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The Impact of Erosion Protection by Stone Dams on Salt-Marsh Vegetation on Two Wadden Sea Barrier Islands

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ABSTRACT

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This paper describes and quantifies the effect of low stone dams on the extent and composition of salt-marsh habitats on two Dutch Wadden islands: Terschelling and Ameland. The stone dams were built to prevent erosion of the salt-marsh edge. Analyses of a series of aerial photographs taken between 1949 and 2010 show a strong reduction in retreat of the marsh edge on the island of Terschelling, from an average rate of 1.3 m per year before construction of the dam to 0.2 m per year after dam construction. Within 20 years of construction of the dam, sedimentation raised the mudflats between the dam and the former cliff, creating a broader foreshore and new marsh area with typical salt-marsh vegetation cover. The dam on the island of Ameland was built on the remnants of a previous low coastal defense. This reinforcement stopped cliff retreat and led to restoration of the eroded salt-marsh strip. Vegetation surveys along transects perpendicular to the coastline revealed that at both sites, typical pioneer salt-marsh vegetation had developed in the raised area between the erosion protection works and the former marsh edge. These habitats were not found in the reference transects without erosion protection. Based on these findings, we conclude that under favorable conditions for sedimentation, erosion protection by low stone dams may bring about a strong reduction in retreat of the salt-marsh edge while helping to restore an ecological attractive foreshore zone.

ADDITIONAL INDEX WORDS: *Foreshore, pioneer zone, habitat restoration, biodiversity*.

INTRODUCTION

Salt marshes and their adjacent mudflats form an attractive transition zone between land and sea. Because they are subjected to regular flooding, they provide typical and valuable habitats. 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 seawater (Adam, 1990; Allen, 2000; Doing, 1995).

Salt-marsh zones and the associated marsh vegetation and fronting mudflats affect wave height and can dissipate wave energy. This wave attenuation capacity gives them a natural sea defense value (*e.g*. Brampton, 1992; Costanza *et al.,* 2008; King and Lester 1995; Möller *et al.,* 2001; Van Loon-Steensma *et al.,* 2012).

Like most coastal sedimentary systems, salt-marsh ecosystems are extremely sensitive to changing environmental conditions (Allen, 2000), including climate change. Elaborate studies have examined the effects of climate change on the intertidal ecosystem as a whole, on habitats and species in the intertidal zone, and on particular intertidal processes (*e.g*. Allen, 2000; Healy, Wang, and Healy, 2002; Schernewski, Hofstede, and Neumann, 2011). The implications for management have been studied as well (*e.g*. Vermaat *et al.,* 2005).

For the Wadden Sea in NW Europe, researchers have studied the effects of climate change at the level of the system in its entirety (*e.g*. Brinkman *et al.,* 2001; Van Goor *et al.,* 2003; Kabat *et al*., 2009), at the level of processes in salt marshes (*e.g*. Houwing *et al.,* 1995; Olff *et al.,* 1997; Janssen-Stelder, 2000), and in relation to species compositions (*e.g*. Van Dobben and Slim, 2011). With moderate rises in sea levels, salt marshes typically build upward (Allen, 2000). To keep pace with the sea level rise, however, a permanent import of sediment is required into the tidal system. If sediment import is insufficient, flats and marshes drown under the influence of the rising waters (Van Goor *et al.,* 2003).

In the Dutch Wadden Sea, some 9000 ha of salt-marsh area are present (Dijkema *et al.,* 2007). These marshes are situated along the shores of both the Netherlands' mainland and the Wadden Sea barrier islands. An explicit aim of Natura 2000, the centerpiece of the nature and biodiversity policy of the European Union (EU), is to conserve the areal extent of salt marshes in the Wadden Sea region, with all of their succession stages and saltwater–freshwater transitions. Other Natura 2000 ambi-

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tions are to increase the variability in geomorphological forms and substrates of salt marshes and to optimize management regimes (Ministry of Economic Affairs, Agriculture and Innovation, 2011). Beyond EU-level conservation efforts, there is a trilateral agreement among Denmark, Germany, and the Netherlands to increase the area of natural salt marshes, to enhance natural morphological and dynamic processes in the Wadden Sea region, to enrich the natural vegetation structure of artificial salt marshes, and to improve conditions for wading birds (Common Wadden Sea Secretariat, 1997).

The salt marshes along the mainland coast of the northernmost Dutch provinces of Groningen and Fryslân are the result of constructed accretion works. These works were originally designed for reclamation of agricultural land, but the goal progressively shifted toward nature conservation from the 1970s onward (De Jonge and De Jong, 2002; Dijkema *et al.,* 2001). Without these accretion works, the total area of the seminatural salt marshes along the embanked mainland coast would be much smaller than it is today. Salt marshes on the barrier islands developed from the deposition of silt on top of sandy layers on the lee side of sand dunes. The barrier islands and the extensive intertidal expanse beyond them were formed some 5000 to 6000 years ago (Oost, 1995). Until the Middle Ages, swamps and salt marshes connected these islands with the mainland. Measures were needed to safeguard agricultural use of the fertile marshlands. This led to the construction of embankments, resulting in island polders. Some parts of the salt marshes remained unprotected by dikes. In general, these were marsh areas seaward of dikes and salt marshes adjacent to dunes and sand flats on the east side of the islands. The construction of sand dikes in the 1880s to 1930s led to a substantial increase in the marsh areas on the easternmost ends of the islands. On the islands of Terschelling and Ameland, these human-induced salt-marsh areas are now formally designated as Natura 2000 conservation sites.

The current study focuses on two marsh areas: Grië on the Wadden island of Terschelling and Neerlands Reid on the Wadden island of Ameland (Figure 1). Both of our study sites are located on the east end of the islands, where no flood defense was constructed to protect the hinterland.

The salt marsh at Grië eroded steadily until a low stone dam was built on the sea side of the marsh cliff in 1991. This dam construction came on the heels of decades of pleas by the owners of lost and endangered land parcels. Between the former cliff edge and the low stone dam, a new salt marsh with gullies quickly developed, within 10 years of dam construction (De Boer, 2002). Grië is used for extensive grazing (of horses and cattle), for hay making, and as a theater location during an annual arts festival. The valuable nature, landscape, and cultural-heritage attributes of Grië have led both regional and local governments to develop management plans for the area.

The salt marsh at Neerlands Reid, like all salt marshes in the Wadden Sea, has been subjected to rising sea levels, but it is influenced by subsidence as well due to extraction of natural gas (Dijkema *et al.,* 2011). For more than half a century, the salt marsh eroded, forming a cliff edge. In 1998–99, a stone dam was constructed on the sea side of the cliff edge, after which new salt-marsh vegetation developed.

A number of factors coincided to prompt renewed exploration of options for salt-marsh protection and restoration: the newly formed salt-marsh area between the former cliff edge of Grië and the low dam, an increased interest in the effects of climate change on both flood protection and the valuable Wadden habitats, and a need for improved flood protection (Van Loon-Steensma, 2011). Plans for salt-marsh restoration attracted support from regional stimulation programs in the Netherlands (*e.g*. Stuurgroep naar een Rijke Waddenzee, 2010). Furthermore, the Delta Program initiated research on the role of salt marshes for flood protection in the Wadden area (Van Loon-Steensma *et al.,* 2012), and salt marshes were being studied from a broad ecosystem services perspective (*e.g*. Costanza *et al.,* 2008; De Groot, 2006; Luisetti *et al.,* 2011). Nonetheless, many questions remained and views differed about the impacts and possible side effects of salt-marsh restoration measures on the natural Wadden Sea system.

This paper presents the results of a study to explore and quantify the effects of low stone dams on the extent and composition of salt-marsh habitat in the Grië and Neerlands Reid marsh areas. The dams were constructed to prevent erosion of the marsh edge. The research aims to contribute to knowledge about foreland restoration and development and habitat diversity.

METHODS

Study Sites

Figure 1 shows the study sites Grië and Neerlands Reid. Both are salt-marsh areas on the SE fringe of their respective barrier islands. On the east side of the islands, no dike has been constructed to protect the hinterland. Likewise, the salt marshes are not artificially bounded on the landward side. Rather, the landscape grades gradually into dunes. A distinct erosion cliff had developed along the salt-marsh front at both sites, and measures had been taken to prevent further erosion of the cliff. For an illustration of the current cliffs at Grië and Neerlands Reid, see Figure 2.

Both locations are protected under the European Habitats Directive as Waddenzee Natura 2000 sites, in particular for three habitat types: (1) halophyte pioneer vegetation (H1310), (2) *Spartina* swards (H1320), and (3) salt marshes, including a diversity of typical vegetation (H1330). The adjacent habitat is designated as mudflats and sand flats not covered by seawater at low tide (H1140). (For further information on the Natura 2000 habitats classification, see European Commission, 2007.)

The dam at Grië is some 60 m seaward of the marsh cliff. It was built in 1991 of loosely stacked boulders approximately 0.3 m in diameter. The dam is some 1.3 m in height, 2 m in width, and some 2500 m in length (Figure 2). It has five openings and the east side is not connected with the coast, allowing seawater to enter and exit during high and low tide. In the sheltered area behind the dam, sedimentation has raised the elevation of the former mudflats, which have become overgrown with typical salt-marsh vegetation. The new salt-marsh zone lies lower than the original salt marsh, and the area is subjected to daily tidal flooding. The openings in the dam have resulted in gully and creek formation between the dam and the former cliff edge.

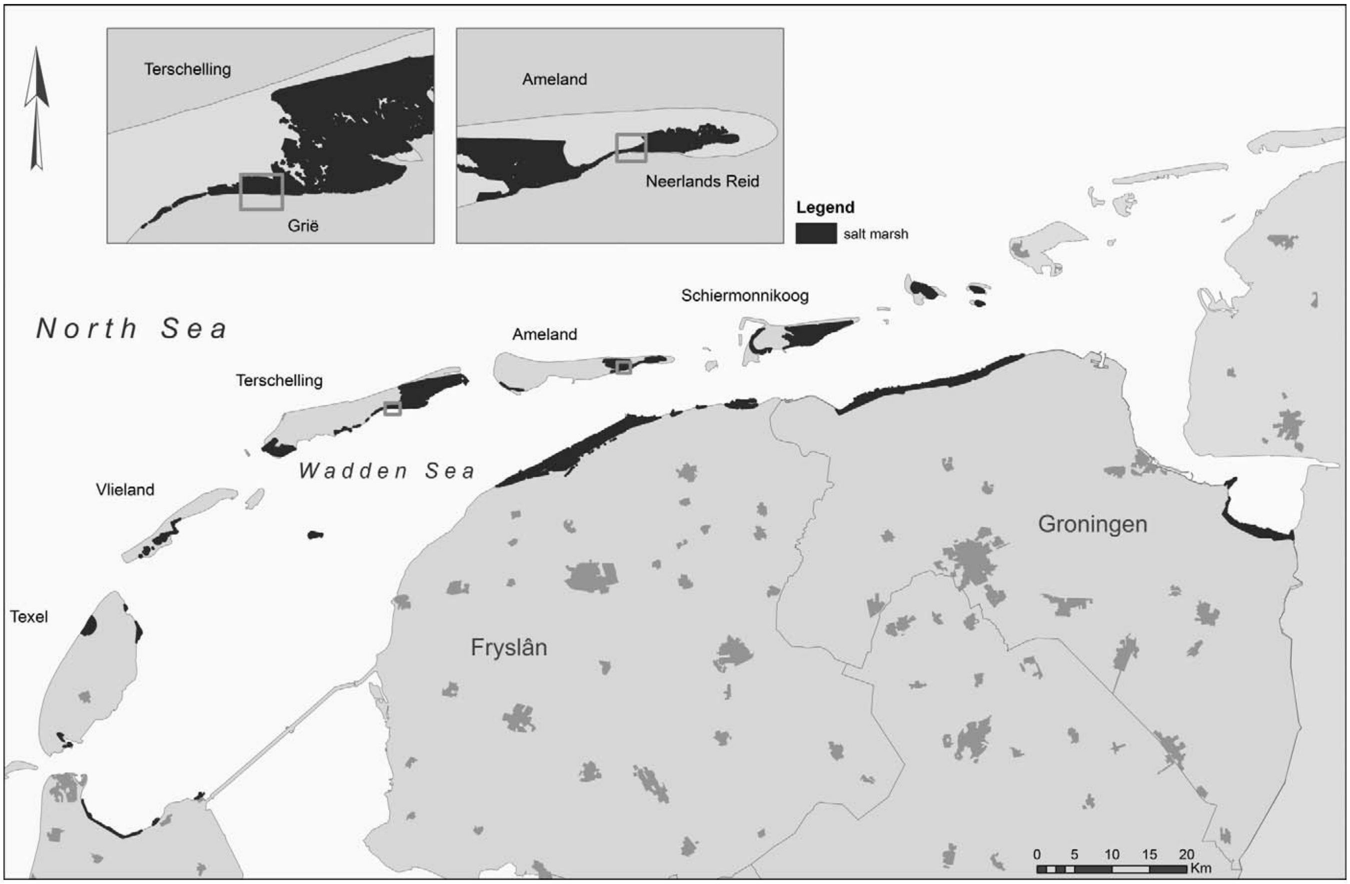

Figure 1. Current extent of salt marsh in the Dutch part of the Wadden Sea and barrier islands of Terschelling and Ameland. The study sites Griё (Terschelling) and Neerlands Reid (Ameland) are highlighted.

The dam at Neerlands Reid (Figure 2) was built in 1998–99 some 5 to 15 m from the marsh cliff on the remains of a low coastal defense made out of asphalt and bricks (this older construction stems from 1962). In 1998–99, the dam was covered by geotextile and subsequently reinforced and elevated using loosely stacked boulders. The fortified structure is some 0.8 m in height, 8 m in width, and 1800 m in length.

Analysis of Salt-Marsh Edge Retreat

Based on aerial photographs, we analyzed the effect of the dams on the marsh areas at Griё and Neerlands Reid. For both sites, we identified the location of the cliff on a time series of aerial photographs taken between 1949 and 2010 at intervals of some 10 years. We divided the coast into a section without a dam (A) and a section with a dam (B). Comparing the digital georeferenced photographs, we then quantified the rates of marsh retreat and extension before and after construction of the dam for the different sections.

At Griё, the studied section without a dam was 250 m long (A, with bounding box: 53°24′12″ N, 5°26′10″ E and 53°24′16″ N, 5°26′23″ E) and the section with a dam was 950 m (B, with bounding box: 53°24′13″ N, 5°25′20″ E and 53°24′16″ N, 5°26′10″ E). At Neerlands Reid, the studied section without a dam was 168 m (A, with bounding box: 53°27′5″ N, 5°53′33″ E and 53°27′13″ N, 5°53′40″ E), and the section with a dam was 150 m (B, with bounding box: 53°27′3″ N, 5°53′25″ E and 53°27′7″ N, 5°53′33″ E). At both sites, section A was east of section B.

The use of chronological sequences of aerial photographs to map and quantify changes in intertidal area and vegetation is well documented (*e.g*. Cox, Wadsworth, and Thomson, 2003; Sanders, Slim, and Wegman, 2005; Slim *et al.,* 2011). In our study, the sets of aerial photographs (scale 1:18,000, source Netherlands Land Registry Office) comprised black-and-white photographs taken between 1949 and 2000, a true color photograph taken for Griё in 2010, and another taken for Neerlands Reid in 2009.

On the photographs, the seaward salt marsh edge is clearly evident as the boundary of continuously vegetated area, ignoring slump blocks left by erosion. Before construction of the dams, and in the areas without a dam, the cliff forms the seaward marsh edge. After construction of the dam, the former cliff forms a seaward edge only at high water and remains visible in the landscape and on the aerial photographs due to

Figure 2. Illustrations of marsh cliff edges and vegetation. Unprotected cliffs at (A) Griё during low tide (15 August 2011); (B) Neerlands Reid during a relatively low high tide (1 September 2011); (C) the area behind the dam at Griё, H1310 (16 August 2011); and (D) the area behind the dam at Neerlands Reid, H1310 and H1330 (1 September 2011).

relief, as well as differences in vegetation. The current study quantified changes in the position of the cliff.

The cliff location at each site was digitalized on-screen from orthorectified images for each available year after the photographs had been scanned and georeferenced to the Dutch National Grid. The marsh edge was identified with different degrees of confidence, due to variation in the quality of the photographs and different levels of contrast between the vegetation and the bare sediment. The edge was distinct where cliff erosion had occurred. Elsewhere, the position of the marsh edge was less clear, and a band was used to indicate the area in which the edge was located. According to Sanders, Slim, and Wegman (2005), the position of salt-marsh edges must be identified within at least 4 m to be significant because of inaccuracies in geometrical corrections of the aerial photographs.

We compared our findings for Griё with measurements conducted by the Dutch Directorate General for Public Works and Water Management (Public Works) (as cited by De Boer, 2002). This government agency monitored the position of the salt-marsh edge from 1941 to 2000 along 12 transects perpendicular to the coast of Griё. Public Works also estimated sedimentation at Griё by comparing elevations in 1992 and 2000 at regular 15-m intervals parallel to the dam.

Vegetation Surveys

To explore the effects of the erosion protection measures on species composition and habitats, we surveyed the vegetation at both study sites. Plots measuring 4 m^2 were chosen inland of the dam and at nearby locations without a dam. In total, 56 plots were chosen along 10 transects perpendicular to the coastline. At Griё, we chose 6 plots in section A and 23 plots in section B. At Neerlands Reid, we selected 16 plots in section A

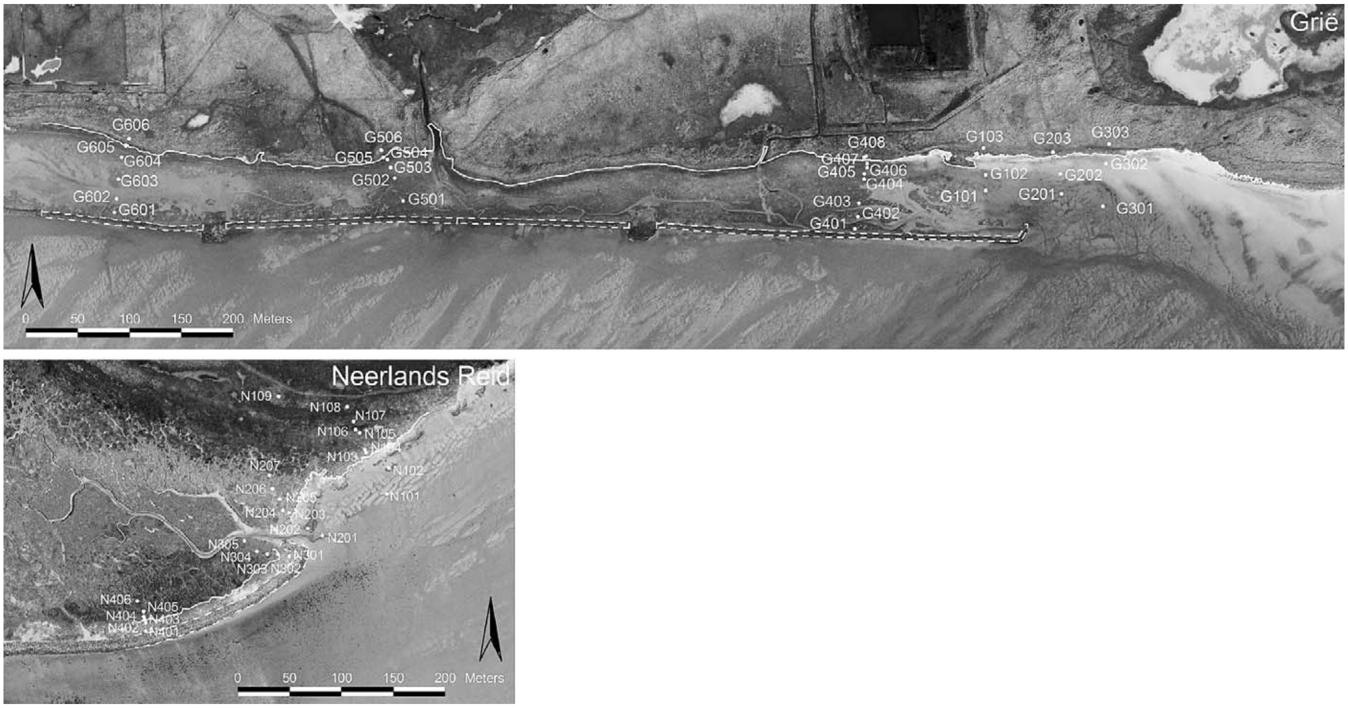

Figure 3. The plots with their numbers along transects perpendicular on the coastline at Grië (2010, top) and Neerlands Reid (2009, bottom). Contours of the erosion protection works are indicated by dashed white lines. The solid white line indicates the salt-marsh edge (Grië, 2010, and Neerlands Reid, 2009).

and 11 plots in section B. Plot spacing was such that key transitions between vegetation zones in the salt marsh were included; the zone inland of the former marsh cliff edge was also sampled (Figure 3). Selecting transects close to one another minimized differences in exposure to tides, wind, and waves and in suspended sediment concentration. We considered transects without a dam to be the reference situation. Here, mudflats were situated directly against the cliff edge of the eroding upper marsh zone. This sampling design is known as an impact-reference sampling design (Morrison *et al.,* 2008) and is applicable to situations in which the effect of an intervention is being evaluated and no reference observations are available prior to the intervention.

The fieldwork was carried out in August and September 2011. At this time of year, salt-marsh vegetation is at its most vigorous. We investigated the vegetation by making 4-m^2 relevés (r = 1.13 m) estimating the abundance of the plant species found (Braun-Blanquet, 1928). An ordinal scale with 10 classes was used for these estimates (Dirkse, 1998). Species were identified according to nomenclature following Van der Meijden (2005). Photographs were taken of each plot. Based on the species found, the plots were classified in plant communities as defined by Schaminée, Weeda, and Westhoff (1998), with ASSOCIA (Van Tongeren, Gremmen, and Hennekens, 2008) and in habitats (European Commission, 2007; Janssen and Schaminée, 2003).

RESULTS

Analysis of Salt-Marsh Edge Retreat

Analysis of the aerial photographs indicates considerable retreat of the salt-marsh cliff edge at Grië during 1949–2010 (Figure 4 and Table 1). Construction of the low stone dam considerably reduced this erosion. The rate of marsh edge retreat declined from 1.3 m per year on average during 1949–90 to just 0.2 m per year during 1990–2010 (section B). The unprotected marsh edge adjacent to the protected stretch continued to retreat, with an average rate of 1.6 m per year during 1949–90 increasing to 1.9 m per year during 1990–2010 (section A). In all situations, the rate of erosion varied from decade to decade. As shown in Figure 4, some spatial variation was also measured in rates of erosion, especially near creek outlets.

Monitoring data from Public Works for the 1941–2000 period from 12 transects perpendicular to the coast of Grië show average retreat over the length of the salt marsh of 1.04 m per year before the construction of the dam and 0.45 m per year during 1991–2000 after dam construction (De Boer, 2002; see also Figure 5). The regression results show edge retreat to be significantly higher before than after dam construction. Moreover, prior to dam construction, edge retreat appears to be significantly greater toward the east, while after dam construction edge retreat was constant along the length of the dam. As Figure 5 shows, retreat measured using the aerial

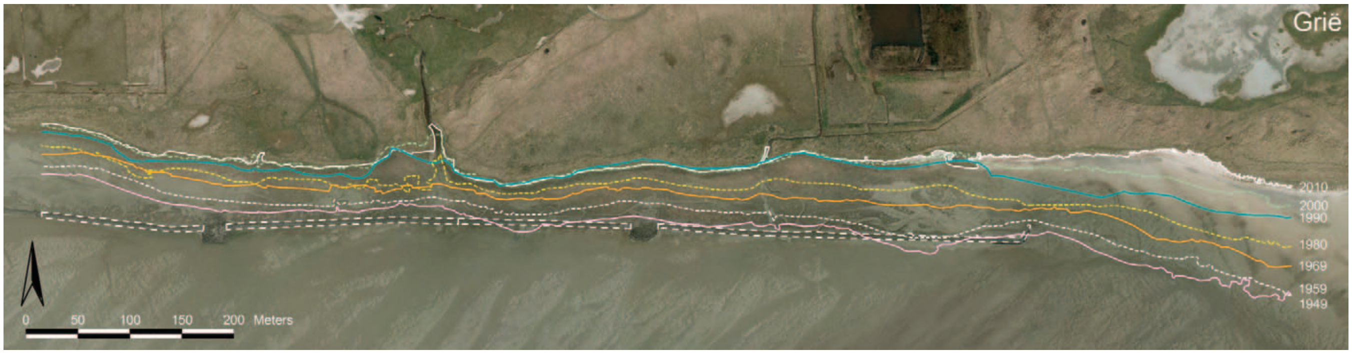

Figure 4. Aerial view of Grië, with the position of the marsh edge in 1949, 1959, 1969, 1980, 1990, 2000, and 2010 and the erosion protection works (dashed lines).

photographs during 1949–90 (section B divided into three subsections, matching the eastern 950 m of the section monitored by Public Works) corresponds with the spatial gradient found in the Public Works monitoring data. In the section without a dam, retreat after 1991 continued in line with this spatial gradient.

Figure 6 shows the changes in salt-marsh elevation at Grië for the 1990–2000 period in 15-m-wide zones parallel to the dam. Changes in elevation are strongly related to distance from the dam. Elevation increases are largest in the zone just landward of the dam, and are less pronounced at some distance of the dam. Both in the zone 60 to 75 m inland from the dam (the zone immediately beyond the former cliff) and in the seaward side directly in front of the dam, there are reductions in elevation.

Figure 7 shows retreat of the salt-marsh cliff edge at Neerlands Reid. Retreat of the marsh edge before construction of the original low brick dam in 1962 was 1.2 m per year (Table 1). The low brick dam functioned as a revetment against and along the top of the cliff edge (Figure 8). Reduced retreat of the salt marsh was observed during 1959–90. Ongoing erosion after 1990 led to increased retreat of the salt-marsh zone behind the low brick wall, which prompted reinforcement of the dam in 1998–99. The cliff behind the dam is difficult to distinguish on the aerial photograph of 2009, indicating that the zone behind the dam had become overgrown with vegetation in the intervening years. At the unprotected part of Neerlands Reid, however, the salt-marsh edge eroded further, though with fluctuations in retreat and expansion between 1949 and 2009 (Figure 7 and Table 1).

Figure 8 shows retreat of the salt marsh due to erosion before the protection works were constructed and development of the salt marsh after construction. At Grië, some 15 ha of salt marsh developed in 20 years' time between the marsh cliff and the

Table 1. *Average and standard deviation of cliff retreat and growth (a negative value indicates retreat) of the coastal zone at Grië (Terschelling) and Neerlands Reid (Ameland). A sections are without erosion protection (reference situation). B sections are with erosion protection. The dam at Grië dates from 1991. The coast protection structure at Neerlands Reid stems from 1962 and was fortified in 1998–99. Bold values represent the periods and areas affected by the erosion protection.*

Location	Period	Average Retreat and Growth (meters per year)		
		Section		Difference
		Section A (250 m)	Section B (950 m) with Erosion Protection after 1991	
Grië	1949–59	−1.2	−1.0	0.1
	1959–69	−2.0	−1.7	0.3
	1969–80	−1.3	−0.9	0.4
	1980–90	−1.9	−1.7	0.2
	Average (SD)	−1.6 (0.39)	−1.3 (0.38)	0.3 (0.10)
	1990–2000	−1.9	**−0.3**	**1.6**
	2000–10	−1.9	**−0.1**	**1.8**
	Average (SD)	−1.9 (0.02)	**−0.2 (0.12)**	**1.7 (0.14)**
		Section A (168 m)	Section B (150 m) with Erosion Protection after 1962 and 1998/1999	
Neerlands Reid	1949–59	−0.5	−1.2	−0.7
	1959–69	0.3	−0.6	−0.9
	1969–79	0.2	0.3	0.0
	1979–90	−0.7	−0.2	0.5
	1990–2000	−1.3	−2.4	−1.1
	Average (SD)	−0.3 (0.62)	−0.7 (1.15)	−0.4 (0.68)
	2000–09	−0.5	**0.7**	**1.2**

SD = standard deviation.

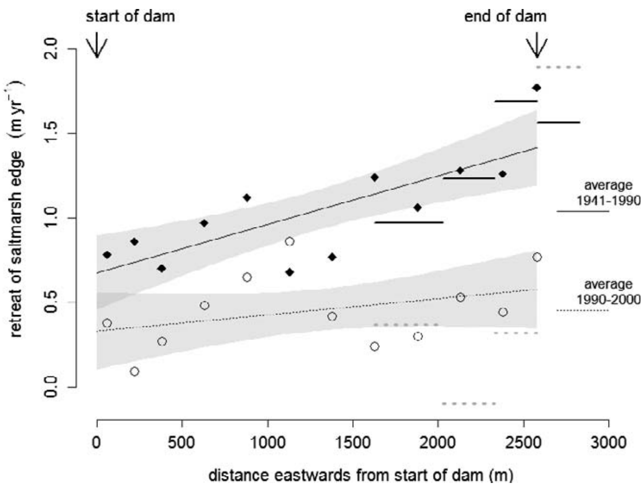

Figure 5. The average edge retreat over the distance from the westernmost part of the dam at Griё. The black diamonds and the solid regression line represent the period 1941–90 (retreat = 0.68 + 0.00029 × distance; R^2 adjusted = 0.56, $p = 0.003$), while the circles and the dashed line represent the period 1990–2000 (retreat = 0.33 + 0.000095 × distance; R^2 adjusted = 0.05, $p = 0.243$). The shaded areas represent 0.95 prediction intervals for the two models. At the right side of the graph, the average edge retreats for the distance range of 0 to 2580 m are shown. The line segments in the graph (from a distance of 1630–2830 m) show retreat measured on aerial photographs. Black solid line segments refer to the period of 1949–90, and gray dashed segments refer to the period 1990–2010. The rightmost dashed line shows that eastward of the dam, the edge retreat rate continues at its original rate, while behind the dam, it has been strongly reduced. (symbols: Public Works, cited in De Boer, 2002; line segments: analysis on aerial photographs).

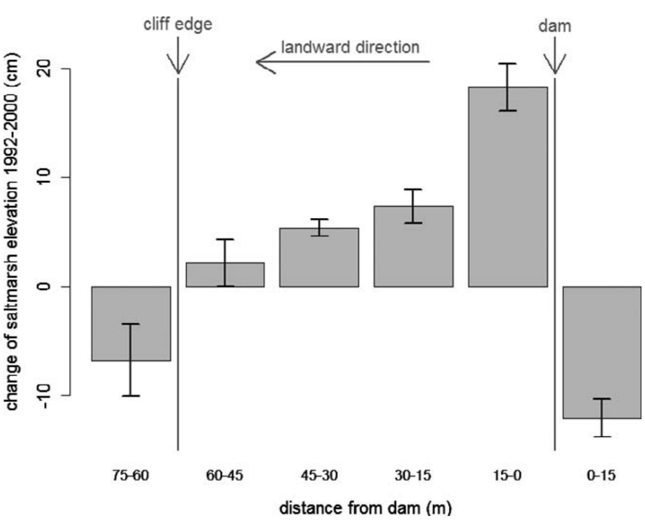

Figure 6. Elevation changes of the salt marsh for the 1992–2000 period for zones 15 m wide and parallel to the dam. The height of the bars represents the average elevation change for each 15-m strip along the length of the dam. The hinges give the standard error of the mean (Public Works, cited in De Boer, 2002).

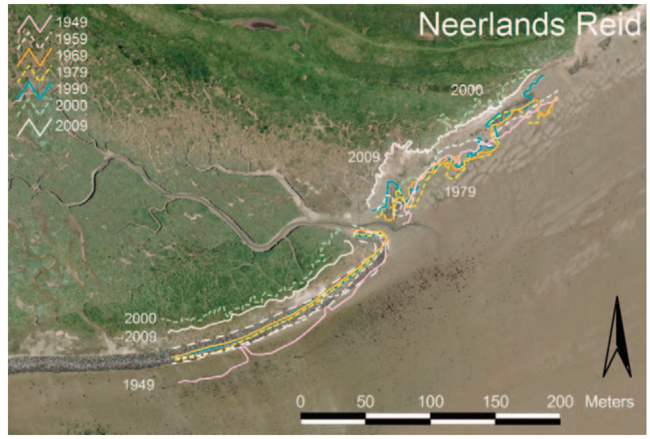

Figure 7. Aerial view of Neerlands Reid, with the position of the marsh edge in 1949, 1959, 1969, 1979, 1990, 2000, and 2009 and the erosion protection works (dashed line).

dam (some 60 m in width along the dam's 2500-m length). The dam at Neerlands Reid was constructed just seaward of the cliff, so only a small strip of salt marsh was restored. At the time of dam construction (1991 at Griё and 1998–99 at Neerlands Reid), the soil level inland of the dam was lower at Griё than at Neerlands Reid.

Vegetation and Habitats

Table 2 lists the plant species found in each transect. Table 3 presents the plant communities (syntaxa) based on the vegetation relevés. In total, 44 plant species (taxa) were found on the plots (35 taxa at Griё and 30 taxa at Neerlands Reid). The top part of Table 2 shows the presence of typical salt-marsh plant species. Some species are restricted to Griё; others are limited to Neerlands Reid (bottom part of Table 2). For Griё, these species represent the dominant *Elytrigia atherica* vegetation at the cliff edge (*i.e.* the climax stage of salt-marsh succession). Species restricted to Neerlands Reid are upper salt-marsh zone vegetation types.

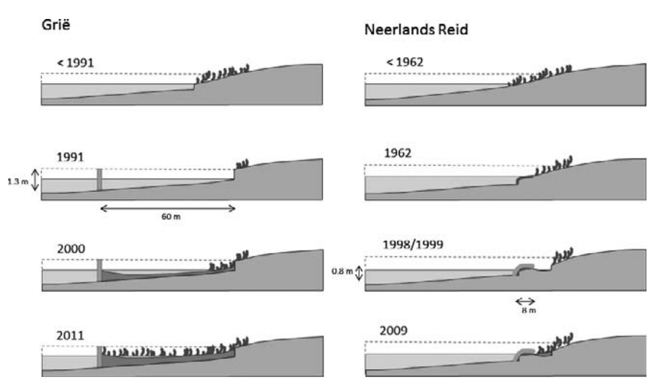

Figure 8. Outline of marsh development behind the erosion protection works at Griё (left) and Neerlands Reid (right).

Table 2. *Plant species and reference numbers recorded in transects at Grië (G) and Neerlands Reid (N). Nomenclature follows Van der Meijden (2005).*

Species	G1	G2	G3	G4	G5	G6	N1	N2	N3	N4
Fucus spp.							+	+		
Ulva lactuca	+	+	+	+	+	+	+		+	+
Vaucheria spp.	+	+	+	+	+	+	+		+	+
Salicornia europaea	+	+		+	+	+	+	+	+	+
Spartina anglica	+			+	+	+	+	+		+
Suaeda maritima	+			+	+	+	+		+	+
Puccinellia maritima	+			+	+	+	+		+	+
Agrostis stolonifera	+	+	+				+	+		
Festuca rubra	+	+	+		+		+	+	+	+
Atriplex prostrata	+			+			+	+	+	+
Plantago maritima	+	+		+	+	+	+	+		+
Aster tripolium				+	+	+	+	+	+	+
Atriplex portulacoides				+	+	+	+	+	+	+
Spergularia media				+	+	+	+	+	+	+
Limonium vulgare				+	+	+				+
Artemisia maritima					+		+	+	+	+
Triglochin maritima					+		+	+		+
Glaux maritima					+		+	+		+
Potentilla anserina		+			+		+	+		
Armeria maritima			+				+			+
Elytrigia atherica	+	+	+		+	+	+	+	+	+
Atriplex littoralis	+		+	+						
Cochlearia officinalis subsp. *anglica*				+	+	+				
Odontites vernus subsp. *serotinus*					+					
Hennediella heimii						+				
Juncus gerardi							+	+		
Bolboschoenus maritimus subsp. *compactus*							+			
Parapholis strigosa							+			
Carex distans								+		
Carex arenaria	+									
Sonchus arvensis var. *maritimus*	+	+								
Trifolium repens	+	+	+		+					
Poa pratensis		+	+							
Polygonum aviculare		+	+							
Ammophila arenaria			+							
Leontodon saxatilis			+							
Lolium perenne			+							
Vicia cracca			+							
Lotus spp.			+							
Rumex crispus							+			
Vicia lathyroides							+			
Cirsium arvense								+		
Phragmites australis								+		
Stellaria media								+		
Total species per transect	15	12	15	14	20	14	25	20	12	18

We encountered 11 salt-marsh plant communities ranging from those representing the early pioneer phase with *Salicornietum dolichostachyae* to those of the upper salt-marsh zone with the climax *Atriplici-Elytrigietum pungentis* vegetation. Figure 9 shows the spatial distribution of the EU-protected habitats (Habitats Directive, 1992) and the number of plant species found per plot. The following four habitats were encountered: "mudflats and sand flats not covered by seawater at low tide" (H1140), "*Salicornia* and other annuals colonising mud and sand" (H1310), "*Spartina* sward *(Spartinion)*" (H1320), and "Atlantic salt meadows *(Glauco-Puccinellietalia)*" (H1330). All relevant salt-marsh habitats were thus present. These last three habitat types enclose the "Atlantic and continental salt marshes and salt meadows" (European Commission, 2007).

Pooling the data from the two sites, the plant species found were categorized into three classes. Class boundaries were set such that 25% of the plots had zero to five species, 50% of the plots had five to eight species, and 25% of the plots had more than eight species.

The newly formed marsh areas between the dams and the former marsh cliff habitats were well established, representing the pioneer salt-marsh zone with *Salicornia* and *Spartina* (H1310 and H1320) (Figure 9). Habitat 1330, which is the vegetation of the upper marsh zone, was found behind the marsh cliff edges at both sites, but at some locations it was still developing between the dam and the former salt-marsh front. Species richness was greatest behind the cliff (the old salt marsh) and in the dam-protected area just in front of the cliff. Habitat 1140, "mudflats and sandflats," was found not only in front of the marsh cliff without a dam (the reference situation) but also on the seaward side of the dams (visual registration, but not included in the vegetation survey).

Table 3. *Plant communities (syntaxa) and reference numbers recorded in transects at Grië (G) and Neerlands Reid (N). Syntaxa and syntax codes follow Schaminée, Weeda, and Westhoff (1998). Habitat codes follow Janssen and Schaminée (2003).*

Syntaxa	Syntaxa Code	Habitat Code	G1	G2	G3	G4	G5	G6	N1	N2	N3	N4
Spartinetum townsendii	24AA02	1320	+			+		+	+	+		+
Salicornietum dolichostachyae	25AA01	1310		+	+				+	+		
Salicornietum brachystachyae	25AA02	1310	+	+		+	+	+		+	+	+
Suaedetum maritimae	25AA03	1310								+		
Puccinellietum maritimae	26AA01	1330							+			+
Plantagini-Limonietum	26AA02	1330						+				
Halimionetum portulacoidis	26AA03	1330				+	+				+	+
Juncetum gerardi	26AC01	1330							+			
Artimisietum maritimae	26AC05	1330							+	+	+	
Atriplici-Elytrigietum pungentis	26AC06	1330	+	+	+	+	+	+	+	+	+	+
RG *Scirpus maritimus (Asteretea tripolii)*	26RG01	1330							+			

RG = rompgemeenschap (community of impoverished vegetation).

DISCUSSION

Impact of Erosion Protection on Salt-Marsh Extent

This study's analysis of the lateral development of the seaward salt-marsh edge demonstrated that erosion protection by means of a low dam effectively diminished retreat of the marsh edge, subsequently reducing the loss of salt marsh at both locations. It even stimulated the formation of new salt marsh between the dam and the former marsh edge.

Grië

Based on a comparison of historical maps, De Boer (1986) estimated a 1.0 m per year average retreat of the salt-marsh edge at Grië during the past centuries. This implies that 0.25 ha of salt marsh was lost per year before 1991, when the dam was built (2500 m). After dam construction, within 20 years, some 15 ha of newly formed salt marsh was observed between the dam and the former cliff. Obviously, the dam provided favorable boundary conditions for sedimentation, leading to vertical accretion of the mudflats to such a height that salt-marsh pioneer vegetation could become established. Expansion of salt marshes requires relatively stable conditions with low wave energy and tidal scour and a sufficient supply of sediment (Adam, 1990). Figure 6 shows that during 1992–2000, the greatest change in elevation was found in the zone just behind the dam (increased elevation of 0.18 m from 1992 to 2000). Inland of the marsh cliff, the elevation of the upper salt marsh diminished (by 0.07 m from 1992 to 2000). On the sea side of the dam, the elevation of the mudflats also decreased (by 0.12 m from 1992 to 2000). Based on its monitoring data, Public Works concluded that most sediment behind the dam had originated from the mudflat adjacent to the low stone structure, with some additional sediment eroded from the upper marsh zone.

The strip directly behind the dam had risen to almost the height of the dam by 2011 (the height of the dam was *ca.* 1.3 m above the ground surface in 1991). This implies that in the 2000–11 period, the sedimentation rate directly behind the dam was greater than in 1992–2000 (*i.e.* some 0.09 m *vs.* 0.02 m per year). The strip some 30 m inland of the dam, however, seemed lower in elevation in 2011 than did the strip right behind the dam and that adjacent to the former salt-marsh edge (visual inspection). Because this area is not included in the Dutch coastal monitoring program (Rijkswaterstaat, 2012), no detailed data are available on the elevation of the area between the dam and the former salt-marsh edge.

The spatial gradient of retreat during 1941–1990 is in line with De Boer (1986), who found that the eastern part of Grië has eroded faster than the western part for centuries. From 1668 to 1984, retreat in the west (at Dwarsdijk) was 0.65 m per year, in the center (at Horrekooi) was 1.09 m per year, and in the east (at Rimkeskooi) was 1.38 m per year. This spatial gradient is probably due to differences in hydrodynamic conditions.

Neerlands Reid

After construction of the original low coastal defense at Neerlands Reid in 1962, erosion decreased, from an estimated 1.2 m per year during 1949–59, and stabilized until the 1990s. However, in section A without protection, cliff position fluctuated, and both retreat and advance were observed on the aerial photographs. After 1990, erosion increased, with an estimated 4.3 ha of salt marsh lost behind the worn protection works (1800-m dam × 24-m average retreat). After reinforcement of the dam in the late 1990s, the zone behind the dam became overgrown with vegetation relatively quickly. Apparently, only the top layer with salt-marsh vegetation behind the protection works was eroded, and just a short period of sedimentation and stable hydrodynamic conditions was needed for the typical salt-marsh vegetation to settle in.

General

Under natural conditions, sedimentation increases the elevation of salt marshes, and subsequently the slope increases between the adjacent mudflat and the marsh until it reaches the point of cliff formation (Allen, 2000; Dijkema *et al.,* 2007; Van de Koppel *et al.,* 2005). A cliff constitutes a natural but abrupt vertical transition from mudflats to salt marshes. Under favorable conditions, new salt marsh can develop in front of a cliff, resulting in a series of seaward-descending terraces, each separated by a small cliff (Allen, 1993). As such, cliff formation can be part of a cyclic process of salt-marsh succession (Allen, 1993; Dijkema *et al.,* 2007). At both field sites, after a period of sedimentation, the dam formed an abrupt vertical transition from mudflats to salt marshes, like a cliff. The newly formed salt-marsh expanse lies lower than the old salt marsh behind the former cliff and

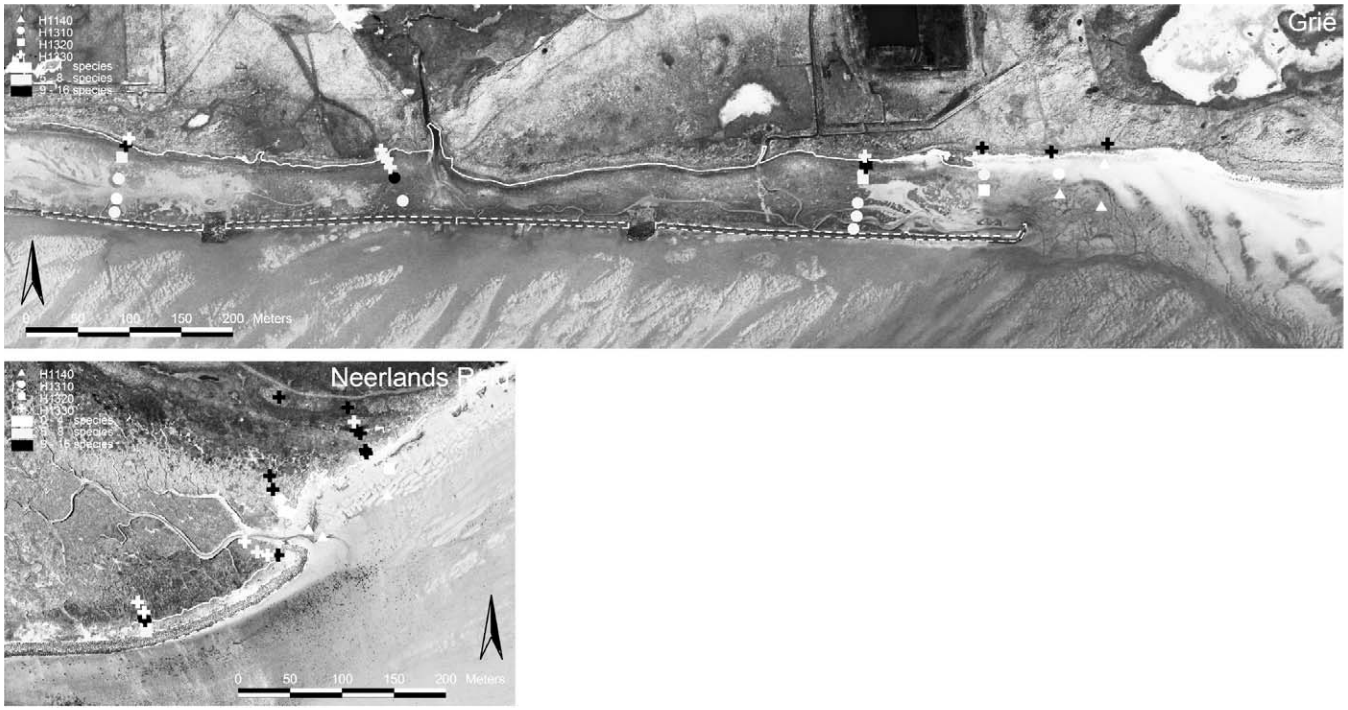

Figure 9. Spatial presentation of habitats and number of species per plot at Grië (top) and Neerlands Reid (bottom). The meanings of the habitat codes are H1310 for halophyte pioneer vegetation; H1320 for *Spartina* swards; H1330 for salt marshes, including a diversity of typical vegetation; and H1140 for mudflats and sand flats not covered by seawater at low tide (European Commission, 2007).

can be regarded as a terrace in front of the eroded older salt-marsh zone. However, the stone dam fixes the transition from mudflats to salt marsh and prevents the natural retreat of the salt-marsh edge in response to extreme events. Under conditions of rising sea level and an abundant supply of sediment, the development of a new salt-marsh zone seaward of the dam is not prevented; the dam may even be buried in newly formed salt marsh, like former cliffs in an advancing salt marsh (Allen, 1993). However, we do not expect this to happen, given the centuries-long salt-marsh retreat at Grië and the increased demand for sediment import in the Wadden Sea system to keep pace with sea level rise (Van Goor *et al.,* 2003). Over the long term, sea level rise may even lead to erosion of the salt-marsh zone behind the dam. With this in mind, it would be wise to take into account uncertainties in sea level rise and sediment supply when implementing erosion protection measures. Furthermore, sedimentation on minerogenic barrier-island salt marshes is spatially heterogeneous (De Groot *et al.,* 2011). The presence of spatial patterning (nested and ranging from a few meters to several hundreds of meters on the scale of the entire marsh) adds uncertainty to scaling up of data on salt-marsh sedimentation (De Groot *et al.,* 2011).

Hard coastal defense structures may lead to offsite effects, like erosion elsewhere. At Grië, the mudflat zone seaward of the dam deepened slightly after dam construction. The high water slack is close to Grië but is still on the move after closure of the Zuiderzee (1932) and Lauwerszee (1969), which in the longer term may result in changed hydrodynamic forces and increased erosion in front of the dam. The overall impacts and side effects of the stone dam thus remain uncertain.

Although we found that the stone structure led to establishment of natural salt-marsh vegetation behind the dam, the dam is an unnatural element in the Wadden Sea landscape. It is a fixed and straight line, while a natural cliff edge forms a meandering and dynamic coastline. Furthermore, stone is a nonlocal material. Nonetheless, a low stone dam is a relative simple management measure. Unlike wooden groins, no regular maintenance is required. Since the construction of the dams at Grië and Neerlands Reid, no damage to the dams has been observed (T. Overdiep, *personal communication;* T. van der Valk, *personal communication*).

The situations at Grië and Neerlands Reid differed not only with respect to the dimensions of the dams, as well as the position of the structures in relation to the eroded cliff, but also with respect to the elevation of the eroded salt marsh at the time of dam construction. At Grië, the eroded area lay lower than at Neerlands Reid. As a result, the vegetation settled in faster at Neerlands Reid than at Grië.

Impact of Erosion Protection on Salt-Marsh Vegetation

At both sites, characteristic pioneer salt-marsh vegetation (H1310 and H1320) developed in the raised area between the erosion protection works and the former marsh edge (Table 3 and Figure 9). These habitats were not found in transects without erosion protection, which was our reference situation. The low dam in front of the eroding marsh edge thus appears to have created favorable boundary conditions for sedimentation, in addition to preventing retreat of the salt-marsh cliff. This effectively meant the restoration of pioneer marsh vegetation (H1310 and H1320, and at some places H1330) in areas reduced by erosion to mudflats and sand flats (H1140). At Grië, the marsh retreated at an average rate of 1.3 m per year before dam construction (Table 1). This means that the dam (60 m in front of the marsh cliff) reclaimed an expanse of salt marsh that had been eroded in the preceding 45 years. As Figure 4 shows, the salt-marsh edge in 1949 corresponded approximately with the position where the dam was later built, except for the westernmost part of the analyzed area.

The dam did not influence the vegetation of the upper marsh zone (H1330), part of which had already developed to a climax state. Currently, most salt-marsh area on the Dutch Wadden islands is developing toward this species-poor climax state (Dijkema *et al.,* 2007). Natura 2000 and the Dutch–German–Danish trilateral agreements on flora heterogeneity among zones express an ambition to enhance the areal expanse of pioneer salt-marsh vegetation.

We found the same plant species present in the new marsh zone at both locations, although there was a difference in development time, because the dam at Neerlands Reid was constructed 7 to 8 years later than the dam at Grië. These were typical salt-marsh species, mostly annuals characterized as pioneer species (Adam, 1990). Under favorable conditions, restoration of pioneer salt-marsh habitat can be rapid. Within just a few years of construction of the dam at Grië, sparsely settled pioneer marsh species were found, such as *Salicornia europaea, Spartina anglica,* and *Suaeda maritima* (Zonneveld, Von Asmuth, and Van Dongen, 1997). Almost 70% of the area between the dam and the former salt-marsh edge was reported to be vegetated by typical salt-marsh species in 2000. The area was said to be dominated by *Salicornia europaea,* though other common species were *Spartina anglica, Spergularia salina, S. media, Carex distans, C. extensa, Juncus gerardi, Atriplex prostrata,* and *A. littoralis*. At the same time, upper marsh zone species like *Limonium vulgare, Artemisia maritima, Aster tripolium,* and *Atriplex portulacoides* were scarce in the new marsh zone (Zumkehr, 2002). The species assemblage found at both sites in 2011 (Table 3) was in line with further development of the local vegetation (Dijkema *et al.,* 2011; Visser, 1986; Zonneveld, Von Asmuth, and Van Dongen, 1997; Zumkehr, 2002). This is also the case with the plant communities and habitats. All relevant syntaxa and habitats (Table 3) are present in the newly developed salt-marsh area. In relation to plant species diversity, vegetation types, and habitats, we conclude that the nature value of the newly developed salt marsh is not inferior to the marsh zones formerly eroded.

Implications for Policy

Targets for Salt-Marsh Habitats

Formation of pioneer vegetation zones at the two study sites was induced by erosion protection works, because these measures allowed natural processes to take place to some extent. The result was a salt-marsh vegetation and drainage pattern similar to a naturally vegetated pioneer zone with natural drainage patterns mirroring the EU-protected habitats. On the island side, the newly formed salt marsh borders the upper marsh zone. The former salt-marsh cliff is still recognizable, and the current situation resembles a naturally terraced salt marsh due to the salt marsh advancing in front of the cliff. The formation of a seminatural pioneer salt-marsh zone with a seminatural drainage pattern of gullies and creeks between the former cliff and the dam is thus an attractive side effect of erosion protection, complying to some extent with Natura 2000 and trilateral targets. Nonetheless, the stone dam fixes the edge between the salt marsh and the adjacent mudflats, impeding natural retreat and advance of the marsh cliff. This is counter to conservation targets calling for increased natural morphology and dynamics. An edge fixed using wooden groins did not interfere with the seminatural salt marshes designated as Natura 2000 sites along the coast of Groningen and Fryslân. The development of a seminatural pioneer salt-marsh zone with a seminatural drainage pattern of gullies and creeks also appears well aligned with the ambitions of the program "Towards a Rich Wadden Sea" ("Naar een Rijke Waddenzee"). One objective of this initiative is to develop a smooth and broader transition zone from the dry coastal zone to the marine aquatic environment for ecological and climate adaptation reasons (Stuurgroep naar een Rijke Waddenzee, 2010).

Goals Concerning Geomorphological Processes and Human Interventions

Construction of a long-lasting stone dam to prevent natural erosion is to some extent inconsistent with the current goals for the Wadden Sea, which prioritize natural geomorphological processes and strive to minimize human intervention (Ministry of Transport, Spatial Planning & Environment, 2007). However, the long-term goal to limit human interference in salt-marsh development includes an exception for the edges of the marshes, which may need protection against erosion (Common Wadden Sea Secretariat, 1997). Furthermore, at our study sites, development between the dam and the cliff of the pioneer salt-marsh zone with a natural drainage pattern of gullies and creeks is the result of natural processes, stimulated by the dam. The dam only diminished (and did not stop) erosion of the former salt-marsh edge; apparently, the dimensions of the stone dam are such that natural retreat is still possible to some extent.

At both study sites, the dam was constructed of stones, which is a nonlocal, long-lasting, and inert material. However, the accretion works along the mainland coast consist of wood groins. Unlike a stone dam, this protective measure is flexible and temporal, but it may form a source of nutrients and possibly introduce new and invasive biota into the Wadden Sea ecosystem. This also applies to other materials that may be used for erosion protection, like nonlocal shells or clay for dams.

Coastal Protection

Natural foreshores have long been recognized for their ability to stabilize coastlines and protect coastal communities (Gedan *et al.,* 2011). This has led to salt-marsh protection and restoration activities and the embedding of such efforts in government policy. In Germany, for instance, the Schleswig-Holstein State Water Act defines salt-marsh works for coastal defense as a public obligation (Hofstede, 2003). Along the SE coast of the United States, efforts continue to maintain and nourish the existing marshland and to create new marshlands to improve storm buffering capacity (Feagin *et al.,* 2009). In this respect, important advances are being made in seminatural adaptation measures, such as the introduction of coastal wetland species to stabilize foreshores and the combination of manmade structures with salt marshes in ways that mimic nature (Gedan *et al.,* 2011). For example, the effects of engineered oyster reefs on erosion and sedimentation are being investigated in the Eastern Scheldt (the Netherlands) (Fiselier *et al.,* 2011). It is expected that these human-induced reefs will grow naturally and trap sediment. Moreover, they will change the hydrodynamic conditions behind the reefs so that sedimentation may occur and tidal flats may be stabilized and eventually develop into a foreshore zone. The oyster reefs should have a beneficial effect on biodiversity as well, providing habitat for fish and *Crustacea* species and foraging opportunities for birds (Borsje *et al.,* 2011). Our current study is another example of adaptation measures for coastal protection utilizing natural processes.

CONCLUSIONS

In the current study, we investigated the impact of low stone dams constructed for erosion protection in the face of retreating salt marshes. Low stone dams greatly reduced retreat of the seaward salt-marsh edge, from some 1.0 to 0.2 per year during the first decades after construction at two study sites in the Dutch Wadden Sea. The dams also created favorable boundary conditions for sedimentation and subsequently transformation from mudflats and sand flats into salt marshes in the area between the former salt-marsh edge and the dam. However, the stone dam fixes the edge between the salt marsh and the adjacent mudflats, thereby impeding a natural pattern of retreat and advance of the salt-marsh cliff.

Species composition in the newly formed marshlands is comparable with that in natural pioneer salt-marsh zones. Placement of the low stone dam seems to have enabled the restoration of pioneer salt-marsh habitat within 10 to 20 years at our two study locations.

Based on these findings, we conclude that under favorable conditions for sedimentation, the development of an ecologically attractive foreshore zone is feasible using relatively simple measures.

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