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Modelled Impact of Vegetation Heterogeneity and Salt-Marsh Zonation on Wave Damping

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ABSTRACT

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This paper analyses the effect of observed vegetation characteristics on modelled wave heights. Detailed information on species composition, as well as on height, number of stems, and diameter of the plant species of a restored salt marsh on the Wadden barrier island of Terschelling was used to parameterize and apply the Simulating Waves Nearshore – Vegetation wave model to a schematized restored salt-marsh zone in front of the dike. The results indicate that wave damping by vegetated forelands is strongly related to vegetation heterogeneity and salt-marsh zonation. The modelling works suggest that at the study site under storm conditions with a frequency of 5–10 times/y, a vegetated foreland of some 90 m in width will dampen the wave height more than 80%, whereas under extreme conditions (1/2000 y) a foreland covered with dense vegetation will dampen the wave height up to 50%. These results imply that at the study site a vegetated foreland in front of the dike leads to reduced wave attack on the dike, which may result in changed requirements for both height and revetment of the dike while maintaining the required safety level. Although there are still many questions concerning dimensions, management, and performance, developing a vegetated foreland seems an interesting strategy to adapt existing flood protection works to the effects of climate change.

ADDITIONAL INDEX WORDS: *Vegetation characteristics, wave attenuation, SWAN-VEG, climate change adaptation.*

INTRODUCTION

The foreseen effects of climate change on sea-level rise and on storminess (IPCC, 2007) led in many countries to intensified research on the potential impact of climate change on flood risk in coastal zones. Important questions in this context are how to adapt the existing flood-protection works, and how to develop new flood-protection strategies. Measures that serve multiple functions or contribute to reach policy tasks other than flood protection form interesting no-regret adaptation options. Against this backdrop, the attention increases for the flood-defence service of vegetated forelands such as salt marshes. By the dissipation of wave energy, a salt-marsh zone reduces wave heights (*e.g.*, Brampton, 1992; Costanza *et al.*, 2008; Gedan *et al*. 2011; King and Lester, 1995; Möller *et al*., 2001; Shepard, Crain, and Beck, 2011), and subsequently buffers the loads on the coastline and on coastal protection works (such as dikes). Furthermore, salt marshes form a transition zone between the marine and the terrestrial environment that harbours typical and valuable habitats. Hence, the application of salt marshes for coastal protection offers chances to enhance nature and landscape values in the coastal area (van Loon-Steensma and Vellinga, 2013). Furthermore, under conditions of abundant sediment supply, salt marshes may keep pace with sea-level rise by accretion (*e.g.*, Allen, 2000; Dijkema *et al*., 2011). This makes them particularly attractive from a climate adaptation perspective.

Wave damping by salt marshes can be defined as wave height reduction over a certain distance of salt marsh. It is affected by water depth above the salt marsh, topography of the coastal profile, incident wave height, and wave period, as well as vegetation characteristics (see studies cited in Anderson, Smith, and McKay, 2011), and is the subject of numerous studies (see studies cited in Gedan *et al*., 2011; Shepard, Crain, and Beck, 2011). In general, waves break when they encounter shallow water depth. When the significant wave height is some 0.4–0.5 times the water depth, a wave becomes too high and steep to support itself, which results in wave breaking. The area where waves break is called the surf zone. In coastal wetlands, often a surf zone can be found near the most seaward salt-marsh zone. After breaking, wave energy is further dissipated by drag induced by marsh vegetation and by bottom friction. This often results in a reduction of wave height across the salt marsh.

The wave-damping capacity of vegetation has been studied in the field as well as in the laboratory by various authors (see tables 1 and 2 in Anderson and Smith, 2014). Such studies pointed out that wave heights were significantly more reduced by salt marsh covered with vegetation than by bare sand flats (*e.g.,* Möller *et al*., 2001; Yang *et al*., 2012). Even under simulated storm conditions 60% of the observed wave reduction was attributed to vegetation (Möller *et al*., 2014). Not only have the effects of vegetation presence been investigated in this context, but also the effect of several vegetation properties. Zones with a higher plant-stem density of *Spartina alterniflora*, for example, were more effective in wave damping than

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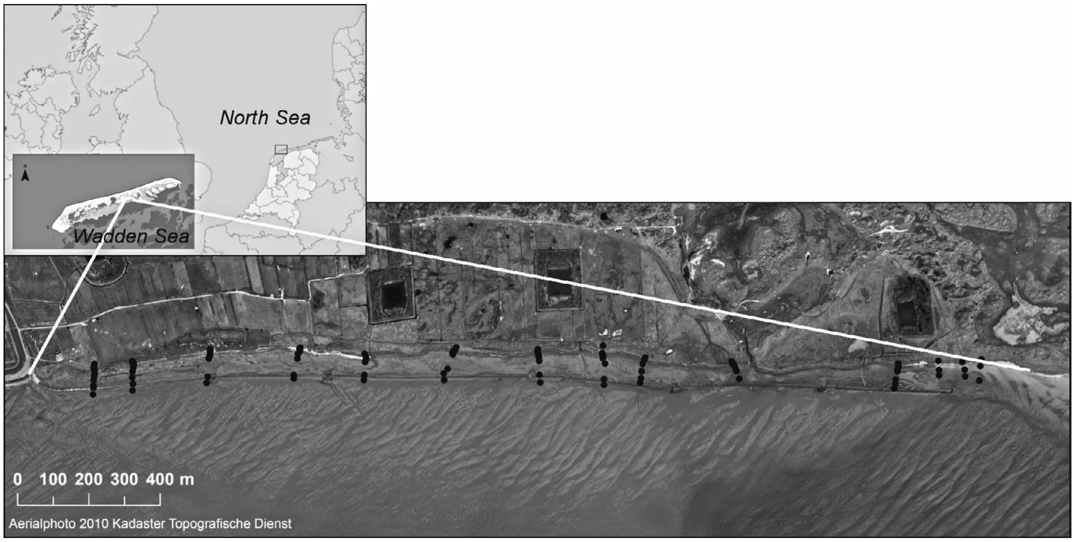

Figure 1. Location of the restored salt marsh at Grië on the Wadden Sea barrier island of Terschelling (The Netherlands) and the surveyed 90 plots along the 14 transects. Source aerial photograph: Kadaster (Netherlands Land Registry Office), 2010.

zones with a lower density (Yang *et al.*, 2012). A tall canopy of *Spartina* spp. in Essex (U.K.) damped the waves more than a shorter canopy of the *Salicornia* spp. (Möller, 2006). Dissipation was roughly three times higher in vegetation with stiff leaves than in vegetation with flexible leaves (Bouma *et al.*, 2005), which may bend with flow and sway back and forth. On a biomass basis, however, the dissipation of stiff and flexible leaves appears to be comparable (Bouma, De Vries, and Herman, 2010). In the laboratory the interaction of waves and plants can be studied under controlled conditions. Although recently an interesting flume experiment was conducted with transplanted natural salt-marsh vegetation (Möller *et al.*, 2014), most laboratory studies use artificial plants that are placed in a regular grid (*e.g.*, Anderson and Smith, 2014; Hu *et al.*, 2014; Suzuki, Arikawa, and Stive, 2009). Under natural conditions, however, salt-marsh vegetation is heterogeneous and grades from a seaward zone of pioneer plant species to a more mature plant community landward (Adam, 1990). Such a zonation may affect wave damping. The impact of vegetation structure of mangroves on wave damping was recently explored by Cuc *et al.* (2015). They simulated the wave-dissipation capacity of different types of mangrove vegetation for different water levels (as a proxy for the impact of climate change) with the numerical wave-propagation model Simulating Waves Nearshore – Vegetation (SWAN-VEG). Differences in modelled wave damping between natural and planted mangroves were attributed to the different characteristics of the mangrove vegetation (root structure, average size, diameter, and density) (Cuc *et al.*, 2015).

The goal of this study was to explore the potential effect of vegetation heterogeneity and salt-marsh zonation on wave damping. The effects of differences were assessed for stem density, height, and diameter on wave damping by modelling wave propagation along a schematized restored salt marsh for different vegetation scenarios and different extreme conditions. The specific objectives of this research were to (1) gain insight in vegetation characteristics of the salt-marsh zones in our study site, and (2) explore the potential effect of vegetation characteristics and salt-marsh zonation on wave damping in a conceptual and realistic way. In this way, a relative comparison of potential wave damping was obtained between different vegetation scenarios and extreme conditions.

METHODS

This study investigated salt-marsh vegetation characteristics at the Dutch Wadden Sea island of Terschelling. To explore the potential effect of such vegetation characteristics on wave height, the observed mean stem density, plant height, and stem diameter was translated into relevant parameters for the SWAN-VEG model. The SWAN model is a third-generation wave model developed at Delft University of Technology (Booij, Ris, and Holthuijsen, 1999). The SWAN model explicitly accounts for the processes of wave generation by wind, quadruplet wave–wave interactions, white-capping, bottom friction, depth-induced breaking interactions, and triad wave–wave interactions. The effects of vegetation have been recently incorporated into the model by Suzuki *et al.* (2012). SWAN-VEG was applied in two different extreme situations to a fictional restored salt-marsh zone (inspired by the actually measured salt-marsh profiles in the region) in front of the dike along Wadden Sea barrier island Terschelling.

Characteristics of Salt-Marsh Vegetation

The study site was a restored salt marsh (Grië) along the southern coast of the island Terschelling (53°24′15″ N, 5°25′00″ E; Figure 1).

This marsh developed in 20 years between the edge of a formerly eroding salt marsh and a low stone dam built in 1991 *ca*. 60 m in front of the salt-marsh cliff to prevent ongoing erosion. Sedimentation of sand and silt raised the mudflats

Figure 2. Series of subsamples of the vegetation relevés along one of the transects in the restored salt marsh at Grië on the Wadden Sea barrier island Terschelling (June 2013) with (a) densely vegetated pioneer zone behind the dam, (b) sparsely vegetated pioneer zone, (c) vegetation with dominance of *Spartina anglica*, (d) low salt-marsh zone, (e) middle salt-marsh zone, (f) zone around flood mark, and (g) vegetation with dominance of *Elytrigia atherica* on the upper salt-marsh zone. Note the layered soil profile of the upper marsh zone (g) caused by sand deposition during extreme conditions on top of the organic layer, in contrast to the clay-dominated profile of the restored salt marsh (a–f).

between the dam and the former cliff, creating a broader foreshore with typical salt-marsh vegetation of the pioneer (with species as *Salicornia europaea*, *Spartina anglica*), low (*e.g.*, *Puccinellia maritima*, *Salicornia europaea*), and middle zone (*e.g.*, *Atriplex portulacoides*), whereas behind the edge of the former cliff climax salt-marsh vegetation of the upper marsh zone (*Elytrigia atherica*, *Festuca rubra*) was found (Bakker, 2014; van Loon-Steensma and Slim, 2013).

Vegetation was surveyed along 14 transects at regular intervals perpendicular to the coast (Figure 1). The six eastern transects were surveyed in August 2011, when salt-marsh vegetation was at its most vigorous, and the eight western transects were surveyed in June 2013 at the start of the growing season. The vegetation was examined in 90 circular relevés measuring 4 m^2 (radius of 1.13 m) to gain insight into the species composition, vegetation types, and habitats. Plot spacing was chosen so as to include key transitions between vegetation zones in the salt marsh (*i.e.* from bare mudflats in front of the dam, via the pioneer zone just behind the dam, and the low and middle salt-marsh zones between dam and the former cliff, toward the upper salt marsh behind the former cliff). The abundance of each plant species was estimated in the vegetation relevés (Braun-Blanquet, 1928). Species were identified using nomenclature following Stace (2010). An ordinal scale with ten (10) classes was used to estimate the abundance (Dirkse, 1998). Handheld GPS devices served for plot localization. Photographs were taken of each plot. Storage and handling of the vegetation relevés were done using the TURBOVEG data management system (Hennekens and Schaminée, 2001; www.synbiosys.alterra.nl/turboveg/). On the basis of the species found, the vegetation relevés were classified in plant associations as defined by Schaminée, Weeda, and Westhoff (1998) with ASSOCIA (van Tongeren, Gremmen, and Hennekens, 2008) and for nine misclassifications by expert judgment (P.A.S.), and in habitats (European Commission, 2007; Janssen and Schaminée, 2003).

Furthermore, all stems were counted in a subsample (10×10 cm) of each of the 60 surveyed relevés in the eight western transects and estimated the diameter of the stems of the encountered species (at about 1/3 of their height), as well as their height (Figure 2). The subsample was randomly taken from each relevé. Because it was at the beginning of the new growing season, *S. europaea* plants were just establishing and not yet branched. Therefore, every *Salicornia* plant was counted as one stem. Because the grasses had multiple stems per plant, the number of stems per area was taken (instead of the number of plants per area), but the thin leaves that came from the stems were not accounted for. For species like *Suaeda maritima*, stems per area were noted without taking into account their tiny leaves.

On the basis of the plant composition in the subsamples, the mean number of stems per square meter was calculated, as well as the weighted mean diameter per stem (in which was accounted for the plant composition) and the weighted mean height (in which was accounted for the species composition) for each subsample. Then the mean height, plant density, and stem diameter (June 2013) was calculated for the salt-marsh vegetation zones in the restored salt marsh.

On the basis of the observed vegetation characteristics in the field, the following was distinguished: (i) unvegetated sand and mudflats in front of the dam, (ii) a densely vegetated pioneer zone behind the dam, (iii) *Spartina* swards, (iv) a sparsely vegetated pioneer zone along the gully in the salt marsh, (v) a low and middle salt-marsh zone dominated by *P. maritima*, (vi) a zone around the flood mark, (vii) an upper salt-marsh zone in front of the former cliff, and (viii) an upper salt-marsh zone behind the former cliff with a thick layer of several centimeters of dead stems of the former year and dominated by *E. atherica* (Figure 3). Also found was a small area with dead *Salicornia* spp. of the previous year, a patch of *Bolboschoenus maritimus*, and atypical vegetation on a narrow walking path. However, neither the vegetation characteristics nor the characteristics of eight unclear subsamples were used as SWAN-VEG input.

Although the flexibility and the configuration of the plants also affects wave damping (*e.g.*, Anderson, Smith, and McKay, 2011; Bouma *et al.*, 2005; Dijkstra and Uittenboogaard, 2010; Feagin *et al.*, 2011), this study did not investigate the flexibility or the effects of the form of the leaves and branches of the encountered species, but applied two different values for the bulk drag coefficient.

A handheld GPS (Trimble® Juno SB with an accuracy of 2–5 m) determined the approximate location of the relevés and based on the found *x*- and *y*-coordinates, this study estimated the elevation (*z*-coordinate) of each relevé in meters above mean sea level (NAP) using the digital elevation map of the Netherlands (AHN, 2012: grid 0.5×0.5 m, accuracy *z*-coordinate 5 cm). In such a digital elevation model the elevation of a given location is based on bilinear interpolation of the measured heights of the neighbouring four points of the grid, which may lead to levelling of local elevation differences in the data (Figure 4).

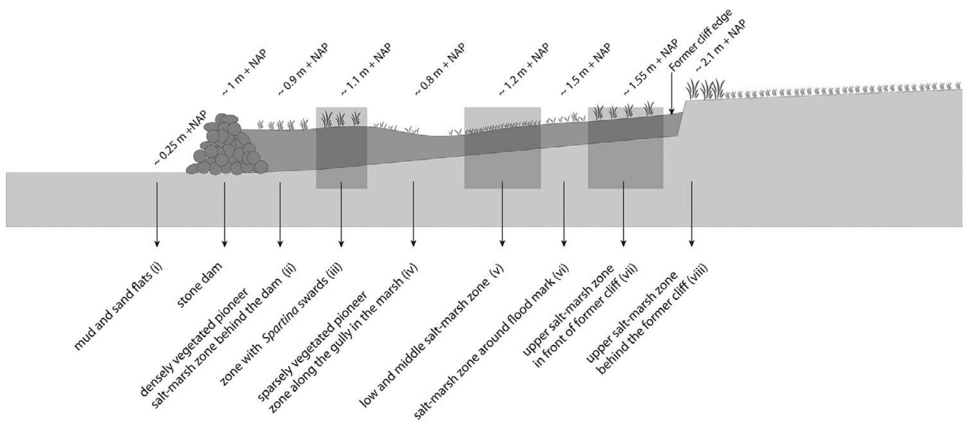

Figure 3. Cross-section of the restored salt marsh between the dam and the former cliff edge with the different salt-marsh zones and mean height at Grië (Terschelling).

Parameterisation and Inputs for the SWAN-VEG Wave Model

Wave height was modelled with SWAN-VEG to explore the potential effect of our observed salt-marsh vegetation characteristics on wave damping. Wave damping by vegetation in SWAN-VEG is induced by drag force acting on the plant stems (Suzuki *et al.*, 2012), which results in less wave energy behind the vegetation field and thus a lower wave height. The SWAN-VEG model is validated by Suzuki *et al.* (2012), who modelled the vegetation as cylindrical obstacles. Vegetation characteristics such as height, width, density, and drag coefficient were used by them to determine the magnitude of the dissipation term. In this vegetation-wave model the vegetation drag coefficient forms a bulk coefficient that varies greatly with vegetation characteristics (such as flexibility and the form of the leaves and branches) as well as the hydrodynamic regime (Hu *et al.*, 2014; Nepf, 2011). Previous studies often found that the bulk vegetation drag coefficient is most suitable in the range between 0.1 and 1.0 (Nepf, 2011; Suzuki *et al.*, 2012). For simplicity, often a bulk drag coefficient of 1.0 is used (*e.g.*, Cuc *et al.*, 2015). The SWAN-VEG model was recently validated by Vuik *et al.* (unpublished data) for locations along the Wadden Sea mainland coast and the Scheldt Estuary. They found a bulk drag coefficient of ~0.4 for the vegetation in the Scheldt Estuary by calibration of the SWAN-VEG model results.

This study evaluated wave propagation for 12 foreland scenarios (Table 1) along two transects (indicated by black lines in Figure 5 right) on the schematized (fictional) restored salt marsh (Figure 5 left) for different conditions (Table 2). These two transects were chosen to represent the dike system on the south of Terschelling. The dimensions of the fictional restored salt marsh were inspired by actually measured salt-marsh profiles in the region. Although transects 1 and 2 share a similar structure as shown in Figure 5 left, their different

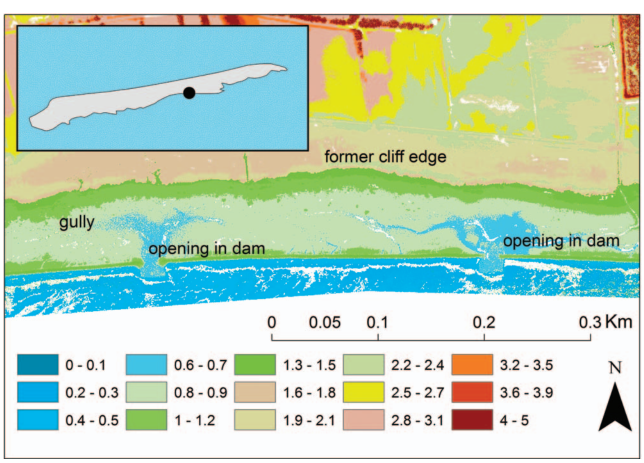

Figure 4. Map of digital elevation model (DEM) in meters above mean sea level (NAP, Dutch reference height) of the salt marsh at Grië (Terschelling) (source: AHN, 2012).

Table 1. *Different foreland scenarios applied in the Simulating Waves Nearshore-Vegetation (SWAN-VEG) wave model. The width of the restored salt marsh is ~120 m (in front of the dike), and the level at seaward side is 0.9 m +NAP and at landward side 1.5 m +NAP (see Table 5 for the found vegetation characteristics of these scenarios).*

Scenario	Salt Marsh
Current situation (no silted-up area in front of dike)	No
Dam/groyne (0.9 m in height) in front of dike (120 m)	No
Unvegetated salt marsh (silted-up area in front of dike)	Restored
Densely vegetated pioneer salt marsh (as found behind dam)	Restored
Salt-marsh zone with *Spartina anglica*	Restored
Sparsely vegetated pioneer zone (as found along the gully)	Restored
Low/middle salt-marsh zone	Restored
Salt-marsh zone around flood mark	Restored
Upper salt-marsh zone in front of former cliff	Restored
Upper salt-marsh zone (including layer of dead vegetation)	Restored
Upper salt-marsh zone with only *Elytrigia atherica*	Restored
Zonation of pioneer, low/middle, and upper salt-marsh vegetation	Restored

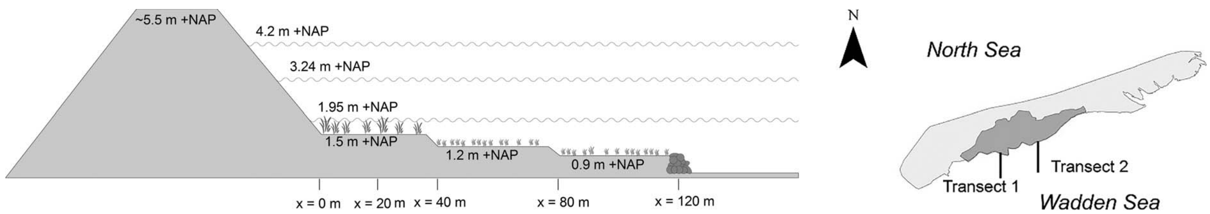

Figure 5. Hypothetical restored salt marsh and vegetation in front of dike (left). The dike ring at Terschelling consists of a dike along the Wadden Sea and dunes along the North Sea (right). The two analysed transects are indicated by black lines.

orientation relative to the sea dike results in slightly different dimensions.

The foreland scenarios differed with respect to the presence or absence of a schematized foreland (*i.e.* a shallow zone in front of the dike) of some 120 m in width and 0.9 m +NAP at the seaward side and 1.5 m +NAP at the landward side (Figure 5 left), and the type of vegetation. One scenario concerns a dam/ groyne of 0.9 m +NAP at ~120 m in front of the dike, and represents the initial state of foreland restoration, when the area between the dam and the dike is not yet filled with sediment. Except for the last scenario (which concerns a zonation in salt-marsh vegetation), the same vegetation characteristics (height, diameter, and stems per square meter) were applied to the entire modelling domain.

Because 1.0 is a commonly used value for rigid stems and the drag coefficient of flexible stems is somewhat smaller (*e.g.,* Anderson, Smith, and McKay, 2011; Augustin, Irish, and Lynett, 2009), bulk drag coefficients of 0.5 and 1.0 were applied to test how their variations affect vegetation wave dissipation. In this way, a relative comparison was obtained between different vegetation characteristics (including flexibility and plant configuration) and extreme conditions.

The wave modeling is carried out in a two-dimensional domain. Parameters that describe wave propagation processes but do not directly relate to vegetation-induced wave damping in the SWAN model are default values (see http://swanmodel.sourceforge.net). Bottom friction, wave breaking, directional spreading, and white capping were switched on, whereas diffraction, wave growth, and wave setup are switched off in the model.

This study used information from the Department of Public Works on the Wadden Sea's bathymetry (with a grid of 20 × 20 m). Our fictional foreland was placed on top of the bathymetry in front of the existing dike. The spatial orientation of the dike with respect to the wind direction resulted in a difference in the actual length between transects 1 and 2.

RESULTS

This study found a range of typical salt-marsh plant species (Table 3), plant communities, and habitats (Table 4) in the restored salt marsh at Grië. On the basis of elevation and plant species, different salt-marsh zones were identified and mean stem density, height, and diameter were assigned to these zones. The observed differences in vegetation characteristics strongly affect the modelled wave damping. Even under extreme conditions (initial wave height of ~1 m) a salt-marsh area of 90 m in width covered with vegetation of the low and middle salt-marsh zone dampens our modelled wave heights 50%.

Characteristics of Salt-Marsh Vegetation

It was found, in total, 78 plant species (including 2 algae and 11 mosses), 14 syntaxa, and 3 habitat types within the 90 vegetation relevés along the 14 transects.

Specifically, this study found many plots of the *Salicornietum brachystachyae* plant community (*i.e.* 27 of the 90 plots). These plots, dominated by *Salicornia europaea*, are located on the relatively low-lying zone in the lee of the dam and along the gully in the centre of the restored salt marsh (parallel to the dam). Besides *S. europaea*, some *Spartina anglica* swards were present in this pioneer zone. In the zone just behind the dam, the short plant *Suaeda maritima* was abundant, whereas in the low-lying marsh along the gully, no *S. maritima* was present. In the zone landward of the central gully, most plots were dominated by *Puccinellia maritima*, characteristic for the low and middle salt-marsh zone. In this zone also typical salt-marsh species as *A. portulacoides*, *Plantago maritima*, and *Limonium vulgaris* were present. On the more elevated areas toward the former cliff, also species like *Juncus gerardii*, *Agrostis stolonifera*, and *F. rubra* were found. The upper salt-marsh zone behind the former cliff (which is the old salt marsh that was eroding before the stone dam was build) is dominated by *E. atherica*.

The stem density per square meter, weighted stem diameter, weighted height of the plants (June 2013), and the elevation of the relevés in the observed salt-marsh zones are presented in Figure 6 (see Methods section for a description of salt-marsh zones i–viii). The encountered mean vegetation characteristics were applied in the 12 foreland scenarios (Table 5).

Stem density is highest in the low and middle marsh zone (*ca.* 70,000 stems/m^2), which is dominated by short and thin grasses like *Puccinellia maritima*. However, the variability of stem density within this zone is considerable (zone v in Figure 6 top left). These typical salt-marsh species were also found in the zone around the flood mark, and here also a relative high stem density was observed. Stem density in the other zones was in the same order of magnitude (*ca.* 8000–9000 stems/m^2), including the upper salt-marsh zone if dead stems were included here.

Mean stem diameter in the salt-marsh pioneer zone is higher than in the low and middle salt-marsh zone. Especially *Spartina anglica* has relatively thick stems (3.5 mm in June 2013).

Table 2. *Different hydraulic conditions.*

Water Level (m +NAP)	Water Depth at Seaward Edge of Marsh (m +NAP)	Wave Height (m) at Seaward Edge of Marsh	Wave Height (m) at 3000 m from Dike	Peak Wave Period[a] (s)	Angle between Wave Propagation and Sea Dike (°)	Background and Source	Foreland Scenarios (see Table 1)	Drag Coefficient
4.2	3.3	~0.95	2	3.5	135	Design water level and wave height for the dike along Terschelling (*i.e.* for an extreme event with a return period of 2000 y) (Ministry of Transport, Public Works and Water Management, National Institute for Coastal and Marine Management, and Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling, 2007)	12	0.50 1.00
3.24	2.34	~0.6	1	3.5	135	Observed at Wadden Sea side of Terschelling during storm surge in January 1976 (Rijkswaterstaat n.d.)	12	0.50 1.00
1.95	1.05	~0.45		3.5	135	Water level during storm surges that occur with a frequency of about five times/y	12	0.50 1.00
1.95	1.05	~0.15		3.5	135	Water level during storm surges occurring with a frequency of about five times/y	12	0.50 1.00

[a] Assumed to be constant as there are no data available to differentiate different scenarios. 3.5 s is chosen as a representative value.

Stem density in the small area dominated by the tall (mean height 0.9 m) and thick (mean stem diameter 4.5 mm) *B. maritimus* was 890 stems/m^2. However, the vegetation of *B. maritimus* is atypical for the Wadden Sea coast because *B. maritimus* is not a typical halophytic species.

The tallest vegetation was found in the upper salt-marsh zone (mean height 0.27 m). However, the dominant species in this upper salt-marsh zone, the tall and thin *E. atherica*, easily bends when exposed to wind and waves, and then forms a layer of flattened vegetation. When the mean height of the broken dead stems is omitted, then the mean height of the *E. atherica* stems is ~0.4 m.

Wave Damping by Salt-Marsh Vegetation

Figure 7 presents for the 12 different foreland scenarios (Table 5) the modelled wave propagation along ~120 m of the most seaward zone of transect 1. Figure 7 (top) presents wave damping under storm conditions that appear some 5–10 times per year (*i.e.* water level 1.95 m +NAP with wave height ~0.45 m at the seaward edge of the marsh) and drag coefficient 1. Figure 7 (bottom) presents wave damping under design conditions (*i.e.* water level 4.2 m +NAP with wave height ~0.95 m at the seaward edge of the marsh, which may appear once per 2000 y) and drag coefficient 1. In Supplementary Appendix 1 graphs of the modelled wave propagation for the other conditions, transect 2 and drag coefficient 0.5, are presented.

Although wave height near the dike toe is important for wave overtopping estimation, this study did not present the modelled wave damping near the dike toe ($x = 0$–20 m) because the exact location of the dike toe was blurred by the applied relatively large grid size (20 m × 20 m). Furthermore, the sharp bathymetry changes at the dike toe often lead to complicated wave patterns, which may distract the reader from the main purpose of this paper, *i.e.* vegetation characteristics and salt-marsh zonation affect wave damping.

As seen in Figure 7, vegetation considerably contributes to wave damping, even under extreme conditions. Under storm conditions that appear some 5–10 times per year, when water depth at the toe of the dike is ~0.45 m (see Figure 5), waves are almost damped by vegetated foreland before they reach the toe of the dike. Under extreme conditions, when the water depth at the toe of the dike is ~2.7 m (see Figure 5), a salt-marsh area of 90 m covered with vegetation of the low and middle salt-marsh zone dampens the waves 50%. Although wave decay is nonlinear, a linear approximation for our modelling results seems reasonable for the most seaward part of the salt marsh (see Figure 7). Figure 8 presents the modelled wave damping (cm/m) and relative wave damping (1/m) over 40 m of salt marsh (at the seaward side of the salt marsh) for all different scenarios and two drag coefficients (0.5 and 1.0). Figure 8 indicates that in the modelled results the effect of the bulk drag coefficient is less than the combined effect of stem density and diameter and plant height. The modelled results also indicate that wave damping by vegetated forelands at the study site is most effective under "normal" storm conditions (storm conditions that appear 5–10 times per year).

Table 3. *Most frequent plant species (phanerogams; algae* marked with asterisk) found at Grië in 14 transects with 90 vegetation relevés. All these species are halophytes. The nomenclature follows Stace (2010).*

Scientific Name	Vernacular Name	No. of Relevés (n = 90)
Salicornia europaea	Common Glasswort	66
Puccinellia maritima	Common Saltmarsh-grass	61
Spartina anglica	Common Cordgrass	53
Suaeda maritima	Annual Sea-blite	52
Vaucheria species*	-	49
Aster tripolium	Sea Aster	42
Atriplex portulacoides	Sea-purslane	36
Spergularia media	Greater Sea-spurrey	29
Festuca rubra	Red Fescue	26
Plantago maritima	Sea Plantain	24
Limonium vulgare	Common Sea-lavender	23
Cochlearia anglica	English Scurvygrass	21
Elytrigia atherica	Sea Couch	21
*Ulva lactuca**	Sea Lettuce	19
Glaux maritima	Sea-milkwort	18
Agrostis stolonifera	Creeping Bent	15
Triglochin maritima	Sea Arrowgrass	14

DISCUSSION

There is a considerable spatial heterogeneity of vegetation properties as well as surface topography in salt marshes under natural conditions (Balke *et al*., 2012; van de Koppel *et al*., 2005). With a survey of vegetation along transects in an existing restored salt marsh and the detailed analysis of the plant characteristics in the investigated relevés, this study was able to attribute mean vegetation characteristics to the different encountered salt-marsh zones. In this way, a realistic spatial distribution of vegetation characteristics was found for the restored salt marsh at Terschelling. An important limitation to the study was that the vegetation characteristics were only analyzed at one moment, *i.e*. June 2013. In addition to spatial variability, there is also a temporal variability in salt-marsh vegetation characteristics due to seasonal vegetation growth and decay (*e.g*., Möller, Spencer, and Rawson, 2002). In temperate climates, which is where this study is situated, the height of the salt-marsh vegetation as well as the diameter of the stems will increase during the growing season. This may result in a tapering of the stems (see Feagin *et al*., 2011). These regular growth cycles can show considerable interyear variability. In June 2013 (which was the start of a new growing season after a relatively cold winter and spring) the height of *Salicornia europaea* varied between 0.025 and 0.04 m, whereas a maximum height for *S. europaea* of 0.30 m is reported (van der Meijden, 2005). Also, the mean heights of the other encountered species in June 2013 were considerably smaller than reported in literature (Feagin *et al*., 2011; van der Meijden, 2005). Furthermore, species like *S. europaea* will develop branches during the growing season. There may be a difference in characteristics between the stem and the canopy of branches and leaves. It is also very likely that stem density will change during the growing season because of competition or because of grazing. In winter annual salt-marsh species will

Table 4. *Plant communities (syntaxa) and habitats recorded at Grië in 14 transects with 90 vegetation relevés. Syntaxa and syntaxa codes follow Schaminée, Weeda, and Westhoff (1998). Habitat codes follow Janssen and Schaminée (2003).*

Syntaxon	Syntaxon Code	Habitat Code	No. of Relevés (n = 90)
Pioneer salt-marsh zone			
Salicornietum dolichostachyae	25AA01	1310	5
Salicornietum brachystachyae	25AA02	1310	27
Spartinetum townsendii	24AA02	1320	9
Suaedetum maritimae	25AA03	1310	2
Low and middle salt-marsh zone			
Puccinellietum maritimae	26AA01	1330	13
Plantagini–Limonietum	26AA02	1330	4
Halimionetum portulacoidis	26AA03	1330	8
Juncetum gerardi	26AC01	1330	2
RG[a] *Scirpus maritimus (Asteretea tripolii)*	26RG01	1330	1
Zone in front of former cliff edge			
Armerio-Festucetum litoralis	26AC02	1330	6
Upper salt-marsh zone			
Atriplici-Elytrigietum pungentis	26AC06	1330	9
Sagino maritimae-Cochlearietum danicae	27AA01	1310	1
Centaurio-Saginetum	27AA02	1310	1
Trifolio fragiferi-Agrostietum stoloniferae	12BA03		2

[a] RG = Rompgemeenschap (community of impoverished vegetation).

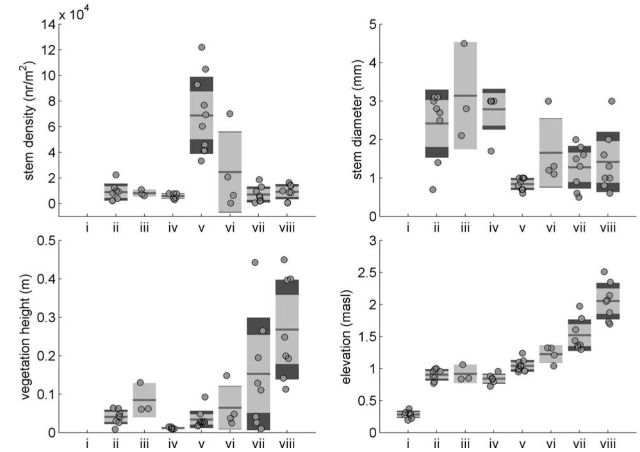

Figure 6. Stem density per square meter (top left), stem diameter (top right), height of the plants (bottom left), and the elevation in meters above sea level (bottom right) of the samples (June 2013) in the observed salt-marsh zones at Grië (Terschelling): (i) unvegetated mudflats in front of the dam, (ii) densely vegetated pioneer zone behind the dam, (iii) *Spartina* swards, (iv) sparsely vegetated pioneer zone along gully in the marsh, (v) low and middle salt-marsh zones dominated by *Puccinellia maritima*, (vi) zone around the flood mark, (vii) upper marsh zone in front of the former cliff, and (viii) upper marsh zone behind the former cliff with a thick layer of several centimeters of dead stems of the former year and dominated by *Elytrigia atherica*. The central line represents the mean value; the light-grey inner area the 95% confidence interval around the mean, and the dark-grey outer area the standard deviation of the data (added to or subtracted from the mean).

Table 5. *Different scenarios with observed salt-marsh plant characteristics at Terschelling (June 2013). For all vegetation types a bulk drag coefficient of 0.5 and 1.0 was applied.*

	Scenarios	Salt Marsh	Plant Height (m)	Plant Density (Stems/m^2)	Stem Diameter (m)
i.	No salt marsh (no silted-up area in front of dike)	No	*	*	*
	Dam/groyne (0.9 m in height) in front of dike (120 m) on mudflats	No	*	*	*
	Unvegetated salt marsh (silted-up area in front of dike)	Restored	*	*	*
ii.	Densely vegetated pioneer salt marsh (as found behind dam)	Restored	0.0407	8799	0.0024
iii.	Salt-marsh zone with *Spartina anglica*	Restored	0.0845	8120	0.0031
iv.	Sparsely vegetated pioneer zone (as found along the gully)	Restored	0.012	5767	0.0028
v.	Low/middle salt-marsh zone	Restored	0.0339	68742	0.0009
vi.	Salt-marsh zone around flood mark	Restored	0.064	24407	0.0017
vii.	Upper salt-marsh zone in front of former cliff	Restored	0.1524	7052	0.0013
viii.	Upper salt-marsh zone (including layer of dead vegetation)	Restored	0.2677	9122	0.0014
	Upper salt-marsh zone with only *Elytrigia atherica*	Restored	0.3857	4644	0.0023
	Zonation of pioneer, low/middle, and upper salt-marsh vegetation	Restored	ii–v–vii	ii–v–vii	ii–v–vii

* Salt-marsh vegetation absent.

mostly disappear and the aboveground vegetative parts of some perennial species like *E. atherica* will wither.

By translating the observed spatial distribution of the different vegetation types typically found on natural salt marshes into relevant parameters and boundary conditions for the SWAN-VEG model, this study was able to explore the potential effect of vegetation heterogeneity and salt-marsh zonation on wave height. Such information about wave-height reduction for realistic scenarios is important in the search for alternative flood defence options (as is explored in the Dutch Wadden Region Delta Programme). However, to obtain results that can be generalized and treated as evidence, these scenarios (as well as other relevant scenarios) would need to be replicated at different locations, with different models and preferably also verified with experimental work. In addition, it would be desirable to conduct an independent validation of the vegetation effects in the SWAN-VEG model to ensure that the model used in this study is indeed adequate for these purposes.

The explorative modelling work found here confirms the effects of vegetation on wave damping that have been described in various studies that were based on experiments in flumes (*e.g.*, Anderson and Smith, 2014; Augustin, Irish, and Lynett, 2009; Bouma *et al.*, 2005; Koftis, Prinos, and Stratigaki, 2013; Möller *et al.*, 2014), model work (*e.g.*, Maza, Lara, and Losada,

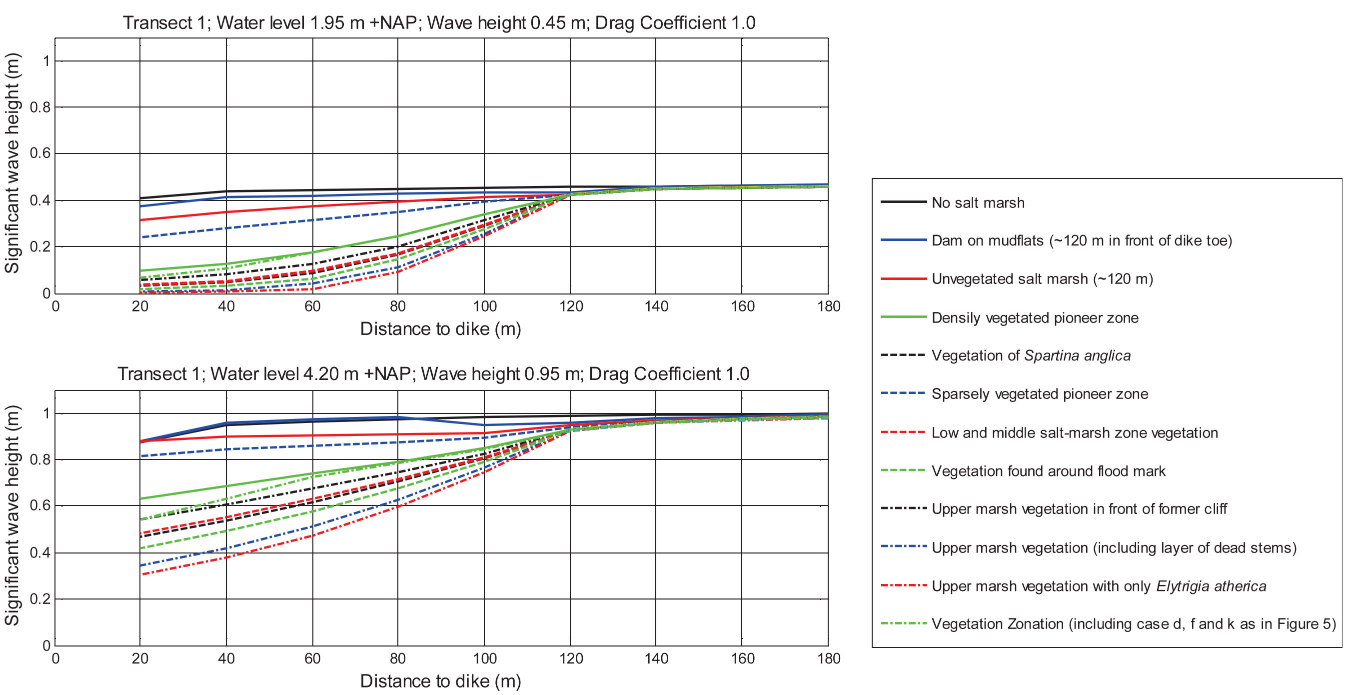

Figure 7. Modelled significant wave height along transect1 perpendicular to the coast of Wadden barrier island Terschelling for 12 different fictional foreland scenarios (see Table 5) for water level 1.95 m +NAP and wave height of ~0.45 m (top) and water level 4.2 m +NAP and wave height of ~0.95 m (bottom) and bulk drag coefficient 1.0. In Supplementary Appendix 1 graphs of the modelled wave propagation for the other conditions as well as for transect 2 and drag coefficient 0.5 are presented.

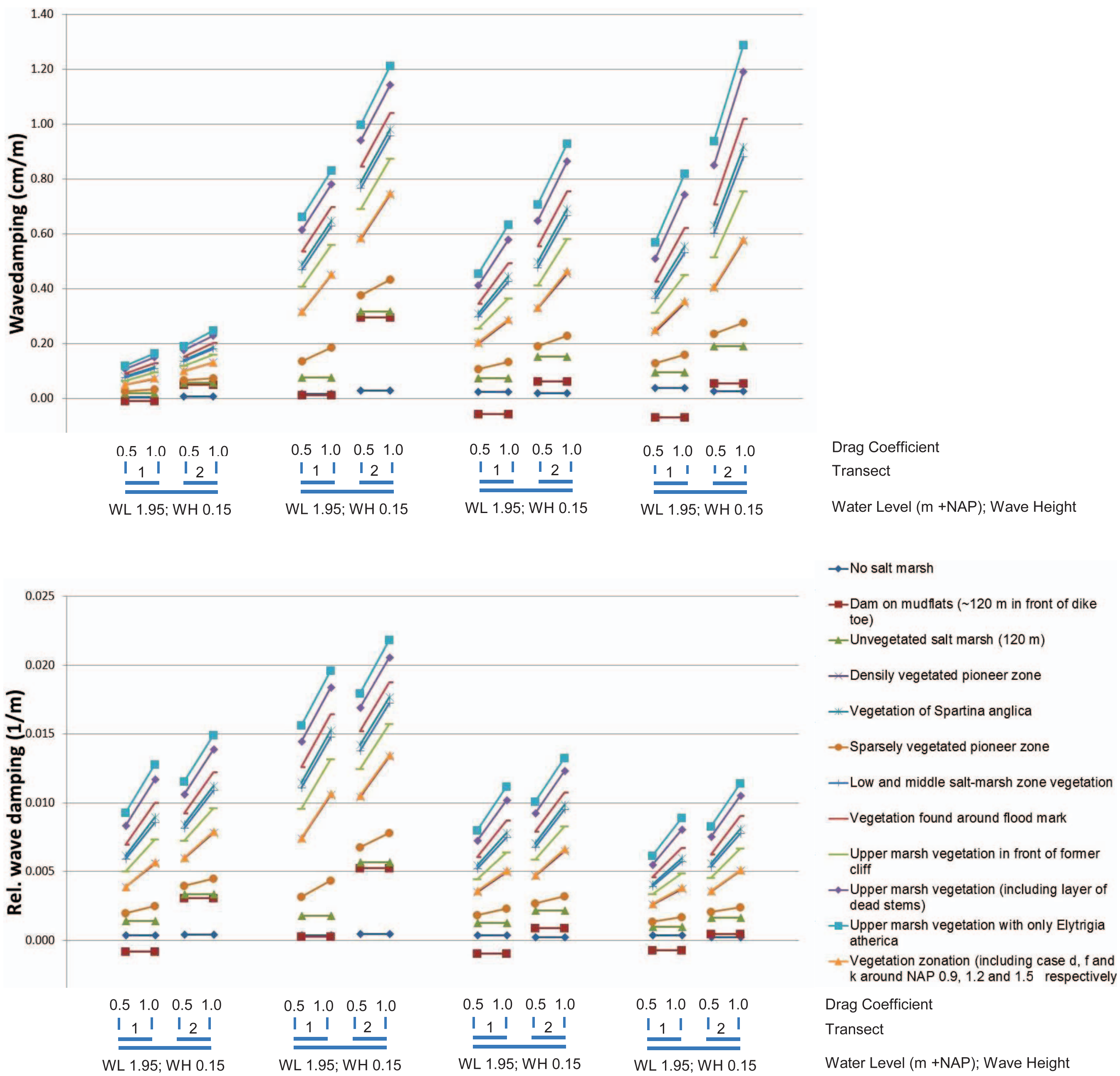

Figure 8. Modelled wave damping (cm/m) and relative wave damping (1/m) over 40-m salt marsh (at the seaward side of the salt marsh) for the different conditions (see Table 2), 12 scenarios (see Table 5), two transects, and two drag coefficients (0.5 and 1.0).

2013; Mendez and Losada, 2004; Suzuki *et al*., 2012), or field observations (*e.g*., Möller, 2006; Möller *et al*., 2001; Möller, Spencer, and Rawson, 2002; Yang *et al*., 2012; Ysebaert *et al*., 2011). Although wave-height dissipation in SWAN-VEG is defined in such a way that an increase in stem diameter, stem density, and vegetation height will result in increased wave damping (Suzuki *et al*., 2012), the modelled results are comparable with field measurements at vegetated coastal wetlands of comparable width and with comparable plant species in NW-Europe (see *e.g.,* Cooper, 2005; Möller *et al*., 1999; Möller, Spencer, and Rawson, 2002).

It is noted that bottom friction and vegetation-induced wave dissipation are both switched on in the SWAN-VEG modelling. Dissipation by bottom friction is simply calculated on the basis of wave height, and does not take into account the velocity reduction in the vegetation area. Therefore, wave damping by bottom friction may be overestimated. However, in the vegetation field dissipation is often dominated by vegetation-related damping. Möller *et al.* (2014) and Yang *et al.* (2012) attributed 60–80% of the overall wave damping to the presence of vegetation. In this study, 62–75% of wave damping can be attributed to vegetation on the basis of the differences in wave damping between the unvegetated marsh scenario and the vegetated marsh scenarios. Thus, the overestimation of bottom friction may not induce large errors in the overall model prediction.

Although the observed vegetation characteristics were applied, there are still several simplifications that may lead to biased results and need to be considered in future work.

First of all, this study applied the encountered vegetation characteristics, except for the last scenario, for the entire transect. The results prove the effect of the different vegetation characteristics in the typical salt-marsh zones, and therefore it is advisable to account for salt-marsh zonation in modelling work.

As already mentioned, this study's observations did not account for temporal variability in salt-marsh vegetation characteristics. The seasonal change in height, stem diameter and density, and in the shape of the plants (*i.e.* development of branches) will affect the wave-damping capacity. Therefore, during winter and early spring, the wave-damping capacity of the restored salt marsh may differ considerably from the wave-damping capacity during summer and autumn. The modelling results indicate that in late summer, when vegetation is at its most vigorous, wave damping may be three to seven times higher than when no vegetation is present (which may form a proxy for winter, when vegetation has withered).

The parameterisation of plant characteristics into the model may need further attention. Whereas including the vertical characteristics of the vegetation layer is possible in SWAN-VEG (Suzuki *et al.*, 2012), it is still difficult to take the detailed morphology for the plants into account. Bending of plants may lead to a much lower effective height of the vegetation during flooding and subsequently to a reduced wave-damping capacity of the vegetation. To explore the effect of flexibility and the configuration of the leaves and branches (together with the effects of different hydrodynamic conditions), this study applied drag coefficients of 0.5 and 1.0. Interesting in this regard is that Bouma, De Vries, and Herman (2010) found that, on a biomass basis, dissipation of hydrodynamic energy from waves is very similar between the stiff grass *Spartina anglica* and the flexible grass *Puccinellia maritima*. The combined effect of flexibility and plant configuration (*i.e.* the bulk drag coefficient) is in the model results less than the combined effect of stem density and diameter and plant height (see Figure 8).

Finally, the degree of wave damping may be influenced by magnitude and direction of local currents (Hu *et al.*, 2014).

Nevertheless, it might be worthwhile to investigate both morphology and flexibility of natural salt-marsh vegetation (including the possible seasonal variability) and to incorporate these properties in the calculation of the drag coefficient, if possible taking variable local currents into account.

To incorporate natural vegetated forelands in a flood-protection strategy, they must be integrated in design and assessment criteria for flood defences and in management schemes. This requires profound insight in their wave attenuation performance during extreme storm events. There is still little real data about their effects during extreme conditions. It is important to keep in mind that models like SWAN-VEG are developed and evaluated on the basis of either scaled-down lab tests or field measurements under less-than-extreme conditions. Hence, applying these models to predict effects under extreme conditions relies on extrapolation. Therefore, monitoring of wave height during storm conditions is required to further calibrate and validate the model. Noteworthy in this context are the recent flume experiment of Möller *et al.* (2014) to assess wave dissipation over a transplanted section of natural salt marsh under simulated storm surge conditions (water level of 2 m, waves of 1 m), and a recently launched Dutch research programme to conduct field observations during storm events and use these to calibrate and refine existing models (Vuik *et al.*, unpublished data).

Furthermore, the spatial and seasonal variability of vegetation characteristics makes it difficult to model the wave attenuation process by vegetation (van der Meer, 2002) and to incorporate salt-marsh vegetation in a flood-protection strategy. On the other hand, salt-marsh vegetation succession, species compositions, and effects on these by management and restoration measures have been well studied and monitored (*e.g.*, Adam, 1990; Bakker, 1989; Dijkema *et al.*, 2007; Olff *et al.*, 1997; Wolters, 2006). Therefore, it might be feasible to model the seasonal variability of the vegetation characteristics and incorporate this in SWAN-VEG (or other models). This can, *e.g.*, be achieved by a piece-wise linear relation, similar to the way in which crop factors are specified to estimate potential evapotranspiration of agricultural crops over a growing season. In view of this, we recommend looking at the importance of variation in time (or time and space together) both according to the annual vegetation cycle and to succession of salt-marsh vegetation on the wave-damping capacity of the salt marsh. Monitoring the seasonal variability of vegetation characteristics together with measuring *in situ* wave damping will contribute to knowledge development on this topic.

A next step would be the coupling of the seasonal variability in vegetation characteristics with the seasonal variability in storm characteristics. This would provide information about the reliability of the contribution of a vegetated salt marsh to flood protection.

CONCLUSIONS

By investigating the characteristics of salt-marsh vegetation in an existing restored salt marsh this study was able to identify realistic input parameters for SWAN-VEG and to explore the potential effect of vegetation heterogeneity and zonation on wave damping.

The modelling work here indicates that the spatial distribution of the different vegetation types typically found on natural salt marshes can have a considerable impact on wave damping. Therefore, it is recommended that further investigation occurs of the potential effect of different management strategies on relevant vegetation characteristics in view of flood protection.

The current modelling works suggest that, for this study site under storm conditions that appear about 5–10 times/y, waves are almost damped by vegetated foreland before they reach the toe of the dike, although under extreme conditions (1/2000 y) a salt-marsh area of 90 m covered with dense vegetation dampens the waves 50%. These results imply that at this study site a vegetated foreland in front of the dike leads to reduced wave attack on the dike, which might result in changed requirements for both height and revetment of the dike while maintaining the required safety level. Therefore, restoring a salt-marsh area in front of the existing dike might form an interesting strategy to adapt the existing flood-protection works to the predicted effects of climate change, something worthwhile to further investigate.

However, to incorporate natural vegetated forelands in an adaptation strategy, they must be integrated in design and assessment criteria for flood defences and in management schemes. This requires a profound insight in their wave-attenuation performance during extreme storm events as well as in the performance of models like SWAN-VEG. To verify whether SWAN-VEG is able to quantify wave attenuation by vegetation under extreme situations, monitoring of wave height during storm conditions is required to further calibrate and validate the model.

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