Vertical Accretion and Profile Changes in Abandoned Man-Made Tidal Marshes in the Dollard Estuary, the Netherlands

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ABSTRACT


In the Wadden Sea, an increasing area of the man-made tidal marshes, which cover over 17,000 ha, are becoming nature reserves or parts of national parks. Consequently, management aims altered from reclaiming land towards restoring natural-like marshes. Within this scope, maintenance of the drainage system was discontinued in a 460-ha nature reserve in man-made tidal marshes in the Ems Dollard Estuary, the Netherlands. We collected elevation data in four sections of the nature reserve to study vertical accretion rates and to evaluate marsh-profile changes. Elevations were surveyed in 1984 and in 1991/1992 along transects with a total length of 9,700 m. Generally, vertical accretion rates were negatively correlated with (a) marsh elevations of 1984, (b) distance from the intertidal mudflats, (c) distance from main creeks, and (d) in many cases, distance from minor creeks. At most of the transects that ran from the seaward marsh edge to the inland seawall, distance from the intertidal mudflats affected vertical accretion rates more than did the 1984 marsh elevation. As a consequence of a gradient in grazing intensity, vegetation structure (density and height) decreased inland and was probably an important auxiliary factor in determining vertical accretion patterns. After abandonment of the drainage system in 1984, the number of levees increased along minor creeks (former ditches), as did elevation differences at many existing levees. Levee development was more pronounced inland, which may be explained by the greater differences in vegetation structure between inland levees and marsh interiors (between minor creeks) as a result of the gradient in grazing intensity. Levee development, together with formation of badly drained depressions, increased elevation differences and abiotic and biotic diversity in the marshes. Vertical accretion rates in the Dollard marshes ranged from 6.6 mm/yr to 11.4 mm/yr among the four marsh sections. These values are relatively low compared to those of other man-made marshes, which might be a consequence of abandoning the drainage system.

ADDITIONAL INDEX WORDS: Salt marsh, vertical accretion, ditching, drainage, grazing, levee formation, restoration, Wadden Sea.

INTRODUCTION

The Wadden Sea fringes the coasts of the northern parts of the Netherlands and Germany and southern Denmark over a distance of nearly 500 km and a maximum width of 35 km. The mesotidal Wadden Sea developed in the wake of the Holocene transgression (VEENSTRA, 1980; OOST and DE BOER, 1994) and is separated from the North Sea by some twenty large and many small barrier islands and sandbanks. Today, it encompasses Europe’s largest intertidal area and major areas of salt marshes. The marshes, approximately 31,700 ha in area, form the remainder of an extensive natural landscape of coastal marshes, peat land and lakes that once existed at the boundary between Pleistocene deposits and the sea. The Wadden Sea reached its greatest extent during the Middle Ages, when extensive land losses occurred, which were at least partly caused by man’s impact on the environment. Extracting peat and draining for agricultural purposes caused subsidence of the land, which consequently became more vulnerable to flooding (EISMA and WOLFF, 1980; HOFFMANN, 1980; OOST and DE BOER, 1994). In the Dutch Wadden Sea area, dike construction began around A.D. 1000, initially to protect the land, later also to reclaim land.

Especially in sheltered bays formed by intrusions of the sea, sedimentation led to growth of new foreland. During the last three to four centuries, the Wadden Sea has become smaller due to successive reclamations for agricultural purposes of these newly formed marshes (DIJKEMA, 1987; DIECKMANN, 1988). Marsh extension, and consequently the size of the new embankments, gradually decreased. Coastal farmers therefore started to promote marsh accretion by digging drainage furrows and building small dams. Such techniques were applied as early as 1740 or even earlier (STRAATINGH and VENEMA, 1855). In the early decades of this cen-

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tury, however, farmers abandoned the accretion works. Parallel to developments in Germany, accretion works were taken up by the Netherlands Government in the 1930's and intensified, including the construction of sedimentation fields surrounded with brushwood groins in the pioneer zone and at the intertidal mudflats (Kamps, 1963).

Historical development explains that presently nearly all mainland salt marshes are man-made, making up more than 50% of the total salt-marsh area in the Wadden Sea. The man-made marshes are traditionally used for livestock grazing. They also have an important function in coastal protection by absorbing wave energy, especially during storm tides (Erchinger, 1995). However, maintenance of the accretion works, with the final aim to reclaim land, is no longer economically profitable (Mazure, 1974; Dieckmann, 1988). In recent years, an increasing area of man-made marshes have become nature reserves or parts of national parks because of their importance to nature conservation.

Typical aspects of the man-made marshes are an evenly distributed drainage pattern and a flat topography. Vertical accretion in the marshes is largely determined by sediment deposition during flooding. As flooding frequency decreases with increasing elevation, so does vertical accretion. Vertical accretion is also affected by the proximity of sediment sources to the marsh. Sediment from intertidal mudflats may be mobilized and deposited in the marshes during storm tides (Kamps, 1963). The creek system forms an important transport path for sediment into the marsh area; therefore, creeks may also be considered as sources of sediment (Stoddart et al., 1989). In addition, vegetation decreases near-bed water velocity and thus enhances sedimentation (Andresen et al., 1990; Dijkema et al., 1990; Pethick et al., 1990; Leonard et al., 1995). The main purpose of the ditches was to drain away seawater to promote stability of the marsh surface, soil aeration and plant growth and to prevent the formation of pans and irregular creeks. The drainage system therefore explains why the topography in these man-made marshes is so much flatter than it is in most natural Wadden Sea salt marshes, and accounts probably for the lower spatial variation of elevation, soil conditions and vegetation in the man-made marshes than in natural salt marshes (Jakobsen, 1954; Dijkema, 1983).

In nature reserves and national parks, management objectives are to develop more natural-like marshes. This management may vary from a laissez-faire policy of benign neglect to a strategic maintenance of groins and drainage systems to prevent erosion, with or without livestock grazing at reduced stocking levels, to create a marsh vegetation with more botanical and structural variation (Bakker, 1989; Ovesen, 1990; Dijkema, 1994). In 1981, tidal marshes in the Dollard were among the first man-made marshes in the Wadden Sea that became a nature reserve. Maintenance of the drainage system was stopped, and summer grazing with cattle was continued, but at reduced stocking levels.

In this paper, we use elevation data from these marshes, collected in 1984 and again in 1991/1992, to analyze vertical accretion patterns and to evaluate the profile changes in relation to a) elevation, b) distance from sediment sources and c) vegetation structure.

STUDY AREA

The Dollard (53°16'N, 7°10'E) forms a bay of approximately 100 km² in the Ems Dollard Estuary at the border of the Netherlands and Germany (Figure 1A). Intertidal mudflats constitute the largest part (c. 80%) of the Dollard, and tidal marshes cover c. 1.160 ha at the higher edges of the area. Tidal ranges average 3.3 m. Fresh water enters the Dollard from the Ems River in the NE and, through sluices at low tide, from the Westerwoldse Aa River in the SE. Salinity increases from SE to NW and is generally below 20% (Boede, 1985). Fluvial suspended matter input into the estuary is relatively small, i.e. in the order of 10% of marine suspended matter input (Ruardi, 1988; Zwolsman, 1994). Consequently, almost all sediment in the estuary is of marine origin (Van Straaten, 1960; Irion et al., 1987).

The Dollard dates from the Middle Ages. In 1277, large areas of land were washed away during a storm flood (Stratingh and Venema, 1855). The bay was enlarged stepwise by further flooding and reached its maximum extent in the 16th century (De Smet, 1960). Further transgressions were halted by improved management of the dikes. Since then, land was regained from the sea by embankments of the marshes that developed in sheltered areas of the bay. In the Dollard, human interference to stimulate horizontal and vertical accretion of the marshes presumably started before 1740 (Stratingh and Venema, 1855). The last embankment was constructed in 1924. Accretion works stimulated the development of new marsh area, which extended rapidly (cf. De Vries, 1940). These accretion works were carried out similar to the 'farmers' method (Kamps, 1963; Dijkema, 1983). Main ditches were dug 500 m apart perpendicular to the seawall. An earth groin was built exactly between two main ditches. Parallel to the seawall, ditches (30 m apart) and smaller field drains (5 m apart) were dug in the marsh area and in a narrow mudflat zone in front of it; the field drains were redug every year. In the late 1930s, construction of accretion works was intensified by construction of drained sedimentation fields of 200 m × 200 m that were surrounded by earth groins, and by expanding the works farther onto the intertidal mudflats. Maintenance of accretion works was suspended during World War II, but accretion works were reconstructed afterwards, to be abandoned again in the mid 1950s. To keep the marshes suitable for grazing, however, ditches that were 10–100 m apart were cleared or redug regularly, especially in the landward parts of the marshes. In the most-seaward parts, drainage systems were no longer maintained.

The eastern part (460 ha) of the Dutch Dollard marshes became a nature reserve in 1981. In this reserve, maintenance of the drainage system was abandoned by 1984, and summer grazing with cattle was reduced from a high to moderate or low stocking levels, i.e. from c. 2 to 0.5–1 animals/ha. The reserve is divided into regular 400-m-wide sections by the main ditches (called main creeks below) of the former accretion works (Figure 1B). Because cattle graze near the seawall most of the time, a gradient exists from a high grazing intensity near the seawall to a low grazing intensity in the seaward zone of the marsh. Consequently, short vegetation, predominately the grass Puccinellia maritima, occurs in
a broad zone close to the seawall, and the seaward zone is covered by taller vegetation: *Aster tripolium*, *Scirpus maritimus* and *Phragmites australis* among others. After 1981, the taller vegetation expanded inland due to lower stocking levels.

Water level is continuously registered in the mouth of the Westerwoldsche Aa River. In the period 1983–1992, mean high tide (MHT) averaged 1.45 m + N.A.P. (Dutch Ordnance Level). In 1984, the nature reserve was situated approximately between MHT and 0.6 m above MHT, which meant an average flooding frequency of more than 50 times per year at the highest elevations during the study period, mainly from September through March (Figure 2). The Dollard is subject to subsidence at a rate of approximately 1.5 mm/yr in the west (Section 1) to lower values more eastward, due to gas extraction (OOST and DIJKEMA, 1993). The marshes have a very fine-grained sediment with a clay content of 25–40% and an organic matter content of 4–7% (HARMEN HOEKSTRA, unpublished). The clay content increases from the seaward marsh edge towards the landward seawall.

**METHODS**

Transects with a total length of 9,700 m were established in four study sections (Sections 1–4) of the nature reserve (Figure 1B). Among these sections, distance from the seaward marsh edge to the inland seawall varied from c. 350 m in the east (Section 4) to c. 1,100 m in the west (Section 1). In each section, two main transects extended from the intertidal mudflats, just in front of the marsh, approximately up to the seawall, at 50 and 150 m distance from and parallel to the main creeks in the marsh (see STUDY AREA). Every 200 or 300 m, a cross transect extended from the center of a section to a main creek. The transects were surveyed for elevations in 1984, and again in 1991 (Sections 1 and 3) or in 1992 (Sections 2 and 4). Elevations were measured optically with an automatic levelling-instrument (NIKON 025) to the nearest millimeter every meter along the transects.

To compute the vertical accretion rate, elevation data of the marsh surface, excluding ditches and creeks, were averaged for five-m-long transect segments. The difference of the two mean elevations between the two elevation surveys was di-
Table 1. Legend units of the 1989 vegetation map of the Dollard marshes (Meetkundige Dienst, 1990) ranked into five vegetation-height classes and five vegetation-density classes.

<table>
<thead>
<tr>
<th>Vegetation Type (dominant plant species)</th>
<th>Height Density Class</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salicornia europaea</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Puccinellia maritima (grazed)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Festuca rubra (grazed)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Agrostis stolonifera (grazed)</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Elymus repens (grazed)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Elymus repens (ungrazed)</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Scirpus maritimus (ungrazed)</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Phragmites australis (ungrazed)</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>P. maritima/F. rubra (grazed)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>P. maritima/A. stolonifera (ungrazed)</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>F. rubra/P. maritima with Spartina anglica (ungrazed)</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>F. rubra/S. maritimus/P. australis (ungrazed)</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>S. maritimus/A. stolonifera/P. maritima (ungrazed)</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Notes: 1 = the lowest density and height classes. The last five legend units represent vegetation complexes, i.e. heterogeneous mapping units.

vided by the appropriate time interval (7 or 8 years). We excluded from the analysis those segments that had an average elevation based on fewer than four elevation measurements in one of the two surveys.

To analyze the effect of proximity of the intertidal mudflats on vertical accretion rate, only the main transects from the seaward marsh edge to the seawall were used. The effect of distance to the main creeks was analyzed by comparing the two main transects because other factors complicated a generalization among cross transects: i.e., the seaward cross transect of each section was located close to the intertidal mudflats, and more than half of the others were within a few meters distance parallel to ditches (called minor creeks below). The effect of minor creeks was only studied in Sections 1 and 2 because Sections 3 and 4 had few minor creeks suitable for the analysis.

A 1989 vegetation map of the marsh (scale 1:10,000; Meetkundige Dienst, 1990) was used to analyze the relationship between accretion rate and vegetation structure. Two vegetation variables were used, viz. vegetation density at ground level and vegetation height. Vegetation types were ranked and assigned by expert judgment into five classes for both variables (Table 1). Low vegetation-density classes represent communities that have a low shoot density, the therophytic community of Salicornia europaea being assigned to the lowest class, and swards of the fine-leaved grass Festuca rubra to the highest class. Within the same community, grazed stands were assigned to a lower class compared to ungrazed stands to account for the negative influence of cattle trampling on shoot density. Grazed, grass-rich communities were assigned to the lowest vegetation-height class; the assignment of the other, ungrazed, communities was dependent on the heights of the dominant plant species, which ranged from approximately 0.25 m in Salicornia europaea stands to 1.5–2.5 m in Phragmites australis stands.

SPSSPC + (Norusis, 1990) was used for the statistical analyses. If required, data were log transformed to match the prerequisites for parametric statistics. If transformations were not successful, nonparametric tests were used (Zar, 1984).

RESULTS

Vertical Accretion Rate and Elevation

The structure of the marsh may be best typified by the elevations at the main transects in Section 1. Figure 3 shows the relatively flat topography of the marsh, which is incised by minor creeks. The earlier abandonment of the drainage system explains the lower density of minor creeks in the seaward marsh zone (see STUDY AREA). The lower density of minor creeks at the main transect in the center of a section, i.e. 150 m from and parallel to the main creek, implies that minor creeks were partly filled before 1984. Transect elevation data in Sections 1, 2 and 3, at 150 m from the main creeks, show that the center of each section, on average, had lower elevations than did the sides, 50 m from the main creeks (Table 2).

Erosion of the marsh edge occurred at seven of the eight main transects (Table 3). In both surveys, a weakly developed cliff at the marsh edge could be distinguished from the elevation data. The cliff retreated 4–25 m at six of the main transects. Besides the cliff retreat, a broader zone was affected by net drop in elevation due to surface erosion. The width of the erosion zone (Table 3) is the sum of the cliff retreat and the zone with surface erosion. Erosion was greater at sites with stands of Scirpus maritimus than with Phragmites australis. Because other processes, such as wave erosion, are likely to play an important role at the marsh edge, the zone that had a net erosion was excluded from further analyses.

Vertical accretion rates differed significantly among the four sections (Figure 4). The sections only had small, but significant, differences in their mean elevations in 1984. The mean vertical accretion rate for each section varied proportionally to the mean 1984 elevation for each section. This pattern among sections did not correspond with that of vertical accretion rates as function of 1984 elevations within each section (Figure 5). In Sections 2, 3 and 4, vertical accretion rate was negatively correlated with 1984 elevation, but in Section 1, it was not. Regression slopes differed significantly between Sections 2 and 3 ($t_{977} = 2.571, P < 0.02$), but the slope of Section 4 did not differ significantly from the slopes of Sections 2 and 3. The most apparent differences were, however, the different heights of the three regression lines above the horizontal axis ($t_{978} = 35.406, P < 0.001$ for the comparison of Sections 2 and 3, and $t_{973} = 12.258, P < 0.001$ for Sections 3 and 4). The lack of a significant correlation between 1984 elevation and vertical accretion rate in Section 1, coupled with the limited amount of explained variance ($r^2$ in Figure 5) in the regressions of accretion rates with 1984 elevations in the other three sections, with a highest $r^2$ of only 0.35 (Section 4), indicate that vertical accretion rate is likely influenced by more factors than elevation alone.

Vertical Accretion Rate and Proximity of Sediment Sources

Proximity of the Intertidal Mudflats

Vertical accretion rate diminished with increasing distance from the intertidal mudflats at seven of the eight main...
transects; the central transect at 150 m from the main creek in Section 1 being the exception (Figure 6). At four of these seven transects, accretion rate also correlated negatively with 1984 elevation (Table 4), which raises the question of which of the two factors affected vertical accretion rate more at the main transects: distance from the intertidal mudflats or 1984 elevation? A close relationship existed between these two independent variables at all main transects, with the exception of the transect at 50 m from the main creek in Section 2. The other transect of Section 2 (150 m) was the only main transect where the negative correlation between vertical accretion rate and 1984 elevation remained significant when 1984 elevation was controlled for distance to the intertidal mudflats (Table 4). At six of the other seven transects, partial correlations showed that distance from the intertidal mudflats was affected vertical accretion rate more than 1984 elevation did. That is, partial correlations between vertical accretion rate and distance to the intertidal mudflats, controlled for 1984 elevation, were significant, vertical accretion rate and 1984 elevation remained significant when 1984 elevation was controlled for distance to the intertidal mudflats (Table 4). At six of the other seven transects, partial correlations showed that distance from the intertidal mudflats was affected vertical accretion rate more than 1984 elevation did. That is, partial correlations between vertical accretion rate and distance to the intertidal mudflats, controlled for 1984 elevation, were significant, vertical accretion rate and 1984 elevation remained significant when 1984 elevation was controlled for distance to the intertidal mudflats (Table 4). At six of the other seven transects, partial correlations showed that distance from the intertidal mudflats was affected vertical accretion rate more than 1984 elevation did. That is, partial correlations between vertical accretion rate and distance to the intertidal mudflats, controlled for 1984 elevation, were significant, vertical accretion rate and 1984 elevation remained significant when 1984 elevation was controlled for distance to the intertidal mudflats (Table 4). At six of the other seven transects, partial correlations showed that distance from the intertidal mudflats was affected vertical accretion rate more than 1984 elevation did. That is, partial correlations between vertical accretion rate and distance to the intertidal mudflats, controlled for 1984 elevation, were significant, vertical accretion rate and 1984 elevation remained significant when 1984 elevation was controlled for distance to the intertidal mudflats (Table 4). At six of the other seven transects, partial correlations showed that distance from the intertidal mudflats was affected vertical accretion rate more than 1984 elevation did. That is, partial correlations between vertical accretion rate and distance to the intertidal mudflats, controlled for 1984 elevation, were significant, vertical accretion rate and 1984 elevation remained significant when 1984 elevation was controlled for distance to the intertidal mudflats (Table 4). At six of the other seven transects, partial correlations showed that distance from the intertidal mudflats was affected vertical accretion rate more than 1984 elevation did. That is, partial correlations between vertical accretion rate and distance to the intertidal mudflats, controlled for 1984 elevation, were significant, vertical accretion rate and 1984 elevation remained significant when 1984 elevation was controlled for distance to the intertidal mudflats (Table 4). At six of the other seven transects, partial correlations showed that distance from the intertidal mudflats was affected vertical accretion rate more than 1984 elevation did. That is, partial correlations between vertical accretion rate and distance to the intertidal mudflats, controlled for 1984 elevation, were significant, vertical accretion rate and 1984 elevation remained significant when 1984 elevation was controlled for distance to the intertidal mudflats (Table 4). At six of the other seven transects, partial correlations showed that distance from the intertidal mudflats was affected vertical accretion rate more than 1984 elevation did. That is, partial correlations between vertical accretion rate and distance to the intertidal mudflats, controlled for 1984 elevation, were significant.

Figure 3. Marsh profiles in 1984 and 1991 at the main transects in Section 1, (A) 50 m from the main creek and (B) 150 m from the main creek.

<table>
<thead>
<tr>
<th>Section</th>
<th>Transect</th>
<th>Vegetation Type</th>
<th>Cliff Retreat Zone (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W</td>
<td>Phragmites australis</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>W</td>
<td>P. australis</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>W</td>
<td>P. australis</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>E</td>
<td>P. australis</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>P. maritimus</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>E</td>
<td>S. maritimus</td>
<td>28</td>
</tr>
<tr>
<td>7</td>
<td>E</td>
<td>S. maritimus</td>
<td>38</td>
</tr>
</tbody>
</table>

Notes: $n_{50} =$ number of 5-m segments along transect at 50 m from the main creek; $n_{150} =$ number of 5-m segments at 150 m along transect from the main creek. $P$ denotes the significance in elevation differences according to the Mann-Whitney test, except for Section 2, where the difference in elevation was tested with the $t$ test; n.s. = not significant.
Vertical accretion rates may be influenced by the width of each section (length of the main transects relative to distance from the intertidal mudflats) and section slopes. The higher correlations of the 1984 marsh elevations with the distance from the intertidal mudflats (r_{ij} in Table 4) show that the narrower Sections 3 and 4 had steeper slopes than the wider Sections 1 and 2. This coincided with lower vertical accretion rates inland in the narrower Sections 3 and 4 compared to the wider Sections 1 and 2 (Figure 6).

Proximity of Main Creeks

Figure 6 shows that relationships between distance from the intertidal mudflats and vertical accretion rate differed between the two main transects in Sections 1, 2 and 3. Only in Section 4 did this relationship not differ significantly between the two transects (Figure 6D). On the basis of lower 1984 elevations of the central transects (at 150 m from the main creeks; Table 2), higher accretion rates were to be expected at these transects; however, Figures 6ABC show the opposite result. In Sections 1, 2 and 3, accretion rates were significantly higher at 50 m than at 150 m from the main creeks (t test between the heights of the two regression lines in each section). In this comparison, allowance was not made for the difference in slopes of the two regressions in Section 2 (t_{357} = 5.108, P < 0.001). Different slopes in Section 2 regressions may indicate an interaction between distance from the intertidal mudflats and proximity of the main creek.

Proximity of Minor Creeks

Figure 7A shows the 1984 and 1991 marsh profiles at both sides of a minor creek that crosses the eastern main transect in Section 1 at 750 m from the intertidal mudflats (cf. Figure 3A). At both sides of the creek, a weakly developed levee was identified from the 1984 elevations. The levees were not more

![Figure 4](image_url) 1984 Elevation (mean ± s.e.) and mean vertical accretion rate for 1984–1991/92 in each section. Letter symbols indicate that the vertical accretion rates were significantly different among all sections based on an SNK-type nonparametric multiple comparison test (P < 0.05).

Contrary to partial correlations of accretion rate with 1984 elevation, controlled for distance to the intertidal mudflats. At the main transect at 150 m from the main creek in Section 1, accretion rate did not correlate significantly with 1984 elevation or with distance from the intertidal mudflats (Figures 3B, 6A); this did not change when partial correlations were computed (Table 4).

Vertical accretion rates may be influenced by the width of each section (length of the main transects relative to distance from the intertidal mudflats) and section slopes. The higher correlations of the 1984 marsh elevations with the distance from the intertidal mudflats (r_{ij} in Table 4) show that the narrower Sections 3 and 4 had steeper slopes than the wider Sections 1 and 2. This coincided with lower vertical accretion rates inland in the narrower Sections 3 and 4 compared to the wider Sections 1 and 2 (Figure 6).

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Proximity of Minor Creeks

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Vertical accretion rates may be influenced by the width of each section (length of the main transects relative to distance from the intertidal mudflats) and section slopes. The higher correlations of the 1984 marsh elevations with the distance from the intertidal mudflats ($r_{xy}$ in Table 4) show that the narrower Sections 3 and 4 had steeper slopes than the wider Sections 1 and 2. This coincided with lower vertical accretion rates inland in the narrower Sections 3 and 4 compared to the wider Sections 1 and 2 (Figure 6).

**Proximity of Main Creeks**

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Figure 7A shows the 1984 and 1991 marsh profiles at both sides of a minor creek that crosses the eastern main transect in Section 1 at 750 m from the intertidal mudflats (cf. Figure 3A). At both sides of the creek, a weakly developed levee was identified from the 1984 elevations. The levees were not more...
than 0.04 m and 0.09 m above the marsh at the seaward and seawall creek sides, respectively. By 1991 these differences had increased to 0.14 m and > 0.20 m above the marsh, because vertical accretion rate had a positive relationship with proximity to the minor creek (Figure 7B). The length of the levee slope at the seaward side, and possibly also the differences in elevation at the levee, were limited by the proximity of the neighboring levee of the next minor creek, as is shown by the points at > 20 m distance at the intertidal-mudflats side of the creek.

Degrees of levee development and vertical accretion rates differed considerably among minor creeks. Figures 7CD show the degree of levee development and the vertical accretion rate at the margins of another minor creek at the same transect as the minor creek in Figures 7AB, but 250 m closer to the intertidal mudflats. Mean vertical accretion rate at the more seaward minor creek was much higher, but did not correlate significantly with distance from the minor creek. At the seaward side, a levee was not evident from the 1984 elevations, and only a weakly developed levee, with an eleva-

Figure 6. Annual vertical accretion rate (mean ± s.e.) for 1984–1991/92 as a function of the distance from the intertidal mudflats for the main transects in Sections 1 to 4. Accretion rates were averaged for 50-m segments, but regressions were based on the individual data.

Table 4. Simple and partial correlations of vertical accretion rate with 1984 elevation and distance to the intertidal mudflats at the main transects.

<table>
<thead>
<tr>
<th>Section</th>
<th>Distance from main creek (m)</th>
<th>Zero-order Correlations</th>
<th>First-order Correlations</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$r_{xz}$</td>
<td>$r_{yx}$</td>
<td>$r_{yz}$</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>0.5374****</td>
<td>-0.0698</td>
<td>-0.2314**</td>
</tr>
<tr>
<td>1</td>
<td>150</td>
<td>0.4204***</td>
<td>-0.0447</td>
<td>-0.0496</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0.0898</td>
<td>-0.0798</td>
<td>-0.6810****</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>0.4894***</td>
<td>-0.2021**</td>
<td>-0.1820**</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>0.8784****</td>
<td>-0.6029****</td>
<td>-0.6543***</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>0.8212****</td>
<td>-0.6074****</td>
<td>-0.6811****</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>0.7106****</td>
<td>-0.1815</td>
<td>-0.4962***</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>0.7106****</td>
<td>-0.1815</td>
<td>-0.4962***</td>
</tr>
</tbody>
</table>

Notes: Zero-order correlations give the simple correlations of 1984 elevations with distance from the intertidal mudflats ($r_{xz}$), and of vertical accretion rate with 1984 elevations ($r_{yz}$) and with distance from the intertidal mudflats ($r_{xz}$). First-order correlations are the partial correlations of accretion rate with elevation, controlled for distance from the intertidal mudflats ($r_{yz}$), and for the partial correlations of accretion rate with distance from the intertidal mudflats, controlled for elevation ($r_{yz,x}$). The last column gives the number of 5-m transect segments in the analyses. * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$, **** = $P < 0.0001$ (one-tailed significance).
Vertical Accretion Rate and Vegetation Structure

In addition to being affected by elevation and proximity of sediment sources, vertical accretion rate was also influenced by vegetation structure and, indirectly, by grazing management, which to a great extent determined the spatial variation in vegetation structure (see STUDY AREA). Vegetation density and vegetation height generally had a positive effect on vertical accretion rates (Figure 10). In Sections 1, 2 and 3, accretion rates increased with increasing vegetation densities; in Sections 3 and 4, the greatest accretion rates were found in the tallest vegetation (i.e., Phragmites australis stands; Table 1). The effects of vegetation density and vegetation height could not be separated with a two-way analysis of variance, because not all combinations of vegetation-density and height classes were present. In Section 1, for example, vegetation-density class 1 concurred only with height class 2 (cf. Table 1), and consequently the effect of vegetation height cannot be analyzed within this density class. In the same section, vegetation-density class 2 concurred with height classes 1 and 4, and average vertical accretion rates did not differ significantly between these two height subgroups. Ten of the fourteen average vertical accretion rates presented for all sections in Figures 10A–D allowed such a comparison between subgroups of the same vegetation density, but that differed in vegetation height. Vegetation height had a positive effect on vertical accretion rate in six of these ten possible comparisons, a negative effect in one comparison, and no effect in the three other comparisons. In a similar
way, the influence of vegetation density was analyzed within classes of the same vegetation height. The eighteen average accretion rates presented for all sections and vegetation-height classes (Figures 10E–H) allowed only six comparisons between subgroups having a different vegetation density. Four of the comparisons showed a positive effect of vegetation density on the vertical accretion rate, but a statistical effect was not found in the other two comparisons.

DISCUSSION

Changes at the seaward marsh edge will be examined once more, before vertical accretion rate and marsh-profile changes are addressed. In the light of the proposed greater resistance to wave exposure of *Scirpus maritimus* compared to that of *Phragmites australis* (Coops et al., 1991), the greater erosion of the marsh seaward edge where *S. maritimus* dominated was unexpected (Table 3). This erosion was probably triggered by foraging activity of Greylag Geese (*Anser anser*). These geese staged in low numbers in the Dollard up to the early 1980s, but they became more numerous thereafter. Not only do they graze the above-ground component of the grass-rich marsh vegetation and feed in agricultural fields outside the marsh, they also grub for tubers of *S. maritimus*, especially in autumn and winter (Esselink et al., 1997). The above-ground biomass was removed by this feeding activity in the *S. maritimus* stands, leaving the partly turned-up sediment unprotected against tides and waves in the latter half of the winter season. No quantitative data are available on marsh erosion during the 1960s and 1970s. Overall losses, however, may be considered to be relatively small. Preservation of the other, more exposed, man-made marshes at the Dutch mainland coast requires maintenance of groins and possibly artificial drainage of the pioneer zone (Dijkstra et al., 1990). For the present, no such measures are recommended for the Dollard marshes for two reasons: (a) the marshes are more sheltered in a bay, and (b) *P. australis* distribution has expanded during the last 10–15 years and is expected to do so in the near future, resulting in further protection of the marsh.

In our study, vertical accretion was related with marsh elevation, proximity of various sediment sources and vegetation structure. At most main transects, 1984 marsh elevation and distance from the intertidal mudflats were closely related. Partial correlation analyses showed that at all main transects except one, distance from the intertidal mudflats affected vertical accretion rate more than 1984 elevation did (Table 4). More interrelationships existed among the independent variables. The diagram in Figure 11 illustrates our
Vertical accretion in abandoned man-made tidal marshes

Figure 10. Mean vertical accretion rate per vegetation-density class (A–D) and per vegetation-height class (E–H) for each section. Accretion rates sharing the same letter within the same plot were not significantly different (P > 0.05) according to the Tukey test, an SNK-type nonparametric multiple comparison test, or the Mann–Whitney test (Figure D only). The figure shows mean accretion rates that were based on an n of ≥ 5.

conception of how the spatial variation of the vertical accretion may be explained by these variables. The diagram also has relevancy for other man-made marshes in the Wadden Sea.

The relationship of vertical accretion rate with 1984 elevation (Figure 5) was overshadowed by the relationship between vertical accretion rate and distance from the intertidal mudflats (Figure 6, Table 4), which might be partly due to the small variation in elevation in the marsh. A greater vertical accretion rate in the seaward part of the marsh is a common phenomenon and is generally explained by seaward deposition of coarser-grained particles and transport of finer-grained particles landward (Jakobsen, 1954; Dijkema, 1983; Collewey and Erching, 1992). In addition, more sand may be transported during storm tides in the lowest water layer and also be trapped by vegetation in the seaward part of a marsh (same refs). By the time water gets inland, all the large particles have dropped out. Fine particles have less sedimentation potential and are carried off. Also in the Dollard marshes, grain-size decreases landward (see STUDY AREA). An important auxiliary factor explaining the lower vertical accretion rates inland is the vegetation-structure gradient, which is mainly caused by the cattle grazing of the marsh. The grazed, short and sparse vegetation near the seawall has less effect on reducing water velocity and features lower sediment-trapping abilities during flooding compared to the taller and denser vegetation in the more seaward zone. Figure 12 shows an oblique aerial view of the Dollard marshes in winter. The marsh is sparsely vegetated inland, but seaward is covered with standing biomass of Phragmites australis and other species.

Grazing and vegetation structure may also play an important role in the accretion pattern around minor creeks and in levee development across the marsh (Figures 7–9). Decreasing flow velocities in the water column are generally assumed to promote greater sedimentation on the levees. In their study in a Juncus roemerianus marsh, however, Leonard et al. (1995) showed that vegetation was a more important control over water-flow velocities than proximity to a creek. In our study area, except for some depressions or pans, differentiation in vegetation structure between creek sides and marsh interiors (between the minor creeks) was greater inland near the seawall than in the seaward part of the marsh, in part due to the grazing gradient. In the inland parts of the marsh, the interiors were mostly covered by a sparse Pucci-
vellia maritima sward, which was easily damaged by cattle trampling. An even more sparse and annual vegetation of Salicornia europaea and Suaeda maritima occurred in some depressions; these species increased in the early 1990s as lack of creek maintenance led to deteriorating drainage. The creek sides, in contrast, had mostly a denser coverage of Ely­mus repens or Festuca rubra, also in the seaward part of the marsh. In addition, vegetation at the creek sides suffered less from cattle trampling, due to a better drainage. In the almost ungrazed seaward part of the marsh, the interiors (between the minor creeks) were covered by tall stands of Spartina anglica, Aster tripolium and Phragmites australis, mixed with tall stands of other grasses (Table 1). This produced less differentiation in vegetation structure with respect to the creek sides and might explain the lack of a relationship between vertical accretion rate and proximity to the creek (Figure 7B) and less levee development in the seaward part of the marsh (Figure 9).

Mean vertical accretion rates for each section were lower in the shorter Sections 3 and 4 than in Sections 1 and 2 (Figure 4); vertical accretion rates in the shorter sections were particularly lower at the landward end of the main transects (Figure 6). This indicates that the narrower widths (distance from the seaward marsh edge to the landward seawall) and steeper slopes of Sections 3 and 4 may result in a more rapid filling and draining, higher water-flow velocities, and less time for suspended matter to settle.

If the sheltered position of the Dollard marshes is considered, mean vertical accretion rates, varying from 6.6 mm/yr to 11.4 mm/yr, among the four sections, are rather low compared to those of other man-made marshes in the Wadden Sea, which mostly have vertical accretion rates well above 10 mm/yr (Dieckmann, 1988; Dijkema et al., 1990; Erching er et al., 1996). Those marshes still have well-maintained artificial drainage systems, which may function as delivery paths for sediment to the marshes (Stoddart et al., 1989), and which prevent the widespread development of badly drained, sparsely vegetated depressions (Jakobsen, 1954; Dijkema, 1983).

Perspectives

The below-average vertical accretion rates in the depressions do not seem to constitute a threat to the marshes. In the Wadden Sea, MHTs increased on average 3.0 mm/yr from 1961 to 1995 (Jaap Bossinade, personal communication). Though vertical accretion rates in the depressions were sometimes negative (Figure 7B), they generally exceeded the increase of MHT, and ranged from 5.6 mm/yr to 9.2 mm/yr in the depressions of Sections 1 and 2 (vegetation density class 1 in Figures 10AB). The development of levees along minor creeks, together with the formation of badly drained depressions, resulted in an increase in elevation differences and an increase in the variation of abiotic conditions for the marsh vegetation. To enhance diversity in the marsh is part of the management objectives for the nature reserve. Lower vertical accretion rates inland (Figure 6) may indicate terrace formation in the seaward part of the marsh, with a lower-lying
back-swamp area fringing the seawall. Because the latter part of the marsh is the most important grazing area for livestock, this development, together with the deteriorating drainage system, will cause a decline of the suitability of the Dollard marshes for grazing. Because of the brackish conditions in the Dollard, abandonment of grazing will eventually lead to a dominance of Phragmites australis across the entire marsh area. So, to maintain vegetation diversity in the marshes, additional management measures may be required in the future.

CONCLUSIONS

(1) Erosion at the edge of the marsh was greater in Scirpus maritimus than in Phragmites australis stands. This was due to grubbing by Greylag Geese for Scirpus maritimus tubers.

(2) Generally, vertical accretion rates were negatively correlated with (a) marsh elevation, (b) distance from the intertidal mudflats, and (c) in many cases, distance from minor creeks. In three of the four 400-m-wide study sections, vertical accretion rates were lower at 150 m than at 50 m from the main creeks, despite the lower elevations at 150 m. Distance from the intertidal mudflats proved to be more important than 1984 marsh elevation at most transects that ran from the seaward marsh edge to the inland seawall.

(3) Vertical accretion rates were further influenced positively by vegetation structure, i.e. vegetation density and vegetation structure.

(4) The number of levees along minor creeks increased, as did the elevation differences at many of the existing levees. Levee development was more pronounced inland. This is presumably explained by greater differences in vegetation structure between levees and marsh interiors inland and, by a grazing-intensity gradient. Apparently, vegetation structure affected sedimentation more than did proximity to a creek, a finding that is consistent with other studies.

(5) Development of levees along minor creeks, attended with the formation of badly drained depressions, meant an increase of the variation in elevation and the abiotic diversity of the marsh.

(6) Vertical accretion rate in Dollard marshes ranged from 6.6 mm/yr to 11.4 mm/yr among the four sections. These relatively low values, compared to those of other man-made marshes in the Wadden Sea, might be a consequence of abandonment of the drainage system.

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LITERATURE CITED


