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BARRIER MORPHODYNAMICS UNDER MICRO-TIDAL AND LOW TO MODERATE WAVE CONDITIONS, RØDSAND, DENMARK

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Abstract

Coastal barriers often form a protection of the hinterland for erosion and flooding under extreme events like storms. This study focuses on the morphodynamics of a barrier spit and a barrier island in SE Denmark and look how vulnerable these barriers are towards extreme events and/or sea-level rise. Numerical simulations with MIKE 21 and LITDRIFT are used to examine the sediment dynamics of this coastal system. The multi-energetic and -directional wave climate initiated littoral drifts where gradients caused erosion/accretion patterns along the barriers, which was in line with the evolution of the morphology. Application of a storm impact model showed that collision regimes increase significantly at the barrier spit and the barrier island is constantly exposed to overwashes and inundations under a predicted rise in sea-levels and storm-surges.

Key words: barrier morphodynamics, hydrodynamics, sand transport, numerical simulations, Rødsand

1. Introduction

An increasing pressure from sea-level rise and storm-surges on coastlines in inner Danish waters is already occurring and is expected to increase in the future. Interests in the coastal zone such as summer cottages, infrastructure and ecosystems already feel this pressure. An improved knowledge about coastal morphodynamics at these coastlines is therefore relevant for adapting coastal zone management to recent and future barrier behaviour. Rødsand is a coastal system that historically has been hit be severe storm-surges like in November 1872 where nearly 100 people died and many houses were destroyed (Colding, 1881; Clemmensen et al., 2014; Dahlberg et al., 2017). Recently a storm-surge caused the flooding of low-lying areas in the region with high socio-economic costs (Stormraadet, 2017). This study focuses on recent and future barrier morphodynamics of two different barriers in Rødsand and encompasses three research areas: background morphology, hydrodynamics and sand transport.

2. Study Area

In the waters between Lolland and Falster west-east oriented coastal barriers are situated between Rødsand lagoon in the north and Femern belt to the south (figure 1). Two coastal barriers encapsulate the lagoon at the western part of the system. A 5 km long barrier spit named Hyllekrog is attached to the SE corner of Lolland with dunes at the proximal end and beach ridges at the distal end. A 10 km long incipient barrier island named Western Rødsand is regularly flooded as the barrier is located around MSL with only few elevated parts above MSL. Hyllekrog Rende separates Hyllekrog and Western Rødsand and is a 1 km wide and shallow (ca. 1.5 m deep) inlet with sandy sediments. Rødsand is a micro-tidal area with mixed semi-diurnal tides and a spring tidal range of ca. 0.2 m. The sediments on the barriers are moderately sorted mixed sand and gravel. The mean grain size of the sandy sediments is 0.456 mm. Both barriers have southwards dipping shoreface slopes with a single- or multi-barred profile.

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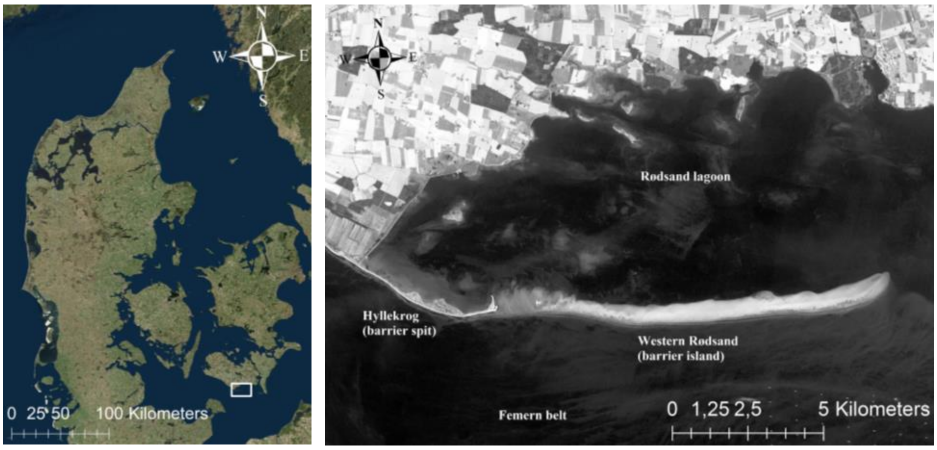

Figure 1. Left figure: Location of study area in SE Denmark. Right figure: Satellite photo of the coastal barrier system. Data sources: ESRI and DHI-GRAS.

Regional topography reflects a geomorphology resulting from the last glaciation where meltwater from the Young Baltic ice sheet deposited an outwash plain and formed elongated moraine ridges in the study area (Houmark-Nielsen et al., 2005). Hyllekrog and Western Rødsand are exposed to a multi-directional low to moderate wave climate where the dominant wave direction is W and subdominant SE. A modeled climate covering the period 1989-2010 is provided by Femern A/S (FEHY time series) and illustrated in figure 3.

3. Data and Methods

The numerical models LITDRIFT and MIKE 21 are used to simulate sediment dynamics at the spit and barrier island. Annual longshore sand transport rates are simulated with the LITDRIFT model. The littoral drift is simulated over two bathymetric profiles from (DONG, 2007) at Hyllekrog and Western Rødsand. The 21-year hydrographic data set (FEHY time series) is used as input to the model and sediment characteristics are from (Jensen, 2006). The model set-up is shown in table 1. The LITDRIFT net and gross results give good estimates on the magnitude and direction of the longshore sand transport rates at the two barriers. A more detailed overview of the sediment dynamics in the system is simulated with MIKE 21 coupled FM model where three modules are coupled: hydrodynamics (HD), spectral waves (SW) and sand transport (ST). The domain is based on bathymetric scatter data provided by DHI where mesh resolutions gradually become finer around the barriers. The model is run with 9 representative (constant) wave climates representing waves from all directions between 130° and 290° with 20° steps. The representative wave climates are defined from a frequency analysis and validated with the LITDRIFT net and gross results. A Q3D sediment table is coupled to the ST module and the set-up is given in table 1. Time selection is set to 3 hours with a time step interval of 60 sec. The simulation results from each representative wave climate are weighted according to the duration of the respective wave climate.

The sub-aerial morphology of the barriers is measured with dGPS (Trimble RTK-R8) at the proximal end of the spit and western end of the barrier island and digital terrain models (LiDAR) are used to complete a volumetric analysis of the spit. Echo-sounder and side-scan sonar (Humminbird 998c SI) are used to measure the sub-tidal part. The volumetric analysis is completed in ArcGIS with the surface volume tool on the DEM-2007 terrain model. The LiDAR map is validated by comparing measured dGPS barrier profiles with extracted profiles from the digital terrain model. The LiDAR map deviates ca. 10 % from the measured profiles due to a time lag between the monitoring of the LiDAR data and the dGPS profiles. The composition of the beach at the proximal end of Hyllekrog is investigated from two trenches where sediment structures and samples are analysed. The FEHY time series is generated with the MIKE 21 SW model where wave conditions are simulated in a regional wave model that covers the entire Baltic Sea supplying the boundary conditions for a high-resolution wave model that covers the Femern belt area. A more detailed description of the model set-up can be found in FEHY (2013a).

Table 1. LITDRIFT and Q3D sediment table set-up.

LITDRIFT		Q3D sediment table	
Parameter	Value	Parameter	Value
Time	Real time	Relative density of sediment	2.65 g cm^{-3}
Bed resistance	0.005 m	Critical Shields parameter	0.045
Water level conditions	Constant	Water temperature	10 ℃
Current conditions	No current	Ripples included	No
Spectral description of waves	Battjes & Jansen	Bed slope effects	Excluded
Reduction factor (constant)	0.6	Bed concentration	Deterministic
Sediment description	Graded sand	Streaming effects	Included
Relative sediment density	2.65 g cm^{-3}	Cross current transport	Included
Grain diameter	0.17 mm	Centrifugal acceleration	Excluded
Grading coefficient	1.29	Undertow	Excluded
Sediment porosity	0.4	Wave theory	Stokes 5th order
Ripples included	No		
Critical Shields parameter	0.045		
Number of fractions	5		
Water temperature	10 ℃		
Wave theory	Stokes 5th order		

4. Results

4.1 *Background morphology*

Hyllekrog and Western Rødsand are the remaining formations of a chain of coastal barriers at the south coast of Lolland that existed until land reclamation and dike construction took place after the storm in 1872 (FEHY, 2013b). Since then the coastal morphology of the two barriers have developed differently. The proximal end of Hyllekrog has well-developed dunes with dune crests of 3 to 4 m and beach ridges and swales at the distal end. Western Rødsand is an incipient barrier island with no vegetation and maximum barrier crests of ca. 0.5 m.

The stability of the barrier spit varies along the proximal end (figure 2), which is in line with simulated erosion/accretion patterns along the barrier (figure 5). Barrier volumes from polygon 2 to 6 (average volume = 92 m^3 m^{-1}) reveal a vulnerable part of the spit and polygon 7 to 13 (average volume = 184 m^3 m^{-1}) indicate a more stable part of the spit. A former inlet was situated around polygon 2, which is the most vulnerable part of the barrier spit in terms of barrier volume. The former inlet was filled up with broken bricks in order to gain access to the lighthouse located at the distal end of Hyllekrog (FEHY, 2013b).

The beach morphology, i.e. berm elevation and beach width, is analysed from measured dGPS profiles. At the stable part of the spit (polygon 7 to 13), the beach width is ca. 16 m and mature berms are turning into embryo dunes and foredune ridges. The vulnerable part of the spit (polygon 2 to 6) has a beach width of 9 m and no embryo dunes are observed. Incipient berm elevations at the proximal end of Hyllekrog are in average 0.51 m and mature berms are 1.05 m. The mature berm height coincides with the 1-year storm-surge return period from Rødby harbour situated west of the study area (DCA, 2012). At the elevated parts of Western Rødsand the barrier volumes are app. half the volume of Hyllekrog (average volume = 44 m^3 m^{-1}) and the average incipient berm elevation is 0.4 m.

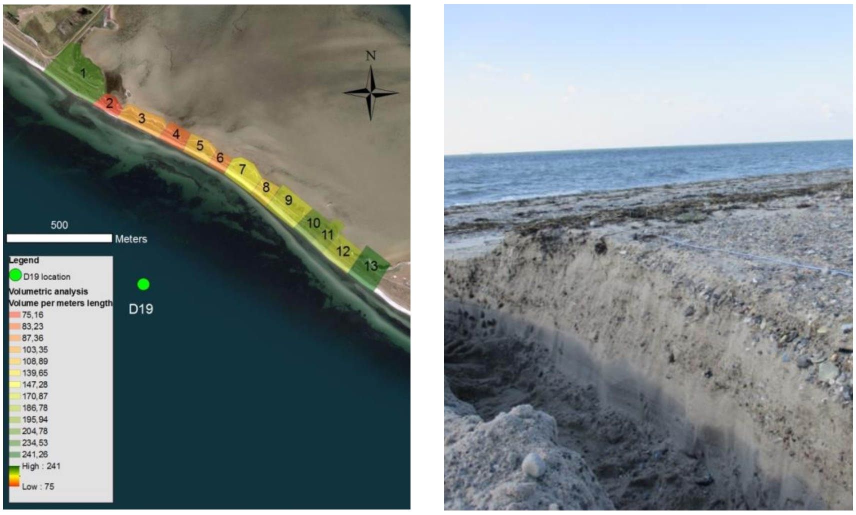

Figure 2. Left figure: Volumetric analysis. D19 is the extraction point of the FEHY time series. Right figure: Beach trench at Hyllekrog.

From two beach trenches at Hyllekrog (located at polygon 6 and 11) sediment deposits are investigated (figure 2). Five sediment layers are observed: (1) the deepest sediment layer showed the former pebbly beach. (2) A thick planar swash-backswash sandy layer has been deposited on top of that. (3) The third layer has sedimentary structures showing the deposits from onshore-migrated slip-face bars. Layer (4) and (5) make up the mature berm that consists of a sandy and coarse-grained deposit. The sub-aqueous morphology is analysed from side-scan sonar and echo-sounder at the southern dipping slopes in front of both barriers and across the inlet. One or two nearshore sandy bars are present at Hyllekrog where medium-to-large boulders are exposed in the bar troughs. The shoreface slopes in front of Hyllekrog (0.009) are generally steeper than Western Rødsand (0.008). The barrier island is multi-barred with two or more sandy bars where remains of the paraglacial system (medium-to-large boulders) are observed in the troughs. Hyllekrog Rende is a shallow inlet (average depth of 1.5 m) filled with sandy sediments and a 3 m deep tidal channel in the middle of the inlet.

4.2 *Hydrodynamics*

The simulated wave climate is extracted from an output point 800 m offshore SW of Hyllekrog at 4.18 m water depth. The wave climate is bimodal and dominated by low to moderate energetic conditions (figure 3). The mean significant wave height is 0.53 m and maximum significant wave height is 2.28 m. The sea state is characterised by wind waves with wave periods between 2 and 4 seconds. 92 % of the wave periods are less than 4 sec and 8 % are less than 2 sec. The dominant wave direction is from W where the longest fetch of ca. 100 km is located. The second dominant wave direction is from SE where the fetch is ca. 50 km. The most energetic waves come from a WSW direction.

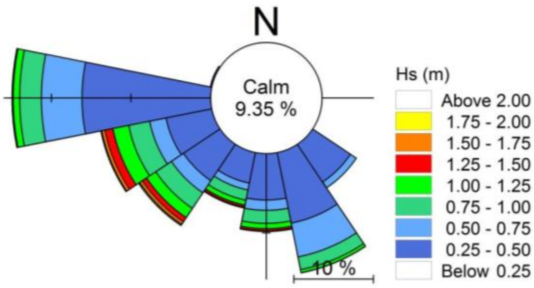

Figure 3. Wave rose showing modeled FEHY wave climate.

Table 2. Joint probability analysis of significant wave heights (Hs) and water levels (WL) from the FEHY time series.

Scenario	Hs	WL	Probability	Comment
1	Hs < 1 m	WL > 0 m	57.15 %	Low wave energy and elevated water levels
2	Hs < 1 m	WL < 0 m	33.26 %	Low wave energy and lowered water levels
3	Hs > 1 m	WL < 0 m	5.32 %	High wave energy and lowered water levels
4	Hs > 1 m	WL > 0 m	4.27 %	High wave energy and elevated water levels

Table 2 shows the results from a joint probability analysis on significant wave heights and water levels. The analysis tells that the dominant sea state (scenario 1) is characterised by elevated water levels and low-energetic wave conditions. Low-energetic wave conditions and lowered water levels is the second dominant sea state (scenario 2). Scenarios 3 and 4 indicate that high-energetic wave conditions both coincide with elevated and lowered water levels. Waves and water levels in the SW part of the Baltic Sea are often disrupted by a lag time between high-energetic wave conditions and subsequently elevated water levels (Feistel et al., 2008; Kroon et al., 2013). Setup/set-down effects at the Rødsand area are typically caused by the passage of low- and high pressures (FEHY, 2013a).

4.2 *Sand transport*

The sand transport at the spit and barrier island is simulated with littoral drift and 2D area numerical models. LITDRIFT and MIKE 21 uncover a multidirectional littoral drift with alongshore gradients. The magnitude of the littoral drift varies both inter and intra the spit and the barrier island. Positive values represent a drift to west and negative values a drift to east.

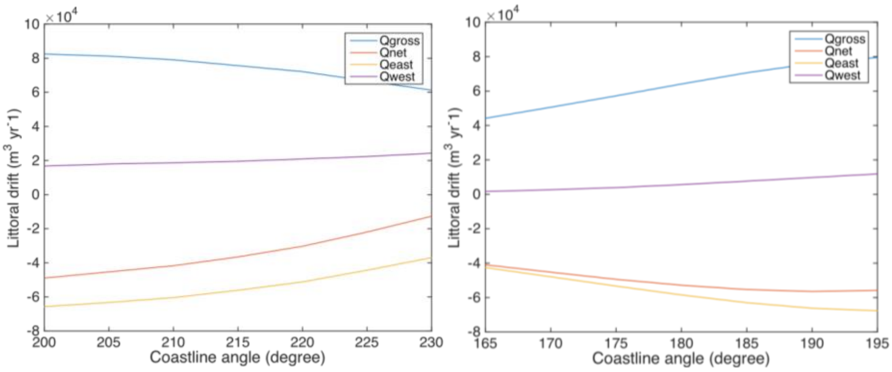

Figure 4. Q-alpha curves from the LITDRIFT model.
Left: Hyllekrog. Right: Western Rødsand.

The mean coastline orientation is 215° at Hyllekrog and 180° at Western Rødsand. LITDRIFT simulations give a net littoral drift of -36553 m^3/yr and a gross littoral drift of 75643 m^3/yr at Hyllekrog (figure 4). The littoral drifts to the east and west are -56098 m^3/yr and 19545 m^3/yr, respectively. The simulations at Western Rødsand give a net littoral drift of -52823 m^3/yr and a gross of 64111 m^3/yr. The drifts to the east and west are -58467 m^3/yr and 5644 m^3/yr, respectively. Incident angular waves drive littoral drifts both to the east and to the west at Hyllekrog, but is significantly dominated by an eastwards drift. The longshore sand transport at Western Rødsand is mainly dominated by an eastwards transport and the westwards littoral drift is low. The net littoral drift is approximately 1.5 times larger at Western Rødsand compared to Hyllekrog at the mean coastline orientations, but the gross littoral drift is higher at Hyllekrog. The littoral drift rates at Hyllekrog are reduced as the coastline angle increases towards 230° since the dominating wave climate from W and SW becomes more perpendicular and the subdominant wave climate from SE becomes more parallel with the coast (see wave rose). At Western Rødsand, the littoral drift rises as the coastline orientation increases towards 190° due to the dominating wave climate from W and SW and the subdominant wave climate from SE become more oblique to the coast.

Variations in sand volumes transported through the output profiles in the MIKE 21 model cause net transport gradients in the system, which are illustrated in figure 5. Line output 1 (upper x-axis) is located at polygon 2 (volumetric analysis figure) and the distance (lower x-axis) is eastwards from this point. All line outputs are perpendicular with the coastline and out to a distance 400 m offshore.

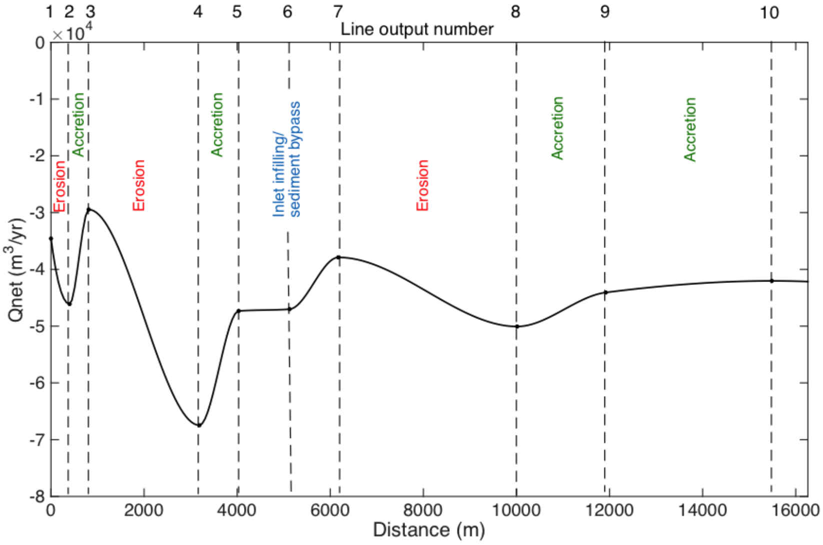

Figure 5. Net transport (Qnet) gradients from the MIKE 21 model.

Figure 5 shows the integrated annual net transport across each line output. Erosion dominates between line output 1 and 2 due to an increase in net sand transport from -34568 to -46106 m^3/yr. Line output 2 is located at the same location as the Hyllekrog bathymetric profile in the LITDRIFT model. The annual net transport here is -36552 m^3/yr (LITDRIFT) and -34568 m^3/yr (MIKE 21) – a difference of 5.4 %. A decrease in sand transport between line output 2 and 3 from -46106 to -29457 m^3/yr leads to deposition of sand. The simulated barrier behaviour (erosion between line output 1 and 2 and accretion between 2 and 3) is in line with the results from the morphologic and volumetric analysis. Erosion dominates between line output 3 and 4 due to a substantial increase in net drift from -29457 to -67458 m^3/yr. This median part of the spit is perceived as a sediment source to the distal end of the spit. A decrease in net drift from line output 4 to 5 of -67458 to -47333 m^3/yr points out that some of the eroded material at the exposed part of the spit supplies the distal end with sand.

The amount of transported sand is approximately equal between line outputs 5 and 6. This indicates that sand is bypassed at the first part of the inlet. A decrease in net transport between line outputs 6 and 7 of -47015 to -37887 m^3/yr leads to sand deposition in this area of the inlet. The numerical simulations show that sand is bypassed and deposited at the inlet. Erosion occurs between line output 7 and 8 with a Qnet increase from -37887 to -50064 m^3/yr, which can be explained by the fact that the coastal orientation of this part of Western Rødsand is more obliquely exposed to the dominating wave climate from W. The net transport gradually decreases from line output 8 to 10 since this part of the barrier island is in lee from the dominating waves from W.

5. Discussion

In this discussion the coastal morphology and hydrodynamic forcing are coupled in a storm impact model (Sallenger, 2000; Stockdon et al., 2006). The impact from waves and water levels on the barriers is investigated under recent and predicted rise in sea-levels and storm-surges. The simulated sediment dynamics (magnitude, direction, gradients) will be contextualised with other studies. A conceptual model illustrating the morphodynamics of the coastal system is presented on the basis of the findings in this study (Figure 6).

Table 3. Storm impact model run on the FEHY time series and predicted SLR and storm-surge setup. Upper table: Hyllekrog. Lower table: Western Rødsand. Zt: dune toe and Zc barrier crest.

Barrier spit		1989-2010			2100 with 1 m SLR			2100 with 1 m SLR and 23 % storm surge setup		
Zt	Zc	Coll.	Overw.	Inund.	Coll.	Overw.	Inund.	Coll.	Overw.	Inund.
m	m	%	counts	counts	%	counts	counts	%	counts	counts
1.31	3.51	0.35	0	0	47.48	7	0	50.95	10	1

Barrier island	1989-2010		2100 with 1 m SLR		2100 with 1 m SLR and 23 % storm surge setup	
Zc	Overw.	Inund.	Overw.	Inund.	Overw.	Inund.
m	%	%	%	%	%	%
0.48	7.43	4.62	99.55	99.41	99.56	99.42

According to FEHY (2013a) the global predicted sea level rise (SLR) of 1 m in year 2100 is expected to propagate into the Baltic Sea. In addition to the SLR, an estimated increase in storm-surge setup of 23 %, due to an average increase in wind speeds of 3 m/s, is added to the scenario (FEHY, 2013a). Hyllekrog is only affected by the collision of waves with the barrier during the period 1989 to 2010. Overwash and inundation events are not typical at the proximal end of the spit, but will slightly increase as the sea-level rises and the storm-surges become more intense. The duration of the collision regime will increase significantly on the spit under future scenarios. Western Rødsand is situated close to MSL and is often overwashed and inundated even under non-storm conditions. Under predicted SLR and increased storm-surge setup, the barrier island will almost constantly be overwashed and inundated (if aggradation is not able to keep up with SLR). The duration of the collision, overwash and inundation regimes depends on the wave energy and water table in Femern belt. Under recent conditions these two partially dependent variables are high-energetic and elevated only 5 % of the time and therefore the probability for overwashes and inundations at the spit are very low. Overwashes and inundations occur on a regular basis on Western Rødsand due to the low-crested morphology of the barrier island.

The magnitude and direction of the simulated littoral drift is comparable with other numerical simulation studies from Rødsand. LITDRIFT simulations in this study give a net littoral drift at Hyllekrog of ca. -37000 m^3/yr and -53000 m^3/yr at Western Rødsand which are transport rates close to the findings in FEHY (2013b) and Jensen (2006) who found littoral drifts of ca. -30000 m^3/yr at Hyllekrog and -50000 m^3/yr at Western Rødsand, respectively.

Figure 6. Conceptual model of the barrier morphodynamics at Rødsand.

The MIKE 21 results showed that erosion and accretion takes place at the proximal end of the spit. Erosion prevails at the median section and supplies sand to the distal end of the spit. The distal end of the spit experiences deposition of sand, which feeds the spit platform and allows it to grow further east and north. The distal end of the spit has a curved morphology caused by refracting waves around the end of the spit, which is a typical forming process of spits (Komar, 1998). This morphodynamic evolution of the spit is in line with the findings from historic maps in Jensen (2006). A barrier spit that is supplied with sand from own sources (cannibalisation process) is also found in other spit studies (Stéphan et al., 2012). Numerical simulations indicate that the spit will continue to grow to the east into the inlet Hyllekrog Rende. This spit growth may be restricted by the presence of the inlet or by the nearby barrier island. Spit evolution models operate with this type of spit evolution as restricted spit growth (Kraus, 1999; Hoan et al., 2011). The investigated sediment deposits indicate that onshore migration of bars has been a source of sediment to the spit, which is found to be an important sediment source to barrier spits in other studies (Aagaard et al., 2004; Lindhorst et al., 2008). Elongation of the spit is most likely a result of the straightening of the south coast of Lolland due to dike construction after the 1872 storm in combination with the incident angular waves that drive the longshore sand transport in the area. The spit is not overwashed under recent conditions and rarely overwashed under future scenarios since high-energetic wave conditions and elevated water levels rarely occur simultaneously in Rødsand, which is different from other coasts e.g. in the Netherlands (De Winter and Ruessink, 2017). Side-scan sonar of the inlet reveals that the inlet is very shallow and covered with sandy sediments. Numerical simulations also indicate that sediment is deposited and/or bypassed at the inlet. It is possible that inlet closure will occur over time, which is typical for the evolution of inlets in wave-dominated areas (Komar, 1998; Davis and FitzGerald, 2004).

Overwashes occur on a regular basis at Western Rødsand both under storm and non-storm conditions. This is different from the overwash mechanisms found in other places where quite a lot of studies found that overwashes are triggered by extreme conditions during hurricanes and storms (Sallenger, 2000; Christiansen et al., 2004; Stockdon et al., 2012). Non-storm overwash has been studied at other low-crested barriers (Matias et al., 2010; Morton et al., 2000). The difference between the study of Matias et al. (2010) and this study is that the Rødsand area is very micro-tidal and the area in the referred article is exposed to meso-tidal conditions, which were one of the factors forcing the non-storm overwashes. The non-storm overwash study by Morton et al. (2000) is carried out on barrier islands in Colombia where land subsidence and local sea-level rise due to El Niño events are the main triggers of non-storm overwash. According to Matias et al. (2010) non-storm overwashes occur on low-crested barriers exposed to wave action with the absence of a berm and exposed to large spring tides. These factors are also involved in the non-storm overwashes at Western Rødsand except for the large monthly tidal oscillations.

6. Conclusions

This morphodynamic study of the barriers in Rødsand, SE Denmark, showed that the two barriers are different in terms of barrier volume, crest height and coastal morphology. The barrier stability varies spatially along the proximal end of the spit, which is in line with the numerical simulations. The wave climate is low to moderate energetic and bimodal with dominant waves from W and second dominant from SE. Incident angular waves drive a multi-directional littoral drift along both barriers that is significantly dominated by an eastwards longshore sand transport. High-energetic waves and elevated water levels only occur around 5 % of the time and therefore overwashes and inundations are not typical at the spit. The barrier island is regularly flooded even under non-storm conditions due to the low-crested morphology of the barrier. Numerical simulations show gradients in net sand transport along the barrier spit that cause erosion/accretion patterns at the proximal end. At the median section erosion prevails and supplies the distal end with sand. Sand is bypassed and deposited at the inlet. The western end of the barrier island is eroding while the eastern end is accreting. Under future hydrodynamical conditions, the collision regimes increase at the spit while overwashes and inundations begin to occur. The barrier island is constantly exposed to overwashes under predicted SLR and storm-surge increase if aggradation is not able to keep up with rising sea-levels and more intense storm-surges.

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