for low-energy beaches in lake systems. However, the response of water levels and waves in a lake like Markermeer is much quicker than in oceans and seas. As this choice influences Z_{DoC} to a certain extent, a sensitivity analysis is added here.

Since water levels and waves in lake Markermeer respond quicker to wind variations than on open coasts, the 12-hour exceeded H_{m0} covers a large part of the storm, while on high-energy beaches, it only covers the peak. The use of for instance the 6-hour exceeded H_{m0} , would imply that the relative depth of closure, Z_{DoC} , would be calculated relative to the 6-hour exceeded water level. From the hydrodynamic data of Pilot Houtribdijk, it follows that averaged over the full period, $H_{m0,6h}$ is higher than $H_{m0,12h}$, h_{6h} is higher than h_{12h} and $Z_{DoC,6h}$ is deeper than $Z_{DoC,12h}$, but the differences are small (Table 4). However, for individual storms $Z_{DoC,6h}$ can be up to 0.49 m deeper than $Z_{DoC,12h}$. Although the method is sensitive for individual storms, it is robust when averaged over a longer period, independently of the exceedance period. The observed platform elevation is on average NAP-0.93 m and at the minimum NAP-1.01 m, therefore with the current information the exceedance period of 12 h gives the best result.

Although the time-averaged $Z_{DoC,12h}$ fits very well with the observed platform elevation, it varies considerably over time. For a high-energy



Fig. 12. Hydro- and morphodynamics Pilot Houtribdijk. Top frame: Cumulative wave energy and average and maximum H_{m0} per 14 days. Middle frame: Volume change per section normalised to the first measurement. Bottom frame: Change to rate of volume change. Grey area: initial profile development after construction. Red areas: periods with energetic wave climate. White area: periods with calm wave climate. Yellow area: period with energetic wave climate but aberrant morphological change.

Table 4

Sensitivity analysis of 12 h compared to 6 h exceedance values of significant wave height (H_{m0}), water level (h) and resulting depth of closure (z_{DoC}).

	12 h	6 h	Difference
$H_{m0,xh}$ [m]	0.42	0.53	0.11
h_{xh} [NAP + m]	-0.21	-0.16	0.05
z_{DoC} [NAP + m]	-1.03	-1.17	-0.14

event with z_{DoC} significantly deeper than the platform elevation before the event, it is not expected that the platform will lower with for instance 0.42 m within 12 h or a similar period. However, a series of events with a z_{DoC} lower than the platform elevation could cause a lowering. With more frequent monitoring of the bathymetry compared to Fig. 9, the timescale of these morphological developments could be studied.

More elaborate monitoring on the depth of closure could also shed more light on the optimal reference water level for non-tidal environment. Nicholls et al. (1998) stated that the best reference is Low Water Level or Mean Low Water in tidal systems. The here used 12-hour exceeded water level is a somewhat conservative choice, since it basically represents the water level before and after the storm, while there is a set-up during the storm. However, the results presented in this paper clearly demonstrate that the platform elevation is controlled by the depth of closure.

Development over time is described for our four study sites, but are they underway to equilibrium? According to Jackson et al. (2002), low-energy beaches do not reach an equilibrium state, but represent a storm artefact or state. But, since morphotypes are based on hydrodynamic conditions in more recent studies (Travers, 2007), we would expect that for relatively constant hydrodynamic conditions, a dynamic morphological equilibrium should be possible. After the short adaptation time, the elevation of the platform of our four study sites reached an equilibrium. Since lake level fluctuations are minimal in the non-tidal lake Markermeer and wave height and surge are always positively correlated, this was expected and we can attribute the equilibrium elevation of the platform primarily to wave action. In other situations, most likely both wave action and continued water level variations are responsible for the platform elevation. The frequency and duration of these fluctuations may influence the elevation of the platform (Eliot et al., 2006), and may lead to variations over time.

Yet, the analysis of the morphology revealed that at none of the four study sites the other morphological dimensions have reached equilibrium yet. For Pilot Houtribdijk, the rate of change slowed down over time, but it did not fully stop after four years. At the Marker Wadden, the morphology is still in full development after little over two years of transformation. Physically, we would expect this process to find an equilibrium once the platform is wide enough to bring the wave height down so wave-induced sediment transport is negligible near the shoreline. Since the platform has a very low gradient, a very wide platform might be needed to meet this condition.

Longshore transport processes are not explicitly addressed in this paper. As natural morphologies of low-energy beaches look similar to laboratory results with only normally incident waves (Hallermeier, 1979), it is a fair assumption that the steering processes are alike and that this typical shape develops due to cross-shore sediment transport. This is also confirmed in field studies such as the study by Lorang et al. (1993a) at Flathead Lake in the United States, where morphology is said to develop through cross-shore transport. However, when inspecting the cross-shore development over time, the offshore-directed growth does not seem to balance out the onshore erosion (Fig. 8). Moreover, the total volume at the selected transects of Pilot Houtribdijk and Noorderstrand increased over time, while at Recreati strand and Zuiderstrand, a net decrease took place. This is inevitably linked to longshore transport processes. At Pilot Houtribdijk, the total sediment budget, over all transects, was kept in dynamic equilibrium due to the

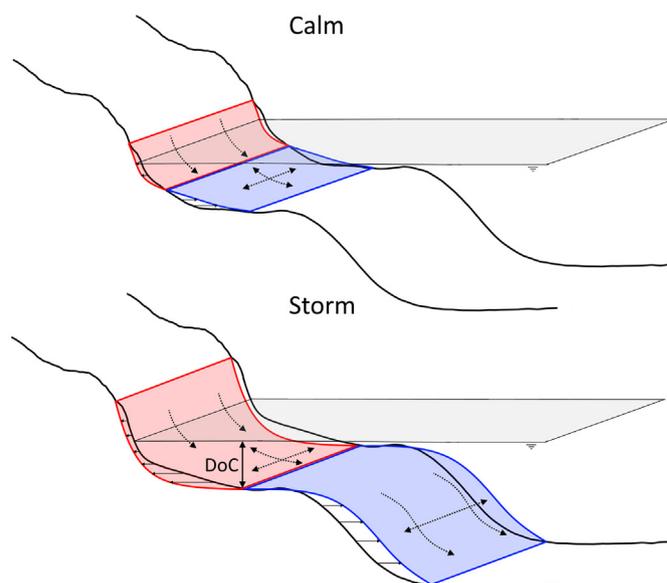


Fig. 13. Visual summary of conceptual model of morphodynamics on a low-energy, non-tidal sandy beach during calm and stormy periods. Red: general erosion; blue: only sedimentation; dotted arrows: possible sediment transport directions; grey: yearly averaged water level.

presence of a sheet pile wall (Steezel et al., 2017). The increase at the middle transects was countered by a decrease at the off-centre transects. Noorderstrand, oriented under an angle compared to the common wave incidence (SW), must be influenced by longshore transport. Since Recreati strand and Zuiderstrand are constructed in such way that they are oriented normally to the average angle of wave incidence, negligible net longshore transport was expected. The sediment budget was negative in September 2019, but perhaps the measurement period was too short to conclude net erosion.

To summarize the above, we have attempted to introduce a conceptual model of the morphodynamic processes on the low-energy, non-tidal beach (Fig. 13). The overall beach face erosion combined with simultaneous accretion lower in the profile suggests that sediment transport in this area is primarily in cross-shore direction. This sediment reaches the platform and most likely travels further in both cross-shore and longshore direction, to meet the equilibrium depth. During calm conditions the depth of closure is limited, causing sediment that has previously been eroded from the beach face to accumulate on the platform. Since the depth of closure is deeper during more energetic periods, erosion over the total platform occurs primarily in these periods. Sediment that is transported “over the edge” of the platform will settle and be deposited on the slope below the platform. In accordance with the Hallermeier (1979) definition, no wave-driven transport can occur in the region below the depth of closure. Therefore, these sediments will not return shoreward causing profile changes in the region below depth of closure. Model simulations can be used to further our insight in the sensitivity and variability of these morphological processes.

6. Conclusions

The goal of this research was to understand the morphological development and hydrodynamic forcing of low-energy, sandy beaches. Through a literature analysis into morphotype classifications of these environments, the general morphology in these environments was characterized. Bathymetric developments were monitored at four low-energy, non-tidal study sites in the shallow lake Markermeer in the Netherlands. Here the typical low-energy morphology with a narrow beach face and low-gradient platform, as described by Jackson et al. (2002), was observed.

The sandy beaches at the study sites were all constructed in recent years, showing a rapid initial profile adjustment during the first years after implementation. Based on measurements of waves and water levels, the depth of closure (Hallermeier, 1980) was calculated and compared to the elevation of the platform. We conclude that the elevation of the platform is indeed located near this depth of closure, and that after reaching this depth, the platform elevation stays relatively stable.

The morphological development was quantified through calculating the volumes of three vertical zones in the cross-shore profile: beach face, platform, and offshore. Both longshore and cross-shore transport are responsible for the development of platform. Results suggest that erosion of the beach face is primarily by storm-driven cross-shore transport, after which the sediment is most likely diffused both cross-shore and longshore over the platform and offshore sections. Although the depth of the platform is stable, the platform width did not reach an equilibrium for the oldest study site (4 years) and the widening is still in full development at the younger sites (2 years).

The typical low gradient platform of the low-energy, non-tidal sandy beach develops at the depth of closure. This insight is an important step towards the prediction of morphology in low-energy environments and contributes to the future prospect of implementing sandy beaches in environments such as lakes, reservoirs and micro tidal seas for purposes such as shoreline protection, wave energy dissipation for flood risk reduction or recreation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is part of the LakeSIDE project, which is funded by Rijkswaterstaat, The Netherlands.

The partnership for the project pilot Houtribdijk consists of Rijkswaterstaat and an EcoShape consortium involving the research institutes Deltares and Wageningen Environmental Research, contractors Boskalis and Van Oord and engineering companies Arcadis Nederland BV, RoyalHaskoningDHV and HKV Consultants. Shore Monitoring is acknowledged for carrying out the morphological surveys for this project.

The research at the Marker Wadden was supported by the Marker Wadden Knowledge and Innovation Programme (KIMA), initiated by Rijkswaterstaat, Deltares, EcoShape and Natuurmonumenten. See <https://kennismarkerwadden.nl/english/>.

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