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Salt-marsh erosion and restoration in relation to flood protection on the Wadden Sea barrier island Terschelling

Jantsje M. van Loon-Steensma · Pieter A. Slim · Mathieu Decuyper · Zhan Hu

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Abstract This paper explores the impact of erosion and restoration measures on habitat development and on wave damping by a small salt marsh nestled alongside a dike on the Wadden island of Terschelling. The aim is to advance knowledge about the benefits and possible side-effects of salt-marsh restoration. Analysis of a time series of aerial photographs from 1944 to 2010 indicates that the salt marsh decreased steadily in size after maintenance of accretion works was terminated. In the western part of the marsh, which is accessible to sheep, vegetation is low (5–15 cm) and dominated by *Salicornia europaea* and by *Spartina anglica*. In the most intensively grazed parts, vegetation is very scarce. The eastern, inaccessible part of the salt marsh is covered by dense patches of the shrubby perennial *Atriplex portulacoides* and *Spartina anglica* (15–25 cm in height). SWAN wave models show that wave height at this location is significantly affected by the areal extent of the salt marsh as well as by the vegetation. High or dense vegetation are in the models nearly as effective in damping waves (with an initial height of 0.15 and 0.5 m) as widening the salt-marsh area by 350 m. A low density of low plants, as observed in the grazed part of the marsh, has almost no wave-damping effect. Even under conditions of sea level rise, a broader salt marsh vegetated with high plants significantly affects modelled wave height. Therefore, salt-marsh restoration is an adaptation measure worth exploring, though an array of effect types must be considered.

Keywords Salt-marsh restoration · Vegetation development · Wave attenuation · Sea level rise

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Introduction

Salt marshes and the adjacent mudflats form a prominent feature of the Wadden Sea, which harbours Europe's most extensive intertidal zone (e.g., Wolff 1983; CWSS 1991; De Jong et al. 1999; Essink et al. 2005; Reise et al. 2010). Coastal salt marshes are defined as areas vegetated by salt-tolerant plants and subject to periodic flooding due to the fluctuating water levels of the adjoining saline water body (Adam 1990). They constitute a vegetated transition zone between sea and land.

The zones of salt marshes represent different stages of vegetation succession. The boundaries of the zones are usually determined by factors related to geological, climatological, vegetation and land-use history, such as sedimentation, erosion and duration and frequency of inundation by sea water (Adam 1990; Allen 2000; Doing 1995).

Salt marshes are one of the habitats named in the European Habitats Directive (Habitats Directive 1992). The various stages of salt-marsh habitats and the mudflats in the Wadden Sea are therefore protected under both national and international legislation (Ministerie van Economische Zaken Landbouw & Innovatie 2011), as well as under trilateral agreements between Denmark, Germany and The Netherlands

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(CWSS 1997). These habitats are characterized as (i) halophyte pioneer vegetation (H1310), (ii) *Spartina* swards (H1320) and (iii) salt marshes, including a diversity of characteristic vegetation (H1330). The adjacent mudflats are another key habitat type (H1140) (European Commission 2007).

Beyond conservation of the areal extent of salt marshes in the Wadden area with all of their succession stages, there are other ambitions as well: to increase the variability of geomorphological forms and salt-marsh substrates, to optimize management, to enrich the natural vegetation structure in artificial salt marshes, and to improve conditions for wading birds (CWSS 1997). For birds feeding on tidal-flat fauna, salt marshes offer a refuge during periods of high water. Furthermore, they serve as a spawning area and nursery for fish. In recognition of the nature values associated with the natural processes in the Wadden Sea, UNESCO designated the Dutch and German parts of the area as a World Heritage Site in June 2009.

In the Dutch part of the Wadden Sea, both the mainland and the barrier islands are protected against flooding from the Wadden Sea by dikes. Along several stretches of these dikes, salt marshes are present (Dijkema et al. 2007). Until the 1970s, sedimentation, and subsequently salt-marsh forming, was actively stimulated on the seaward side of the flood defences by digging drainage systems in the mudflats and by constructing brushwood groynes with the aim of land reclamation. The present salt-marsh area along the Dutch mainland coast is mostly the result of such accretion works (Dijkema et al. 2007). Currently, management of the accretion works aims to preserve their areal extent.

The salt marshes in front of the dikes on the Dutch Wadden barrier islands are not protected against erosion by accretion works. Therefore, they have been exposed to slow but steady erosion. The dikes have prevented a landward shift of the salt-marsh zones under rising sea levels (known as 'coastal squeeze'). The closure of the former 'Zuyderzee' (1932) is suspected of having increased erosion by its effect on the tidal prism (Elias 2006). Some remnants of salt marshes can nonetheless still be found along the Wadden barrier islands dikes. One of these eroding salt marshes (called Salt marsh Stryp) is located in a sheltered corner alongside the dike that protects 'Stryp' Polder on the Wadden island of Terschelling (Fig. 1).

The current salt marsh east of Stryp Polder measures some 4 ha and is covered with characteristic salt-marsh vegetation (Fig. 2). The western part is accessible to sheep grazing the dike, while the eastern part is inaccessible due to a tidal gully resulting from a former pumping station outlet. The salt marsh forms a refuge for the abundant breeding and wading birds.

The tidal flooding of Salt marsh Stryp is easily observed from the dike. This makes the marsh a popular stop for tourists bicycling along the pathway on the Wadden dike. The rich landscape and nature values prompted a group of Terschelling residents to launch an initiative for restoration of the eroding Salt marsh Stryp.

Besides the above-mentioned values, salt-marsh zones, including the marsh vegetation and fronting mudflats, also affect wave height and can dissipate wave energy. This wave attenuation capacity gives them a natural sea defence value (Brampton 1992; Costanza et al. 2008; King and Lester 1995; Möller et al. 2001; Van Loon-Steensma et al. 2012). Wave attenuation is strongly dependent on the slope of the coastal profile, water depth, width of the salt-marsh zone and the vegetation present. With increasing water depths (as during storm surges), wave damping decreases. As several authors point out, wave reduction especially occurs in the first few meters from the salt-marsh edge, and a strip of at least 10–80 m is required for significant wave reduction (Brampton 1992; Möller et al. 1999; Mol 2004; Yang et al. 2012).

This paper analyses erosion of the Salt marsh Stryp (east of Stryp Polder) since the 1940s and its vegetation development from 1996 to 2011. Furthermore, it explores the effects of erosion and of potential restoration measures on habitat development and wave damping. The aim is to advance knowledge about the benefits and possible side-effects of salt-marsh restoration initiatives.

Study site

Figure 1 shows the salt-marsh zone under study on the Dutch barrier island of Terschelling. Salt marsh Stryp is nestled in the lee of the present Wadden Sea dike, adjacent to Stryp Polder. A precursor of Stryp Polder was created in the early 16th century when a salt-marsh area adjacent to the former dike was first embanked. The newly formed polder (seaward of the old dike), however, survived only for a short time, and subsequently new plans for 'inpoldering' were developed (Donkersloot-De Vrij 2002). An embankment around Polder Stryp built in 1602 was short lived as well. The current Wadden Sea dike (which also protects Polder Stryp) was constructed in 1858, since which time no breaches have occurred. The historical dike is still present (and appointed as cultural heritage). Historical maps (e.g., Bonnebladen 1920) show development of a small salt-marsh zone east of the polder between the dike and the drainage gully of a pumping station outlet. In the 1930s, local residents tried to stimulate sedimentation at this location by planting common cord grass (*Spartina anglica*), by digging ditches to improve drainage and by placing wooden groynes (Donkersloot-De Vrij 2002), enclosing an area of some 35 ha (Fig. 3). The drainage gully of the pumping station (which was closed in 1948) developed into a tidal gully (Fig. 3).

Maintenance of these reclamation works was discontinued in the 1950s. Their remnants, in the form of wooden groynes

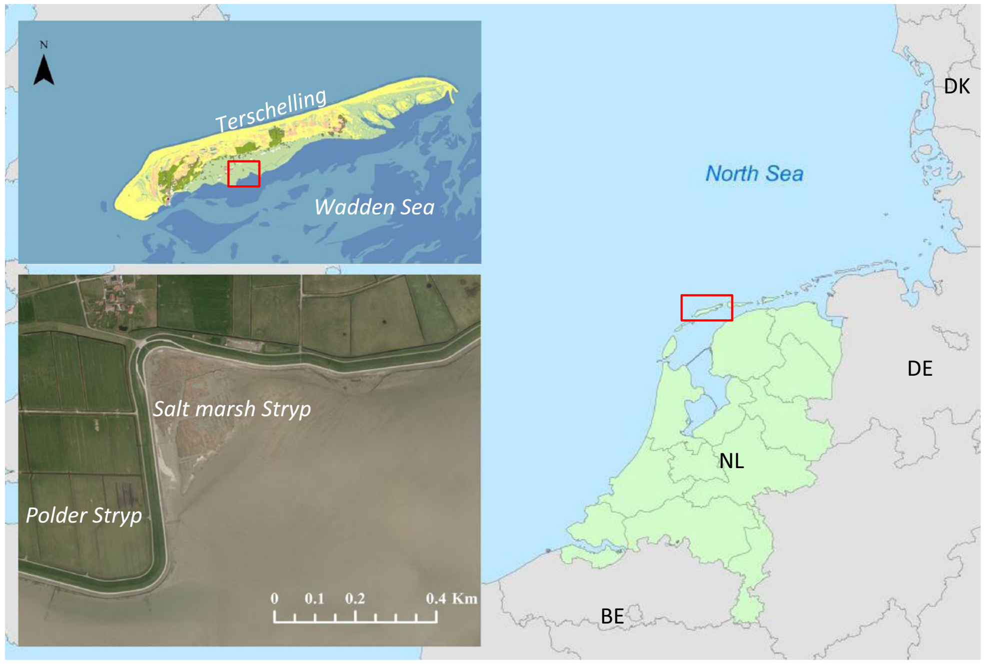


Fig. 1 Location of Salt marsh Stryp, east of Stryp Polder in the lee of the flood defence on the Wadden Sea barrier island of Terschelling

and ditches, are still visible in the field and on aerial photographs. The newly formed salt-marsh area was never embanked.

Stryp Polder, including the dike, was privately owned until 1955. In response to the flooding disaster of 1953, which caused more than 1,830 fatalities in the southwest delta area of The Netherlands, the dike was transferred to the local public water board and reinforcement plans were drawn up. By law, the Wadden dike of Terschelling must protect the hinterland against extreme storm surges, as could statistically be expected once in 2,000 years. Calculated hydraulic conditions of such an extreme storm surge for the dike east of Stryp are 4.2 m+NAP ('NAP' is the Dutch reference height), wave setup 0.9 m, and wind direction 30° (Ministry of Transport, Public Works and Water Management et al. 2007). To meet this standard, the Wadden dike of Terschelling (including the embankment around Stryp Polder) was reinforced during 1962–1968 to a height of 5.5–5.6 m+NAP (Gorter and Muiser 1994). Along the outer berm, a maintenance path was constructed. East of Stryp Polder, this was done at the

Fig. 2 Vegetation in the salt marsh adjacent to the flood defence at Stryp (August 2011). Just seaward of the dike-toe (in the foreground) is a strip of salt marsh dominated by *Puccinellia maritima* (H1330), flanked by vegetation dominated by *Spartina anglica* (H1320)

Fig. 3 Pattern of ditches and wooden groynes constructed to enhance sedimentation and reclamation of new agricultural land on the east side of Stryp Polder (where also the patterns of the old reclamation works are still visible, as well as the historical dike), viewed on an aerial photograph taken by the Royal Air Force (UK) on 4 August 1944 (source: Land Registry Office or 'Kadaster'). The pumping station is marked by a white star. A white line indicates a stretch of dike that was outwardly extended in the 1960s; a stretch that is straightened later, is marked by a white triangle

expense of a strip of some 17 m in width of Salt marsh Stryp (Fig. 3). Furthermore, a small area of land was transformed into sea by straightening a stretch of the dike (Fig. 3). In the 1970s, the stone revetment at the toe of the dike was heightened to improve its resistance to wave action (Gorter and Muiser 1994). In 1997, the revetment was again improved. In order to replace the stones, the toe of the dike east of Stryp Polder was excavated. Since then, the slightly lowered zone adjacent to the dike has tended to develop towards a gully in Salt marsh Stryp. The corner was smoothed in 2009 (compare Figs. 1 and 3) (which cost a small part of Salt marsh Stryp).

Currently, the remaining salt marsh is some 0.90–1.20 m+NAP, with some lower-lying areas 0.60–0.90 m+NAP (Fig. 4). Mean high-tide level is 0.83 m+NAP; spring neap tide is 0.95 m+NAP (Rijkswaterstaat, www.rws.nl/images/WESTTSLG_tcm174-335746.pdf). When storm surges come from the northwest, the water level in the Wadden Sea sets up. On the Wadden Sea side of Terschelling, a water level of 3.12 m+NAP was observed during the storm surge of 1953 (Gorter and Muiser 1994); a water level of 3.24 m+NAP was observed during a storm surge in January 1976 (Rijkswaterstaat, www.rws.nl/images/WESTTSLG_tcm174-335746.pdf). During 'normal' storm surges from a north-easterly direction (occurring with a frequency of some 5 times per year) the water level along the Wadden coast is some 1.95 m+NAP. Southeast storms lead to a water level lower than normal, because the water of the Wadden Sea is blown towards the North Sea. As a consequence, the waves are already dampened before reaching the Wadden Sea coast of Terschelling (A. Kiers pers. comm.).

Analysis of the salt-marsh area

Methods

We analysed erosion over more than half a century by comparing the vegetated area using a time series of aerial photographs. The sets of aerial photographs (scale 1:18,000, source Land Registry Office) comprised black-and-white and true colour images and were taken between 1944 and 2010, at intervals of about every 10 years since 1949. The 1949 photograph was excluded due to high uncertainty regarding the delineation of the eastern part of the study area. Only the last photograph (2010) was a true colour photograph.

The use of chronological sequences of aerial photographs to map and quantify changes in an inter-tidal area and vegetation is well documented (e.g., Cox et al. 2003; Sanders et al. 2005; Slim et al. 2011). On our photographs, the salt-marsh edges were visible as the limit of the continuously vegetated area. We quantified changes in the position of the vegetated area. That area was digitised onscreen from ortho-rectified images for each year, after the photographs had been scanned and geo-referenced to the Dutch National Grid. The delineation of all photographs was done in a consistent way to avoid errors in the calculation of the salt-marsh area. Only the main gullies and trenches were excluded from the areal calculation, because delineation of small trenches would decrease the degree of confidence between the years and the calculated erosion. The edge where cliff erosion occurred was very distinct. At places with poorer contrast, the position of the marsh edge was less clear and the delineation was done by comparison with the previous and subsequent photograph. Sanders et al. (2005) found that, due to inaccuracies in

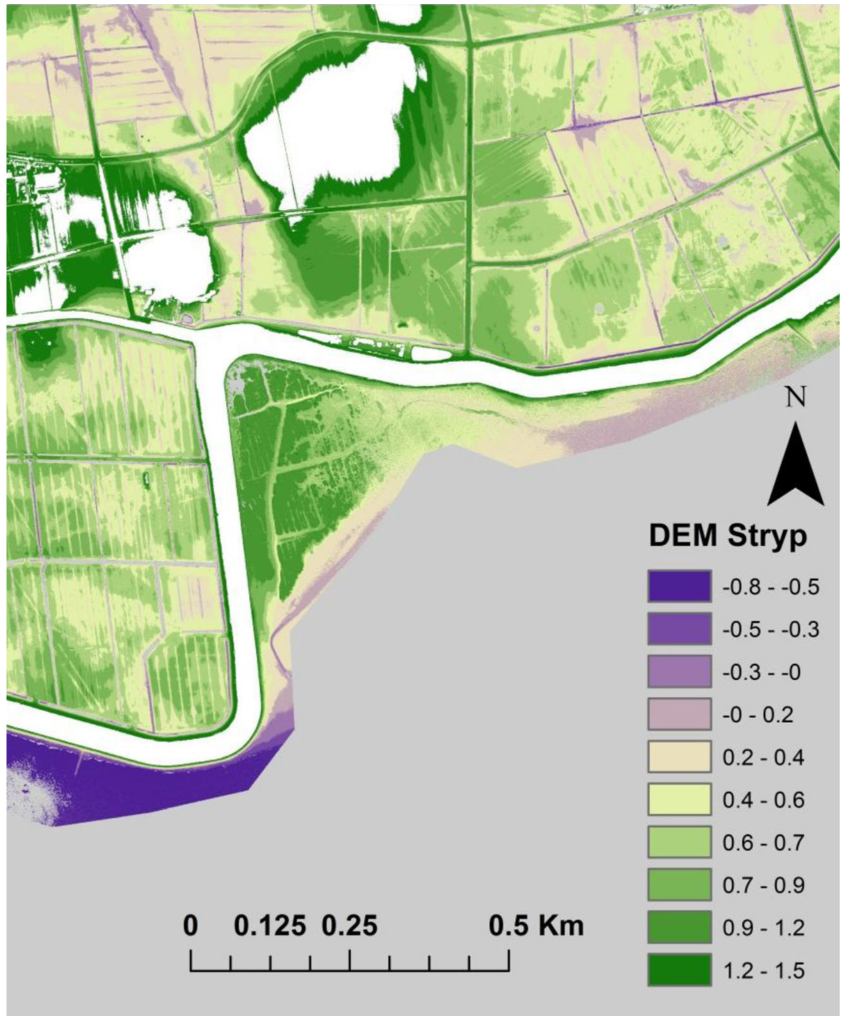


Fig. 4 Map of Digital Elevation Model (*DEM*) in m NAP (Dutch reference height) of the salt marsh east of Stryp Polder. The white areas are the dike or small ponds (source: AHN 2012)

geometrical corrections of aerial photographs, the position of salt-marsh edges on photographs must differ by more than 4 m to be significant.

Results

Analysis of the aerial photographs indicates an increase of the salt-marsh area of some 6 ha (7 ha if the strip used for dike reinforcement is included) between 1944 and 1959. The marsh expanded from approximately 3.2 ha to 9.2 ha (10.2 ha including the strip used for dike reinforcement). After 1959, a steady decrease is observed of some 0.1 ha/year, to reach 3.8 ha in 2010 (Fig. 5). Besides diminishment due to erosion on the seaward side, the area also decreased due to a widening of the gullies and creeks and the onset of low-lying, unvegetated areas within the marsh zone (Fig. 6). Extrapolation of the observed linear decrease indicates that the salt marsh at Stryp will disappear around 2050.

Discussion

The expansion of salt marsh by some 7 ha between 1944 and 1959 demonstrates that the accretion works stimulated sedimentation and subsequently formation of the salt marsh east of Stryp Polder. Nevertheless, the salt-marsh area present in 1959 (10.2 ha including the strip used for dike reinforcement) related to the area enclosed by accretion works (34 ha) indicates that the abiotic conditions east of Stryp are not particularly favourable for salt-marsh development by the applied techniques (digging drainage ditches and construction of low wooden groynes). The disappointing speed of land formation since the start of the reclamation attempt in the 1930s (when a small salt-marsh area was already present) probably contributed to the decision to stop maintaining the accretion works. But other factors may have influenced that decision as well by offering new economic opportunities, such as a land consolidation project on Terschelling (completed in 1952) to improve the area's agricultural potential, the ongoing modernization of farming techniques and the emerging tourism sector.

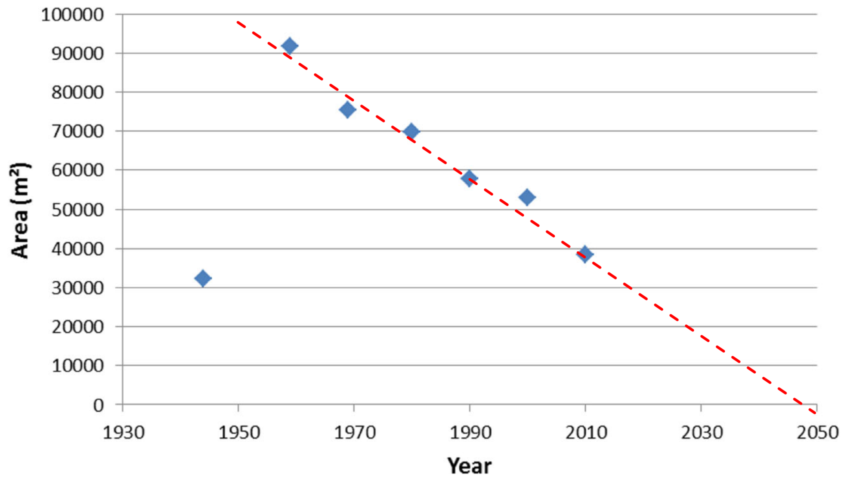


Fig. 5 Development of the salt-marsh area of Salt marsh Stryp (Terschelling). Symbols represent the area measured on aerial photographs, and the dashed line represents the extrapolated decrease

Since cessation of maintenance of the accretion works, the marsh area has steadily diminished. Lateral erosion (at the outer salt marsh edge and the creek edges) and medial erosion (of the salt marsh interior) have both been at work. Interaction between waves and the substrate is very different in each of these cases. Lateral erosion is due mainly to direct wave impact, while medial erosion is brought about by attenuated orbital currents on the bed.

Fig. 6 Salt-marsh area in 1959 (*dashed line*) and 2010 (*solid line*) (source: Kadaster). The star marks the groyne placed in 2010 to prevent erosion of the dike by the gully

Recently, a small stone groyne was constructed perpendicular to the dike (Fig. 6) in order to prevent erosion of the dike by the slowly moving gully. Since that time, sedimentation of sand has been observed on the south-eastern side, along with an increased outflow in the northern gully (A. Kiers and N. Hamstra pers. comm.).

Although a small area of salt marsh might remain in the most sheltered corner, our analysis indicates that under unchanged conditions the salt marsh will probably disappear around 2050. If the responsible authorities wish to preserve the salt marsh, for example, to provide a refuge for wading birds and to maintain a characteristic landscape feature along the Wadden Sea coast of Terschelling, measures will have to be taken to protect the marsh edge against erosion. Suitable erosion protection measures are the covering of the eroding edge (by geotextile and stones) or the construction of a dam of wood, stones, clay or oysters against the marsh edge or at some distance seaward of the eroding marsh (De Groot et al. 2012; Van Loon-Steensma and Slim 2013). Such measures, however, may interfere with inter-governmental aims, which prioritize natural geomorphological processes in the Wadden Sea's salt marshes and strive to minimize human intervention (Ministry of Transport, Spatial Planning and Environment 2007).

Although such measures may not completely fit in the aims for the Wadden Sea salt marshes, we expect that they will be effective in the conservation and restoration of the eroding Salt marsh Stryp, as was demonstrated by the areal extent increase resulting from the land reclamation works between the 1930s and 1950s. Furthermore, some 8 km east of Salt marsh Stryp, a low stone dam erected on the seaward side of the eroding marsh Grië led to formation of a new salt marsh behind the dam within 20 years (Van Loon-Steensma and Slim 2013). Moreover, a few hundred metres east of Stryp, sedimentation of 0.5 m is observed behind a spontaneously developed oysterbank. The new groyne at Stryp led to sedimentation of sand, but it also increased outflow during ebb in the northern gully, causing erosion on this part of the salt marsh.

Vegetation surveys

Methods

To gain insight into the species composition, vegetation types and habitats, we surveyed the vegetation on plots measuring 4 m^2 (r=1.13 m). Eleven plots were chosen along two transects running in north–south (1) and in east–west (2) direction in the during low tide accessible part of the salt marsh. Plot spacing was chosen so as to include key transitions between vegetation zones in the salt marsh. The fieldwork was carried out in August 2011, when salt-marsh vegetation was at its most vigorous. We estimated the abundance of each plant species in the vegetation relevés (Braun-Blanquet 1928). Species were identified using nomenclature following Van der Meijden (2005). To estimate the abundance, an ordinal scale with nine classes was used (Dirkse 1998). Handheld GPS devices served for plot localization. Photographs were taken of each plot. Storage and handling of the vegetation relevés was done using the TURBOVEG data management system (Hennekens and Schaminée 2001; www.synbiosys.alterra.nl/turboveg/). Based on the species found, the plots were classified in plant associations as defined by Schaminée et al. (1998) with ASSOCIA (Van Tongeren et al. 2008) and in habitats (European Commission 2007; Janssen and Schaminée 2003).

Additional vegetation relevés (measuring 4–25 m^2) and charts of the salt marsh were provided by the Data ICT Department of the Dutch Department of Public Works and Water Management (‘Rijkswaterstaat’, henceforth ‘Public Works’) for the years 1996 (n=5), 2000 (n=5) and 2007 (n=7) (in July or September). These data were also stored and handled in TURBOVEG.

The study site was revisited at the end of the growing season of 2012 to sample *Atriplex portulacoides* L. (syn. *Halimione portulacoides* (L.) Aell.) and in June 2013. Although vegetation was not systematically surveyed then (some species are not present or visible in winter or spring), the visits provided an impression of the vegetation present during the winter and spring periods. In total, 20 samples of *A. portulacoides* were taken for age determination from randomized locations (see Decuyper et al. 2014).

Results

In this relatively low-lying salt marsh, we observed a difference in vegetation species composition, height of vegetation and vegetation cover between the grazed and the ungrazed part (Fig. 7). In the western part, which is accessible to sheep, the vegetation is low (5–15 cm) and dominated by *Salicornia europaea* and *Spartina anglica*, with *Puccinellia maritima* and low *Atriplex portulacoides* plants. In the most intensively grazed parts (Fig. 7, in the foreground to the right), vegetation (here comprising solely *Salicornia*) was very scarce. Subsequently most of the sandy substrate was bare and not covered by plants.

The eastern part of the salt-marsh area is not accessible to the grazing sheep because of the gully. It is fully covered by dense patches of the shrubby perennial *A. portulacoides* and with *S. anglica*. The vegetation is higher here (15–25 cm) than in the grazed part (Fig. 7).

Our vegetation surveys were mainly taken in the grazed part of the salt marsh (Fig. 8). Table 1 lists the plant species found in each transect in August 2011. Table 2 and Fig. 8 present the plant communities (syntaxa) and EU protected habitats found by us and by the Department of Public Works. In total, our vegetation survey found 11 plant species, of which 2 are macro-algae. We encountered 5 salt-marsh plant communities.

Discussion

The salt-marsh species and habitats found at Stryp are in accordance with what can be expected on a salt marsh of this height (0.9–1.2 m+NAP, which is 0.05–0.35 m above mean high water) and age (some 70 years). The grazed and lowest-lying parts of the salt marsh are dominated by the respective annual and perennial pioneer species *Salicornia europaea* and *Spartina anglica*, with on the middle section, also *Puccinellia maritima*, which is characteristic of an early successional stage and low elevation. *P. maritima* is a fast-growing and prostrate perennial species that is tolerant to trampling and damage caused by grazing sheep.

In the 1930s, *S. anglica*, with its relatively strong and elongated stem and leaves and extensive roots, was planted to enhance sedimentation. This species is still present, especially in the parts that are not heavily trodden and grazed by sheep.

In general, the vegetation changes during succession from an open system with a low canopy to a dense stand dominated by tall plants (Van Wijnen et al. 1997). On this low-lying and eroding salt marsh, the part that is not accessible to sheep is dominated by the shrubby perennial *Atriplex portulacoides* and by *Spartina anglica. Atriplex* is a late successional species found at sites some 20 cm above mean high water (Olff et al. 1997). This species responds to competition by increasing

Fig. 7 Photograph of Salt marsh at Stryp. In the foreground is the grazed area dominated by *Salicornia europaea*. Visible beyond the creek is the ungrazed area dominated by *Atriplex portulacoides* and *Spartina anglica* (28 June 2013)

stem tissue production, which allows the plant to overtop mid-successional species (Dormann et al. 2000). The high competitive vigour of *Atriplex* might be accompanied by greater vulnerability to mechanical damage, due to ice-scouring as well as to grazing. As a result, trampling and grazing by livestock excludes this plant species from most of the salt marshes in Europe, restricting its occurrence to creek banks (Kiehl et al. 1996; Dormann et al. 2000).

The age of the *A. portulacoides* sampled at Stryp was between 3 and 15 years (average 7–8 years) (Decuyper et al. 2014). Obviously, in the ungrazed area of Stryp, *A. portulacoides* is able to survive for a longer period despite the unfavourable abiotic boundary conditions (ongoing erosion). *A. portulacoides* is also found along the creek banks in the grazed part of the salt marsh. Field and laboratory measurements point out that a tidal creek bank covered with *A. portulacoides* has a higher average erosion threshold than a tidal bank with *Juncus maritimus* (Chen et al. 2012). *A. portulacoides* has a well-developed root system, being relatively wide and densely branched (Decuyper et al. 2014). On the other hand, both laboratory flume studies and controlled field experiments have found that common salt-marsh plants and their living roots do not significantly mitigate the total amount of erosion along a wetland edge (Feagin et al. 2009). These studies attribute the observed erosion gradient along salt-marsh edges not to vegetation but rather to differences in wave energy levels due to differences in microtopography and bathymetry and subsequent wave refraction. Feagin et al. (2009) argue that soil type is the primary variable of influence on the lateral erosion rate. In their experiment, the salt-marsh soils that were most resistant to lateral wave-induced erosion contained more detritus, finer-grained sediments and less 'coarse' organic material than the more erosion-prone soils. Restored sites contained more sand and were less cohesive than natural marsh (Feagin et al. 2009).

Existing evidence for the medial erosion process suggests that above-ground portions of plants attenuate orbital wave currents within relatively densely vegetated salt marshes. But research has also shown that in steady-flow conditions these above-ground portions can result in surface scouring in adjacent locations that are less dense (Balke et al. 2012).

From this perspective, coastal vegetation management should not solely focus on erosion prevention and substrate stabilization during extreme events. Management should instead move towards the goal of landscape-scale sedimentary modification over the long term.

Wave damping

Methods

Using the SWAN wave model (Booij et al. 1999) we predicted the wave damping effect of Salt marsh Stryp under different conditions. SWAN explicitly considers the effect of varying wave/wind conditions and local bathymetry on near-shore wave parameters (height, period and direction). In this study, a detailed computation domain with different salt marsh states was nested into an overall domain in order to obtain suitable boundary conditions. The overall domain is a square, which is 4,000 m from east to west and 4,000 m from north to south. Its origin is 53°21′N, 5°17′E. The detailed domain is a 1,200 m by 1,200 m square located inside the overall domain. Its origin

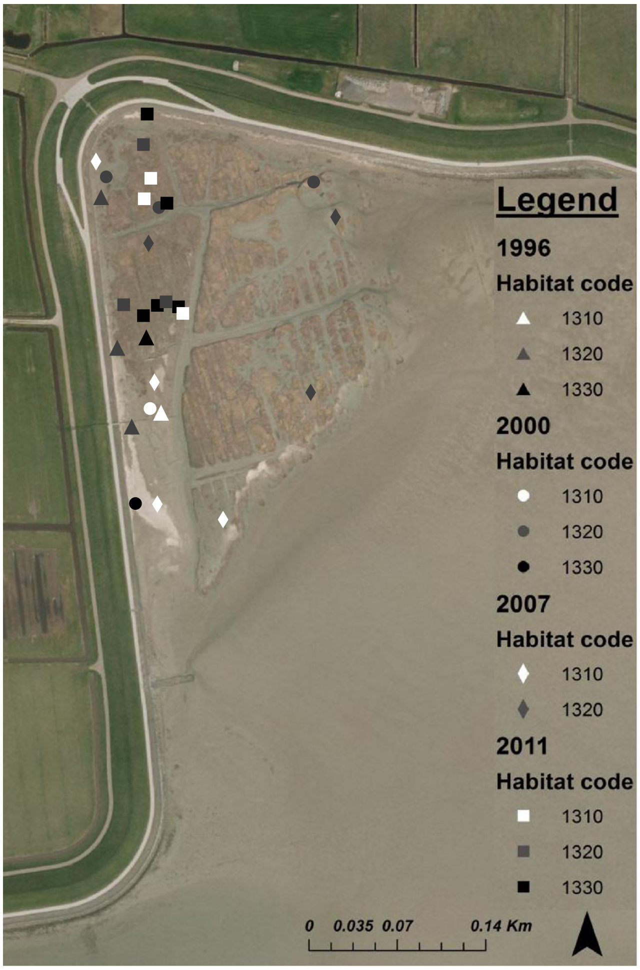


Fig. 8 Spatial presentation of the habitats of the relevés. The meaning of the habitats codes is: H1310- halophyte pioneer vegetation, H1320- *Spartina* swards, H1330- salt marshes, including a diversity of typical vegetation (European Commission 2007). Habitat H1140- mudflats and sandflats not covered by seawater at low tide, is also present, but not indicated in this figure

is 2,000 m north and 1,000 m east to that of the overall domain. Both domains used a rectangular 20 m by 20 m grid.

The model was forced by given incident wave conditions while the effect of wind was not included for simplicity. The incident wave came from the southeast of the overall domain, which is about 3,000 m seaward of the dike. We tested incident significant wave heights of 0.5 m and 0.15 m, while the peak wave period was fixed to be 2.5 s. A JONSWAP spectrum (Hasselmann et al. 1973) was selected to be the incident wave spectrum. Other parameters that describe wave shoaling, breaking and bed friction were set to default values.

To gain insight into the effect of salt-marsh degradation and restoration, we compared the situation with a salt marsh present to a situation without a salt marsh (as a result of ongoing erosion) and to a situation with a broader salt marsh (as a result of salt-marsh restoration) (Table 3). The salt marsh was characterised by the present bathymetry of Salt marsh Stryp, which constitutes an elevated area near the dike with a triangular shape (see Fig. 4). In the situation without the salt marsh, the elevation from dike towards the sea was set at 0 m+NAP, while for the situation of the restored salt marsh the elevated area (at 0.5 m+NAP) was extended by some 350 m in the seaward direction). Furthermore, for the restored salt marsh, the mudflat in front of the saltmarsh (up to ~ 1,000 m in front of the dike) was elevated to allow for a natural gradient between salt marsh and mudflat. To illustrate the bathymetry in these three scenarios, one-dimensional profiles along a north–south transect (vertical white lines in Fig. 9a-g) are shown separately in Fig. 9h. Several detailed results on wave-damping are shown for this transect (see Figs. 10 and 11).

To obtain an impression of the potential effect of the vegetation we compared the situation with an unvegetated salt marsh, to a situation with a salt marsh densely vegetated by low grasses and salt marsh plants (such as *Puccinellia maritima* and *Salicornia europaea*), to a situation with a salt

Table 1 Occurrence of species on the different relevés along two transects (in the accessible part of Salt marsh Stryp) in 2011. Information about coverage is provided in the supplement

Species	1a	1b	1c	1d	1f	2a	2b	2c	2d	2e	2f
Ulva lactuca	+										
Vaucheria species	+	+	+	+	+	+	+	+	+	+	+
Salicornia europaea		+	+	+	+	+	+	+	+	+	+
Spartina anglica		+	+	+	+	+	+	+	+	+	+
Suaeda maritima		+			+	+	+	+	+	+	+
Puccinellia maritima	+	+	+	+	+	+	+	+	+	+	+
Aster tripolium				+						+	
Atriplex portulacoides		+			+	+	+	+	+	+	
Spergularia media	+						+	+			
Limonium vulgare			+	+	+		+	+	+	+	
Triglochin maritima				+	+		+	+		+	
Total species per relevé	4	6	5	7	8	6	9	9	7	9	5

Table 2 Plant communities (syntaxa) at Salt marsh Stryp (*n*=number of vegetation relevés)

			1996	2000	2007	2011
Syntaxa	Syntaxa code	Habitat code	*n*=5	*n*=5	*n*=7	*n*=11
Spartinetum townsendii	24AA02	1320	+++	+++	+++	++
Salicornietum dolichostachyae	25AA01	1310			+	
Salicornietum brachystachyae	25AA02	1310	+	+	+++	+++
Puccinellietum maritimae	26AA01	1330		+		+
Halimionetum portulacoidis	26AA03	1330	+			+++++

Syntaxa and syntaxa codes follow Schaminée et al. (1998). Habitat codes follow Janssen and Schaminée (2003). The + symbols indicate how many relevés contained the plant community

marsh sparsely vegetated by low grasses, and to a situation with a salt marsh vegetated by a shrubby, branched plant (such as *Atriplex portulacoides*). We used the averaged plant height (as observed at Salt marsh Stryp in August 2011). For the class 'salt marsh with high density of low plants' we used plant density (stems/m^2) and stem diameter comparable to these found on a low/middle salt-marsh zone on a nearby salt-marsh location. At that location all stems in sub-samples of 60 surveyed relevés were counted and the diameter of the encountered species were estimated (Van Loon-Steensma et al. submitted). We applied estimations of the density of the sparsely vegetated salt marsh zone and of the shrubby *Atriplex portulacoides* (which has a vertical layered structure because of branching of the main stem). We used the averaged stem diameter of a subsample of *Atriplex portulacoides*.

Also the drag coefficient is important to the modelling outcome, but cannot be obtained easily as well as on hydrodynamic conditions by field surveys as it depends on both plant traits as well as hydrodynamic conditions (Nepf 2011). Accurately determining drag coefficients requires a large number of flume experiment data (Hu et al. 2014). Therefore, for simplicity a drag coefficient of 1.0 and 1.2 was used in our study, as commonly found in previous studies (Nepf 2011; Suzuki et al. 2011).

Furthermore, we analysed the effect on wave propagation of a higher water level, which might become the situation if the elevation of the salt marsh is unable to keep pace with rising sea level (Table 4). We used information from the Department of Public Works on the bathymetry (with a grid of 20–20 m) of the Wadden Sea.

Results

Figure 9 presents the modelled significant wave height distribution for the different situations. We see from the figure that at this location the salt marsh dampens the waves. In a situation without a salt marsh (Fig. 9f) there is hardly any wave damping compared to a situation with an area of salt marsh present (Fig. 9a-e). Broadening the salt-marsh zone in front of the dike (Fig. 9g) increases wave attenuation. Figure 9 shows a clear effect of vegetation. A dense vegetation of low plants (Fig. 9b) and a vegetation of high plants (Fig. 9d and e) affect the height of the waves, whereas a sparse vegetation of low plants (Fig. 9c) shows a wave damping pattern similar to an

Table 3 The different situations for wave height 0.5 and 0.15 m, wind from the southeast, wave period 2.5 s and water depth 0.95 m+NAP (spring tide level) for which SWAN calculations were made

Situation		Salt marsh	Salt-marsh vegetation	Plant height (m)	Plant density (stems/m^2)	Stem diameter (m)	drag coefficient
a.	Salt marsh without vegetation	Current situation	No	–	–	–	–
b.	Salt marsh with high density of low plants	Current situation	Plants	0.04	21,800	0.0005	1
c.	Salt marsh with low density of low plants	Current situation	Plants	0.04	1,000	0.0005	1
d.	Salt marsh with high plants	Current situation	Plants	0.25	385	0.0021	1
e.	Salt marsh with high plants having a high drag coeff.	Current situation	Plants	0.25	385	0.0021	1.2
f.	No salt marsh	Eroded marsh	No	–	–	–	–
g.	Broadened salt marsh	Restored	Plants	0.25	385	0.0021	1.2

The values refer specifically to conditions along the transect indicated in Fig. 9

unvegetated salt marsh (Fig. 9a). Fig. 10 presents the wave propagation along the transect indicated in Fig. 9 by a white vertical line.

The model boundary is 2,000 m seaward from the rightmost values at x-axes in Figs. 10 and 11. Because of wave breaking and friction over this distance, the wave heights at the right in these figures are considerably less than the imposed wave heights of 0.5 m and 0.15 m. In fact, the modelled wave damping in this environment is some 0.08 % per m (for the situation with an initial wave height of 0.5 m), while wave damping by 350 m of unvegetated marsh or sparsely vegetated marsh is some 0.13 % m per m and 0.14 % m per m respectively. The modelled wave damping by the densely vegetated marsh is some 0.22 % per m, and by a salt marsh vegetated with the shrubby plant is some 0.20 % per m. This is strikingly similar to the reported wave damping by salt marshes of the same width and comparable dominant plant species (Anderson et al. 2011, see Table 1 in that study). Figure 11 presents the modelled significant wave height for different sea level rise scenarios. This figure shows that under sea level rise, a broadening of the salt-marsh zone significantly influences the height of the waves.

Discussion

We found wave height to be significantly affected by the areal extent of the salt marsh as well as by the vegetation at Stryp. High vegetation (such as *A. portulacoides*) and dense low vegetation (such as *Puccinellia maritima*) are in our models nearly as effective in wave attenuation as a widening of the salt-marsh area by 350 m. A low density of low plants, as observed in the grazed part of the marsh, had almost no wave damping effect. Therefore, if improved wave damping capacity of a salt marsh is desired, intensive grazing by sheep is not advisable.

In our study we applied a drag coefficient of 1.0 and 1.2, as commonly found in previous studies (Nepf 2011; Suzuki et al. 2011). However, in order to get more insight in actual wave damping by natural salt-marsh vegetation it is advisable to explore the differences in drag coefficient between a dense vegetation of low and thin leaves and a vegetation of shrubby plants in depth by both flume experiments and field observations of wave damping.

We analysed the effect of sea level rise by applying a greater water depth. A water depth of 1.05 m corresponds with an expected autonomous sea level rise of 0.10 m by 2050 (based on the observed sea level rise during the past century). A water depth of 1.30 m corresponds with the ‘low’ Dutch delta scenario with a sea level rise of 0.35 m in 2100 and the ‘high’ delta scenario in 2050, whereas a water depth of 1.8 m corresponds with the ‘high’ Dutch delta scenario of 0.85 m in 2100 (Bruggeman et al. 2013). A broader salt marsh, vegetated with high plants such as *A. portulacoides*, significantly affects the wave height under conditions of a rising sea level. We did not account for elevation change of the marsh surface by sedimentation. If the salt marsh can keep pace with rising sea level (resulting in less water depth) it will dampen the waves more effectively (Fig. 11). However, in the current situation the salt marsh at Stryp is diminishing. Without measures, it will probably disappear around 2050 (Fig. 5).

Our model was parameterized with great care and with the best information available. Nonetheless, it remains difficult to realistically and meaningfully estimate wave height, water level and wind direction for this Salt marsh Stryp, because it is nestled along the dike, in a lee corner. Hydraulic boundary conditions for this dike section given by the Ministry of Transport, Public Works and Water Management et al. (2007) (i.e., 4.2 m+NAP and H_{m0} 0.9 m) are for a situation with northwest wind, meaning that the south side of the island is in the lee of the wind. With a southwest wind, the water level will be lower, but waves might be higher.

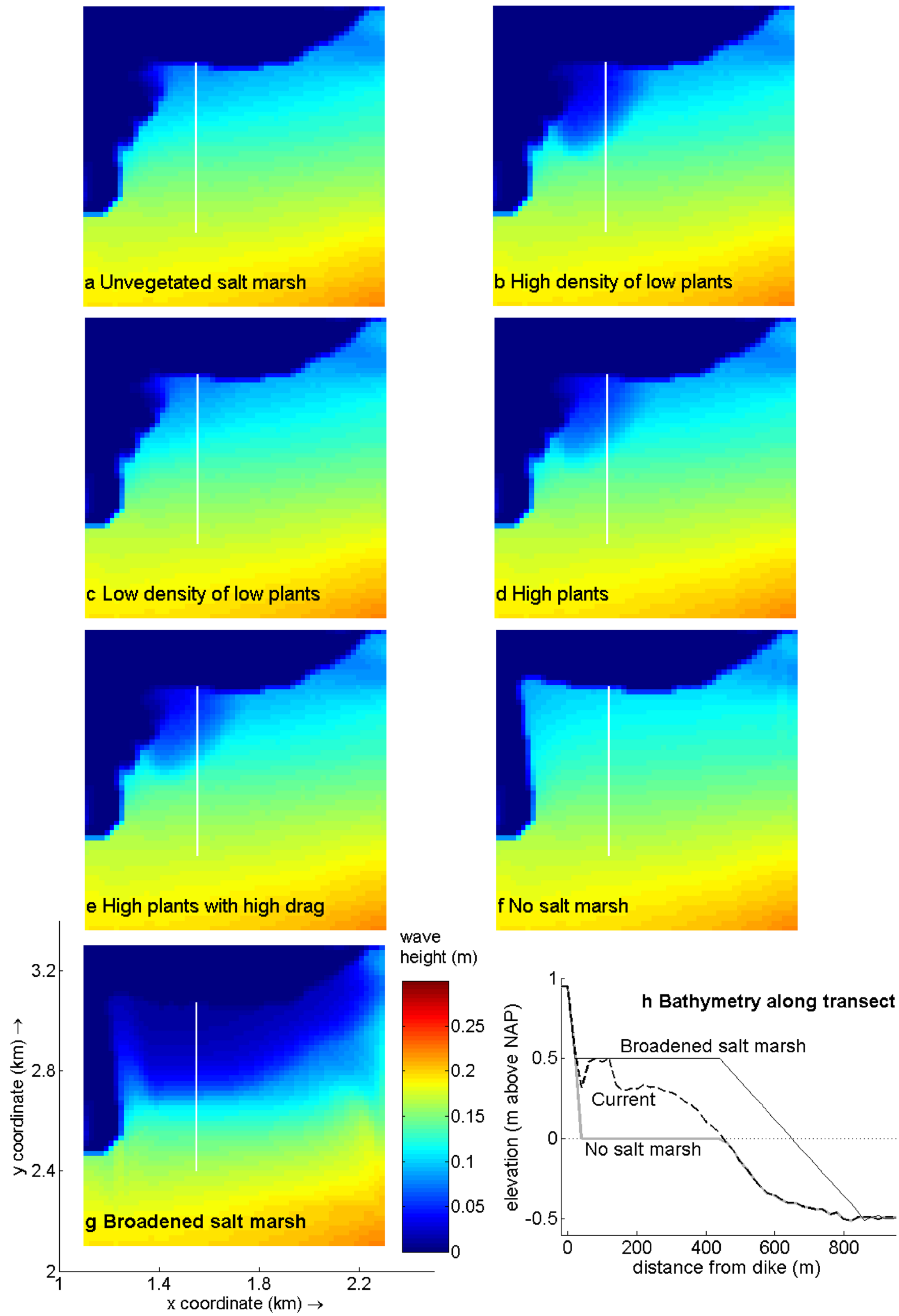
Sensitivity studies show that wave conditions in the Wadden Sea interior are predominantly locally generated by wind, and are strongly determined by the limited water depths above the tidal flats in the Wadden Sea (Van der Westhuysen and De Waal 2008). Therefore, under southwest winds, the highest waves can be expected during spring tide (as in our model).

Accurate and reliable information about wave damping by vegetated foreshores under different hydraulic conditions is a prerequisite for the implementation of vegetated foreshores in dike dimensions. To this end both field and laboratory experiments will be indispensable. Field experiments will be required to understand the influence of complex terrain geometry as well as effects of subtle soil-vegetation characteristics such as soil layering, (high) plant densities, plant rooting characteristics and plant phenology on terrain roughness and stability. Laboratory experiments (e.g. in experimental flumes) will remain important due to the possibility to control many more variables effectively than in the field, and conduct more controllable and less noisy measurements.

Specific to our study location, it is at this stage (after initial model parameterisation and first model results) advisable to measure the development of wave height in the field under different weather conditions to obtain observational data with which the modelled wave attenuation capacity of the current salt marsh can be evaluated and (if necessary) calibrated. While providing more reliable wave-height predictions, such measurements would also advance our understanding of the influence of various attributes of the vegetation structure (stem density, stem diameter, height, drag) on wave attenuation.

Outlook for our study site Salt marsh Stryp

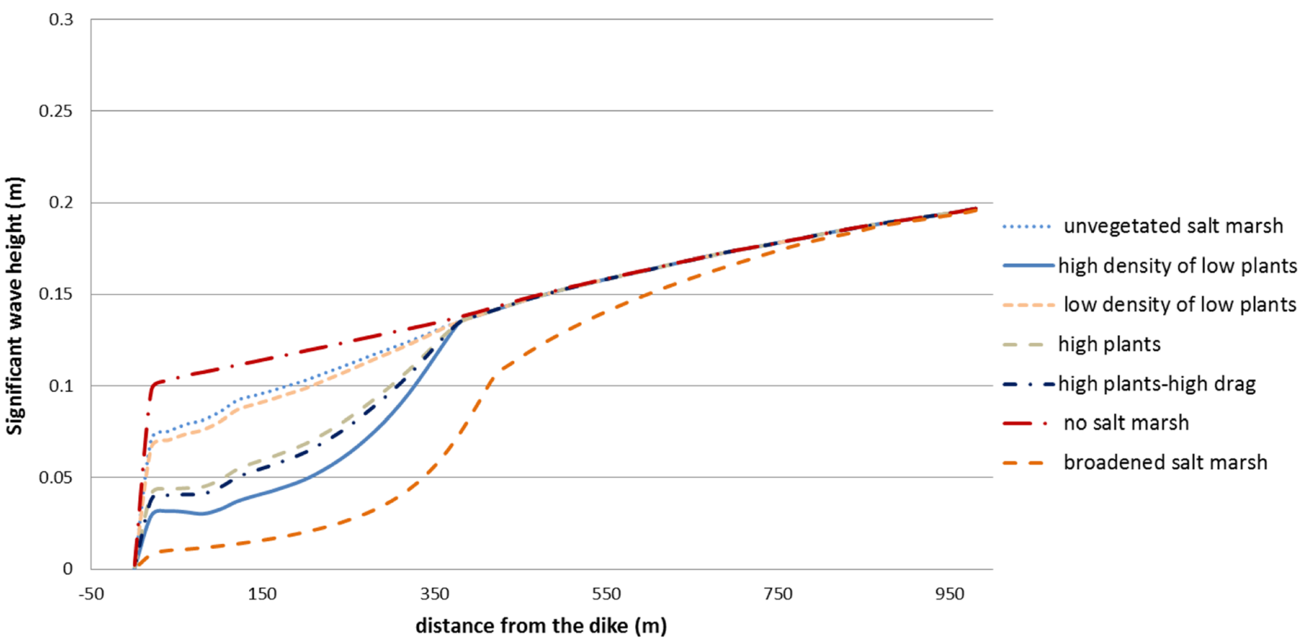
The inhabitants of Terschelling launched an initiative to restore the eroding Salt marsh Stryp in order to preserve and improve the landscape and nature values at this location.


a Unvegetated salt marsh
b High density of low plants
c Low density of low plants
d High plants
e High plants with high drag
f No salt marsh
g Broadened salt marsh
y coordinate (km) →
3.2
2.8
2.4
2
1
1.4
1.8
2.2
x coordinate (km) →
wave
height (m)
0.25
0.2
0.15
0.1
0.05
0
h Bathymetry along transect
elevation (m above NAP)
1
0.5
0
-0.5
Broadened salt marsh
Current
No salt marsh
0
200
400
600
800
distance from dike (m)

◀ **Fig. 9** Modelled significant wave height distribution for the different situations. The white vertical line indicates the transect to which the parameters in Table 3 refer. The bathymetry for this transect (for the three different scenarios) is shown in 9h. The 0,0 coordinate of the graph is situated at 53°21′N, 5°17′E

Without measures, the present human-induced salt-marsh habitats at Stryp will revert within a few decades to sandflats and mudflats. Although sandflat and mudflat habitats (H1140) represent important ecological values, the loss of the salt-marsh area at this location would diminish habitat and landscape diversity. The salt marsh in front of the dike forms a smoother transition zone from the dry coastal area to the marine environment than solely the stone-covered dike. Furthermore, salt-marsh areas covered with *Atriplex portulacoides* are scarce in Europe (Dormann et al. 2000), forming an additional argument for the salt marsh's preservation.

Broadening the salt marsh would impinge upon sandflat and mudflat habitat, and would probably have some negative effect on the abundant breeding and wading birds that feed on the benthic invertebrates on



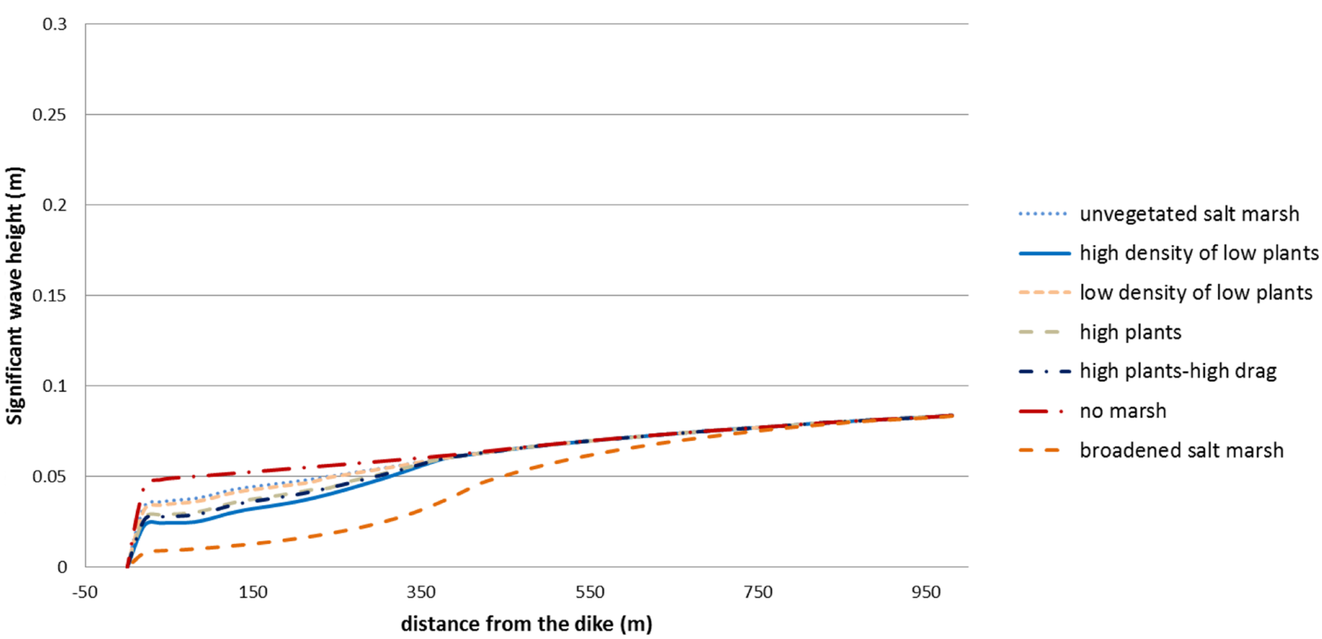


Fig. 10 Modelled significant wave height (top = wave height of 0.5 m; bottom = wave height of 0.15 m, both at 3,000 m) along a transect perpendicular to the coast near the Stryp Polder under different situations (see Table 4)

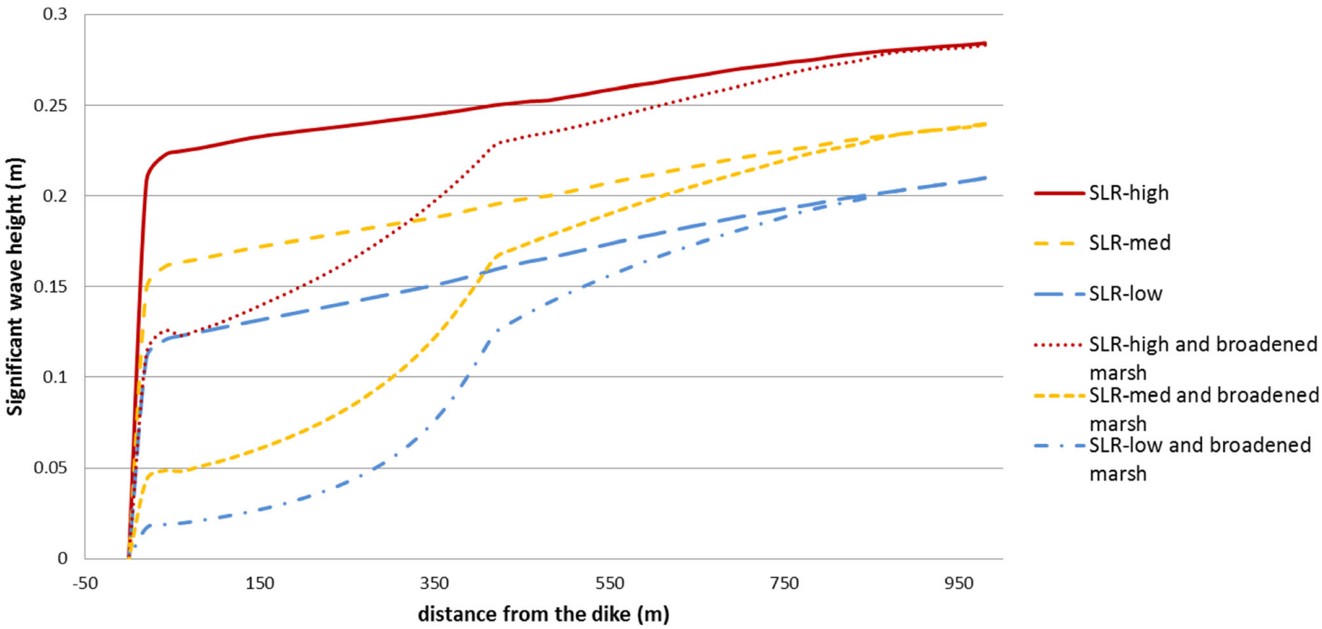


Fig. 11 Modelled significant wave height for different sea level rise (SLR) scenarios (wave height of 0.5 m at 3,000 m) (see Table 4)

the tidal flats in front of Salt marsh Stryp. On the other hand, extensive flats would remain adjacent to a broadened salt marsh.

No design for a broadened salt marsh at Stryp has yet been made. Van Duin and Dijkema (2012) recommend a minimum area of 500 ha in order to stimulate geomorphological as well as ecological processes and to enhance management strategies. However, taking into account the size of the accretion works of the 1930s (some 35 ha) an area of 50–100 ha seems more realistic for this location. Restoration measures that utilize natural processes would be preferred (Van Duin and Dijkema 2012; De Groot et al. 2012). Low wooden groynes, as were used in the 1930s and led to salt-marsh formation at Stryp, allow tidal flows to transport sediment into the protected area and a gradual building up of the restored marsh and colonizing by salt-marsh plant species.

Sediment supply appears to be sufficient for accretion, as suggested by the observed sedimentation behind a spontaneously developed oyster bank close to Salt marsh Stryp and by the formation of a new salt marsh some 8 km east, at Grië. Nonetheless, there are questions about the feasibility of salt-marsh restoration at Stryp. Kirwan et al. (2010) found that when suspended sediment concentrations are above 20 mg/l, salt marshes are able to grow with rising sea level. Monitoring of the sedimentation process and vegetation development might provide insight into the effectiveness of restoration measures, while also allowing timely adaptation in the management of the marsh or additional measures to improve the restoration process. Such additional measures may include sediment nourishment. This has been done in numerous cases, sometimes with dredged material, though this has a different biochemical makeup than natural silt and has been found to lead to immature salt marshes (Spencer and Harvey 2012).

Table 4 The different situations for wave height 0.5 m, wind from the southeast, wave period 2.5 s with a high sea level rise (*SLR*) scenario (85 cm), a medium SLR scenario (35 cm) and a low SLR scenario (10 cm) for which SWAN calculations were made

Situation		Salt marsh	Water depth	Salt marsh vegetation	Plant height (m)	Plant density (stems/m^2)	Stem diameter (m)	drag coefficient
a.	High SLR	Eroded	1.8	No	–	–	–	–
b.	Medium SLR	Eroded	1.3	No	–	–	–	–
c.	Low SLR	Eroded	1.05	No	–	–	–	–
d.	High SLR and broadened marsh	Restored	1.8	Plants	0.25	385	0.0021	1.2
e.	Medium SLR and broadened marsh	Restored	1.3	Plants	0.25	385	0.0021	1.2
f.	Low SLR and broadened marsh	Restored	1.05	Plants	0.25	385	0.0021	1.2

The values refer specifically to conditions along the transect indicated in Fig. 9

Measures to restore Salt marsh Stryp will also influence the wave damping service of the marsh, as they would produce a broadened salt-marsh zone in front of the dike. Moreover, wooden groynes or a dam of clay or oysters themselves affect wave height. A number of landowners and municipal administrators have indicated interest in the possible contribution that salt marshes could make to flood safety (Van Loon-Steensma 2011). For example, they would like to know whether restoration of the salt marsh could reduce the need for future landward strengthening of the dike. Restoration of Salt marsh Stryp could furthermore offer an interesting pilot location to experiment with techniques for protecting, developing and effectively managing salt marshes as an climate adaptation strategy (see, e.g., Van Loon-Steensma and Vellinga 2013). For this purpose too, it will be important to monitor changes in the salt-marsh area and in the condition of the vegetation, in combination with the wave damping capacity.

Conclusion

As illustrated by our study, salt-marsh restoration at Stryp is a multifaceted endeavour, and one in which a large array of effect types must be considered. Care has to be taken to ensure that undesirable side effects of restoration do not outweigh benefits. An *ex ante* assessment of impacts and side effects is therefore a precondition of any decision to restore the salt marsh. Stakeholders, too, should be involved in such assessment, as they play a role in both valuation of the impacts and in defining the objectives of restoration measures.

Furthermore, long-term monitoring of sedimentation processes and vegetation development is key to advance knowledge about the effectiveness of measures taken and to indicate any necessary adjustments of management or additional measures required.

Finally, a restored marsh at Stryp could fulfil an educational purpose. Salt-marsh development and dynamics are very visible at Salt marsh Stryp, because the marsh lies alongside a bicycle path that follows the Wadden flood defence. Using information panels and observation facilities, tourists and residents could be informed about the ongoing unique natural processes and the characteristics of the salt-marsh habitat, increasing appreciation of the Wadden Sea dynamics.

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