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Vertical Growth of a Young Back Barrier Salt Marsh, Skallingen, SW Denmark

Niels Nielsen and Jørgen Nielsen

Institute of Geography
University of Copenhagen
Øster Voldgade 10
DK-1350 Copenhagen K, Denmark

ABSTRACT

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The spatial and temporal distribution of the sediment accretion upon a young (less than 100 years old), predominantly inorganic back barrier salt marsh has been studied based on leveling in 1973, a re-survey in 1998 and observations from 1931 to 1954 of the same area. The surface of the back barrier of Skallingen is not sloping gradually, from the dune ridges to the marsh edge, but is separated into three zones: an inner and an outer marsh at a level of about 1 m DOD (Danish Ordnance Datum), and a lower section in between at 0.9 m DOD. During the last 25 years the rate of sedimentation has been 3 mm a^{-1} on the inner and outer part and about 2 mm a^{-1} on the lower. The accretion on recently developed salt marsh areas along the marsh edge has been 8 mm a^{-1}, a rate which looks characteristic for new marsh building on Skallingen as early investigations in the 1930s indicate a similar magnitude. This relatively high rate may be partly a result of sediment imported by sea ice rafting. Different methods used to measure the rate of sedimentation (marker layers, profiling and ^{210}Pb isotope dating) all agree quite well. The average rate of sedimentation since 1931 on established marsh surfaces has almost been uniform, 3 mm a^{-1}, which is well above the average sea-level rise of 1.3 mm a^{-1} during the last century. However, concerning the last 25 years, the hydrographical conditions have change dramatically. There has been an increased frequency of inundation, more storm surges, and the sea-level rise has increased to 4.2 mm a^{-1}. But the accretion rate has not change, it is still 3 mm a^{-1}. No evidence of stagnation or degradation of the salt marsh, however, has been observed yet.

ADDITIONAL INDEX WORDS: *Salt marsh, rate of sediment accretion, sea-level rise, storm surge frequency, Danish Wadden Sea.*

INTRODUCTION

During the last one or two decades, accretion processes of coastal wetlands have been in focus (*e.g.* ROMAN *et al.,* 1997). One of the reasons is that a possible global warming and a consequently accelerating sea level rise could cause substantial losses of coastal salt marshes (ORSON *et al.,* 1985; STEVENSON *et al.*, 1986; VILES and SPENCER, 1995). A crucial question within this context is if the sedimentation rate in a given area will enable the salt marsh to keep pace with the local increase in the sea level (FRENCH *et al.*, 1994a).

Salt marsh evolution is controlled by the changing balance between tidal regime, wind-wave climate, sediment supply, relative sea level rise and wetland vegetation (REED, 1990; ALLEN and PYE, 1992). However, models of the accretion balance presented by FRENCH (1991, 1993, 1994) and ALLEN (1990) demonstrate that no simple relationship exists between one or more of the above mentioned parameters and the growth or decay of salt marshes. This may explain why different accretion rates are recorded in salt marshes developed under apparently similar conditions. Another reason for this apparent lack of relationship, as stressed by FRENCH (1994) and FRENCH and SPENCER (1993), is that net sediment accumulation may vary greatly within a single salt marsh area as a consequence of the morphology. It is, therefore, important to specify where measurements are performed when evaluating the rate of sedimentation. During the last 70 years or so a number of methods have been used to evaluate sedimentation rates on salt marshes. Most reports on wetland sediment budget have been based on the use of marker horizons (*e.g.* NIELSEN, 1935; STEERS, 1938; STEVENSON and EMERY, 1958; RICHARD, 1978; LETZSCH, 1983; HARRISON and BLOOM, 1977). Radioisotope dating techniques have been used by BARTHOLDY and MADSEN (1985), STEVENSON *et al.* (1986) and KIRCHNER and EHLERS (1998). In recent years, authors (*e.g.* ALLEN and DUFFY, 1998) have used various kinds of traps to elaborate on the direct connection between dynamics and sedimentation on short time scales. A short-coming of all these methods is that they provide little spatial information. Repeated levelling has been used in order to obtain information on a wider scale (*e.g.* MARKER, 1967; CARLING, 1982; REED, 1988, and ESSELINK *et al.,* 1998).

The purpose of this study is to describe the spatial and temporal distribution of the sediment accretion upon a young, predominantly inorganic back barrier salt marsh, and thereby to contribute to information on magnitudes of sedimentation rates in the Danish part of the salt marshes in north-western Europe. This investigation is primarily based on the development of a transect surveyed in 1973 (NIELSEN and NIELSEN, 1973) and in 1998.

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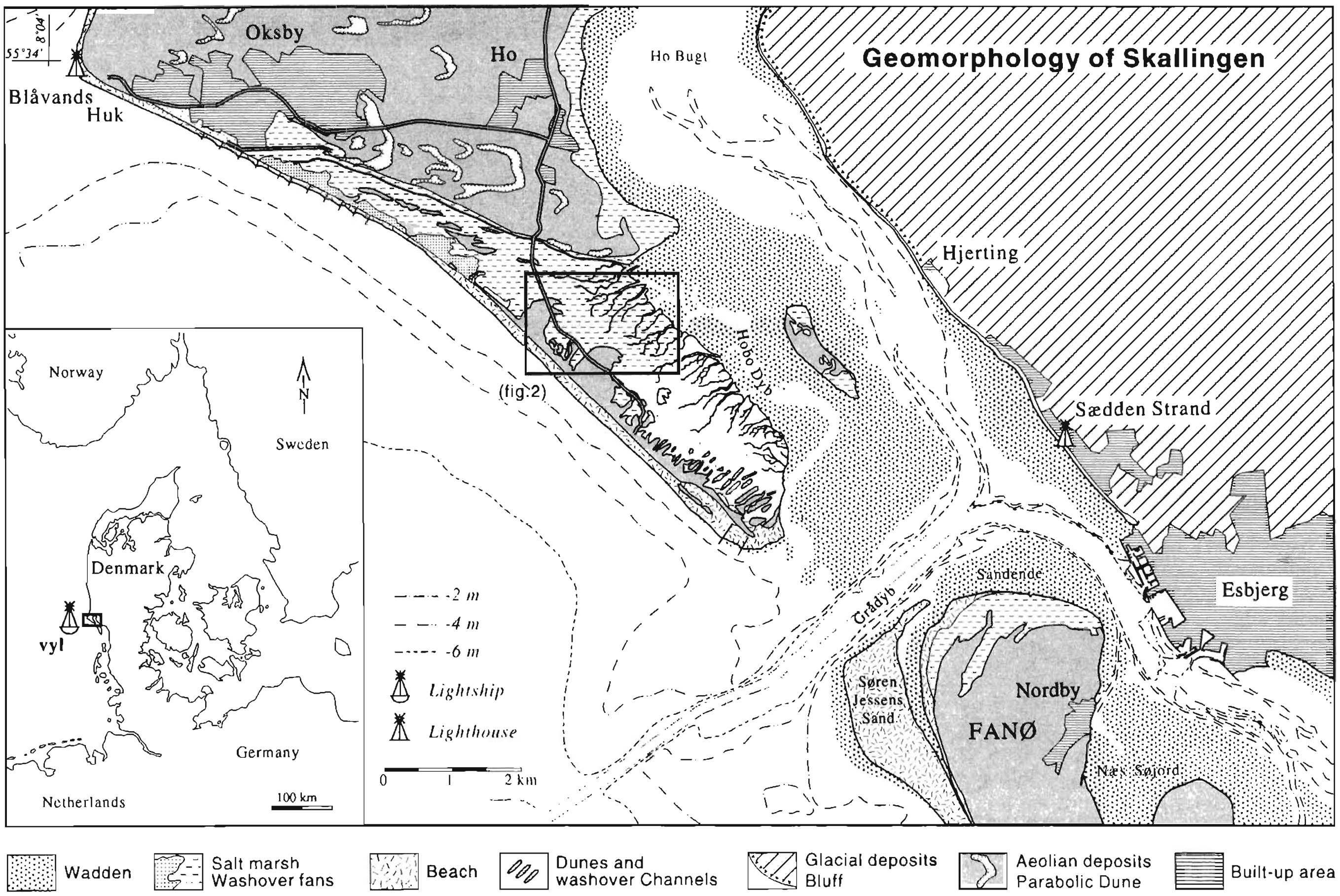

Figure 1. Study area and geomorphological outline of Skallingen.

Basically, tidal characteristics and the frequency and duration of inundation determine the amount of sediment accumulation. Therefore, the study also comprises an analysis of the relative sea level rise, the tide and especially storm surge events during the last one hundred years, especially focusing on the period 1973–1998.

As the Skallingen barrier has been largely untouched by human intervention, apart from grazing cattle, the barrier has been subjected to a wide range of geomorphological, sedimentological and floristic investigations (*e.g.* IVERSEN, 1954). In 1931, marker layers of red (sudan-red) coloured sand were deployed on the Skallingen back barrier (NIELSEN, 1935) in order to monitor the rate of sedimentation. Recently, some of these were re-discovered (BARTHOLDY *et al.,* in press). In 1945–51, a salt marsh area in the central part of Skallingen was investigated with respect to the development of the topography, sediments and vegetation colonization (LARSEN, 1952; JAKOBSEN, 1953 and 1954). Salt marsh areas in southwest Jutland, including important aspects of the geomorphology of Skallingen, are reported by JAKOBSEN, 1964; MØLLER, 1964; NIELSEN and NIELSEN, 1973; JACOBSEN, 1969; PEJRUP, 1981; BARTHOLDY and MADSEN, 1985; AAGAARD *et al.,* 1995; DAVIS *et al.,* 1997; BARTHOLDY, 1997.

SETTINGS

The coastal landscape between Blåvands Huk and the Netherlands is dominated by barrier islands (Figure 1). To the north, Skallingen, a barrier spit, terminates the chain of islands. The spit extends approximately 12 km in a southeasterly direction with a width of about 2.5 km and encompasses three morphological zones typical of a barrier: shoreface/beach, 80–100 m wide, a zone with dune ridges, 0.3–1 km wide, and a 1.5–2 km wide back barrier salt marsh. The mean grain size of both beach and dune sediments is 0.150–0.200 mm. About 80% of the salt marsh deposits are minerogenic, 90% of which has sizes in clay and silt fractions (BARTHOLDY and PEJRUP, 1994). A fine grained sediment budget for the area shows that 85% of the accumulating material originates from the North Sea (BARTHOLDY and MADSEN, 1985).

Skallingen is a transgressive barrier and has "rolled over" at an average rate of 3 m a^{-1} during the last 200 years (AAGAARD *et al.,* 1995). Annual surveys during the last two decades show that shoreline retreat is still occurring at this rate. Erosion occurs intermittently associated with aperiodic, severe storm surges. As an example, the storm from the

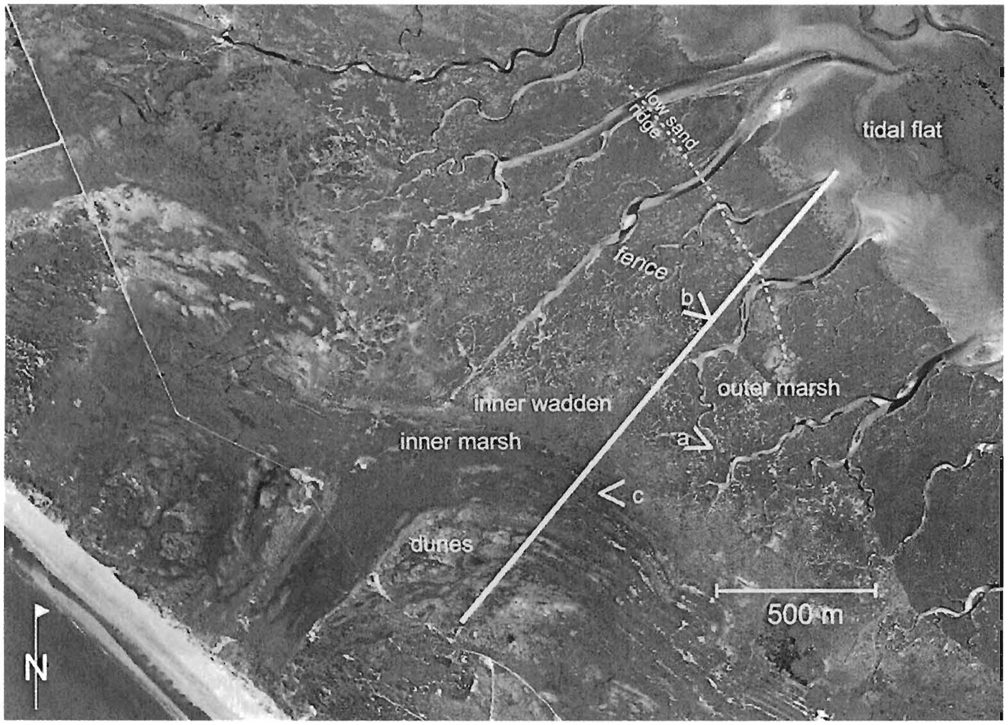

Figure 2. Ortho photo from 1995 showing the environment of the studied profile. a, b and c indicate locations of photos Fig. 3, Fig. 6 and Fig. 11 respectively.

southwest in January 1990 (and a second smaller surge in February) caused a dune recession of approximately 30 m. Water levels reached +4.13 m DOD (Danish Ordnance Datum) at Esbjerg and +3.72 DOD m at the Skallingen-shoreline.

The beach is backed by foredunes which are often scarped, indicating ongoing erosion. On the northern part of the barrier, the row of foredunes is very weak and irregular. In the central and southern parts, the foredunes are more or less continuous for about 7 km. Elevations are usually 3–7 m above the upper backshore (~ 5.5–9.5 m DOD), but 10–12 m high dunes are fairly common. Dune orientations generally follow two directions: One is aligned parallel to the beach, while the other is orientated more or less perpendicular to the former. The latter originates from numerous, former washover fans or breaches (AAGAARD *et al.,* 1995).

Today the back barrier is totally covered by salt marsh vegetation, on the inner part predominantly by *Puccinellia maritima* (*Juncus gerardii* near the dunes) and on the outer part *Halimione (Atriplex) portulacoides.* When the first investigations were conducted in 1931, the morphology and the vegetational coverage of the back barrier was different. Two zones of marsh vegetation had been established, one sheltered behind the foredunes—'the inner-marsh', c. 200 m wide—and another 'the outer-marsh', c. 600 wide, along a low sand ridge running more or less parallel to the eastern edge of the peninsula. The origin of the sand ridge, which is about 50 m wide and rises only 35–45 cm above the surrounding marsh surface, is not known, but it is assumed to be an aeolian feature created along the edge of a large washover fan formed in the beginning of the last century (Figure 2). The area between the inner- and the outer-marsh was avoided by vegetation and resembled a sandy tidal flat, often being subjected to inundation. Therefore, this area was locally termed the 'inner-wadden', approximately 300 m wide. The differences in level between the inner-wadden and the inner/outer-marshes are very subtle and can only be distinguished through accurate surveying. However, different vegetation species in these three zones clearly separate them to the human eye and on aerial photographs. The salt marsh deposits are thin, about 0.2–0.5 m (NIELSEN and NIELSEN, 1973) (Figure 3). The marsh surface which has an elevation of approximately 1 m above mean sea level (~ <1.1 m DOD) is flooded during autumn and winter storms and occasionally by spring tide. A dense net of tidal creeks with a dendritic pattern drains the area.

Tides at Skallingen are semi diurnal with a diurnal inequality. The tidal range is about 1.7 m at springs and 1.3 m at neap. According to DAVIES (1964), the area is thus classified as micro tidal.

Strong southwesterly and westerly (onshore) winds generate sea levels of + 3.0 m DOD (or more), while offshore winds cause low sea levels. Wind set-up (surges) and set-down generated by onshore and offshore gales or storms, respectively, are thus of significant importance. Monthly mean sea-levels display an annual variation of about 0.25 m with high means during the late part of the year and low means during the spring months (DMI, 1970). These variations contribute to the fact that the erosional events at Skallingen are

Figure 3. A view toward northwest with the foredunes in the background (see < a on Fig. 2). The dominant surface vegetation is Puccinellia, and at the levees Halimione appears. The relatively thin layer of salt marsh superposing the original sand flat is clearly seen at the creek bank. The creek is close to the profile line (Photo J. Nielsen).

most frequent during the autumn/winter months when westerly storms are common and intense.

METHODS

The location of the surveyed profile was chosen after analysing the air photos. It covers all morphological zones typical and representative of several kilometres of Skallingen's back barrier (Figure 2). No major tidal creeks are cut by the line, only some minor creek branches. Along the 1850 m long cross section 0.5 m pegs were driven into the marsh surface at intervals of 100 m. In 1973 the levels of the peg-tops were surveyed with a Zeiss Opton Ni2 levelling instrument and related to Danish Ordnance Datum (DOD) with an estimated accuracy of ± 2 mm. The topography in between the pegs was measured tachymetrically and at every 25 m the thickness of the marsh deposit was found by digging onto a clean white sand flat which underlies all the salt marsh. The boundary between the fine grained, dark marsh deposits and the sand flat appears very sharp all through the cross section, and it is, therefore, possible to measure the salt marsh thickness with an accuracy of a few millimetres (Figure 4). Finally the distribution of dominating and subdominating plant species were described.

In 1998 most of the 1973 pegs were re-surveyed and the same procedure as mentioned above was implemented. This time levelling was conducted by using a total-station, Topcon GTS-701 (measurement accuracy: ± (2 mm + 2 ppm) m.s.e.). The thickness of the salt marsh deposit was measured every 100 m. Both surveys used in this study were conducted in May, which will minimize errors owing to shrinkage of the sediment package in the summer due to desiccation, (NEUHAUS *et al.,* 1999).

Analyses of sea level variations are based on records from Esbjerg Harbour about 10 km from the study area.

RESULTS

Geomorphology and Vegetation

The area behind the dune field is characterized by a low (1.5–2.5 m DOD), chaotic, topography of aeolian origin, Figure 2 and 5a (section a), covered by *Empetrum nigrum, Carex arenaria, Festuca rubra* and *Ammorphila arenaria* as dominant species. This zone is succeeded by mixed aeolian and marine features, dunes and beach ridges, section b in Figure 5a, with a similar elevation and vegetation as found in section a. Morphologically, however, section b is characterized by low parallel ridges following the pattern of former dune formations and washover channels (Figure 2). The age of this ridge-zone is unknown, but presumably formed on the lee side of the dunes shortly after they were established more than 200 years ago.

The level of the transition zone, the inner-marsh, between the beach ridges and inner-wadden (section c, d and e on Figure 5a) is now approximately + 1.3 m DOD and the surface is covered mainly by *Juncus gerardii.* Few isolated beach ridges are included in this zone. The ridges are only 5–10 cm higher than the surrounding marsh but their outline is easily recognized by the presence of *Festuca rubra.* The inner-wadden has a level of ≈ +0.9 m DOD, and is partly dissected by the innermost branches of the tidal creeks. Areas in between

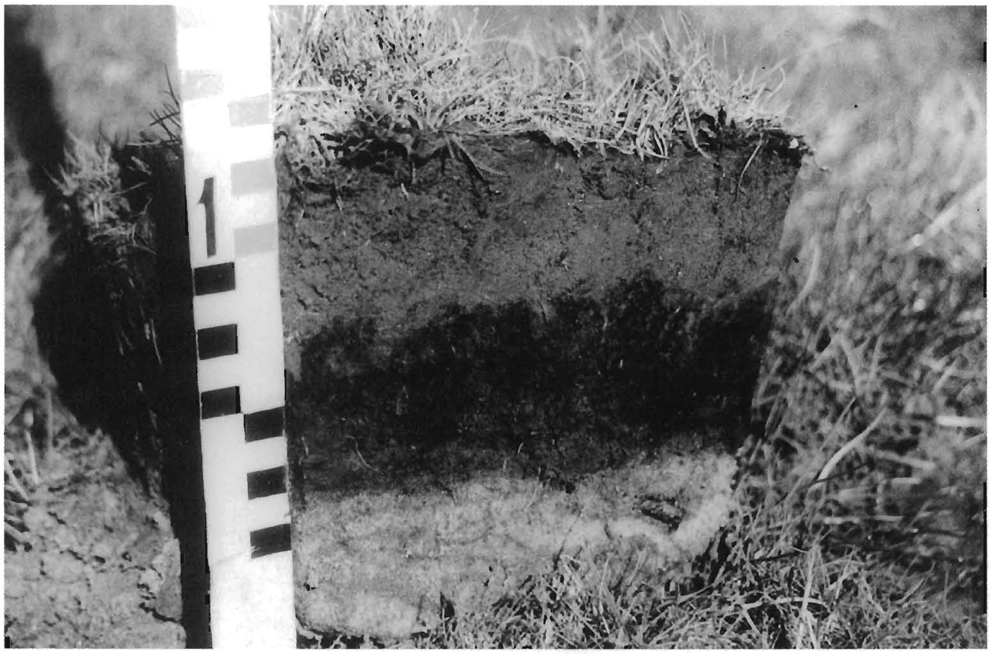

Figure 4. Block cut out of the inner wadden. The white sandy sediment at the bottom of the block belongs to the initial, almost horizontal, sand flat underlying all the salt marsh of Skallingen. (Photo N. Nielsen)

the creeks still indicate waterlogged environments and a few depressions mark the locations of former salt pans. The vegetation changes here to more salt-tolerant species like *Puccinellia maritima, Salicornia europaea, Suaeda maritima* and *Limonium vulgare. Spartina townsendii* occurs in several minor creeks and in shallow ponds. Moving eastward the vegetation changes gradually indicating an increase of the salt marsh elevation to a little more than 1 m above DOD, the level of the outer-marsh. *Salicornia europaea* and *Suaeda maritima* disappear and the occurrence of the species *Puccinellia maritima* and *Halimione portulacoides* becomes more frequent until totally dominating. Subdominant species on the outer-marsh are *Limonium vulgare, Aster tripolium, Plantago maritima, Triglochin maritima* and *Artemisia maritima.*

The outer marsh is separated into two zones by a fence (Figure 2) preventing grazing cattle from entering the outer part of the outer-marsh (if a storm surge occurs the cattle try to escape out there and may get caught by the rising sea). West of the fence the vegetation is dominated by *Puccinellia maritima* (Figures 5 and 6). East of the fence *Halimione portulacoides* characterizes the surface almost until the edge of the salt marsh. In this zone *Festuca rubra* and *Elymus arenarius* outline a low sand ridge (elevation up to 1.4 m DOD).

The outer-marsh is dissected by a pronounced system of tidal creeks (Figure 3), and small but distinct levees typically covered by *Artemisia maritima* and *Puccinellia maritima* have developed along the creeks.

The transition between salt marsh and tidal flat has no or only a weakly developed cliff. The inter tidal mud flat *per se* is nearly horizontal at a level corresponding to the mean high water line (+ 0.6 m DOD) while the eastern part slopes gently towards Hobo Dyb. Salt-tolerant species like *Spartina townsendii,* which often appears in clumps, plus *Puccinellia maritima* and *Salicornia europaea* grow more or less exclusively here.

From Figure 5a it is striking that the zonation of the vegetation is determined only by small differences (10–20 cm) in the surface elevations.

Accretion/Erosion on the Salt Marsh

The development of the salt marsh from 1973 to 1998 is demonstrated in Figure 5b, and the net changes of the surface in Figure 5c. Generally, accumulation has occurred in three morphological units: 1) where the marsh has expanded towards the east, 2) on the marsh, mostly within the inner- and outer-marsh and less pronounced on the inner-wadden and 3) in shape of levees along the creeks. Evidently no net erosion happens on the continuous marsh surfaces. Negative values (erosion) only occur as spikes on the profile (see Figure 5c) in connection with new creek formations or where old creeks are deepened or have moved sideways.

Surface changes and accretion rates from 1973 to 1998, using the selected zones from the 1973-profile, are shown in Table 1, demonstrating the actual profile values and the profile values omitting all negative figures, *i.e.* spots indicating erosion. The last mentioned set of values are estimated to be more real in assessment of the vertical growth of the marsh surface representing an area, as negative values solely is connected to creek-erosion, which as such only represent confined areas.

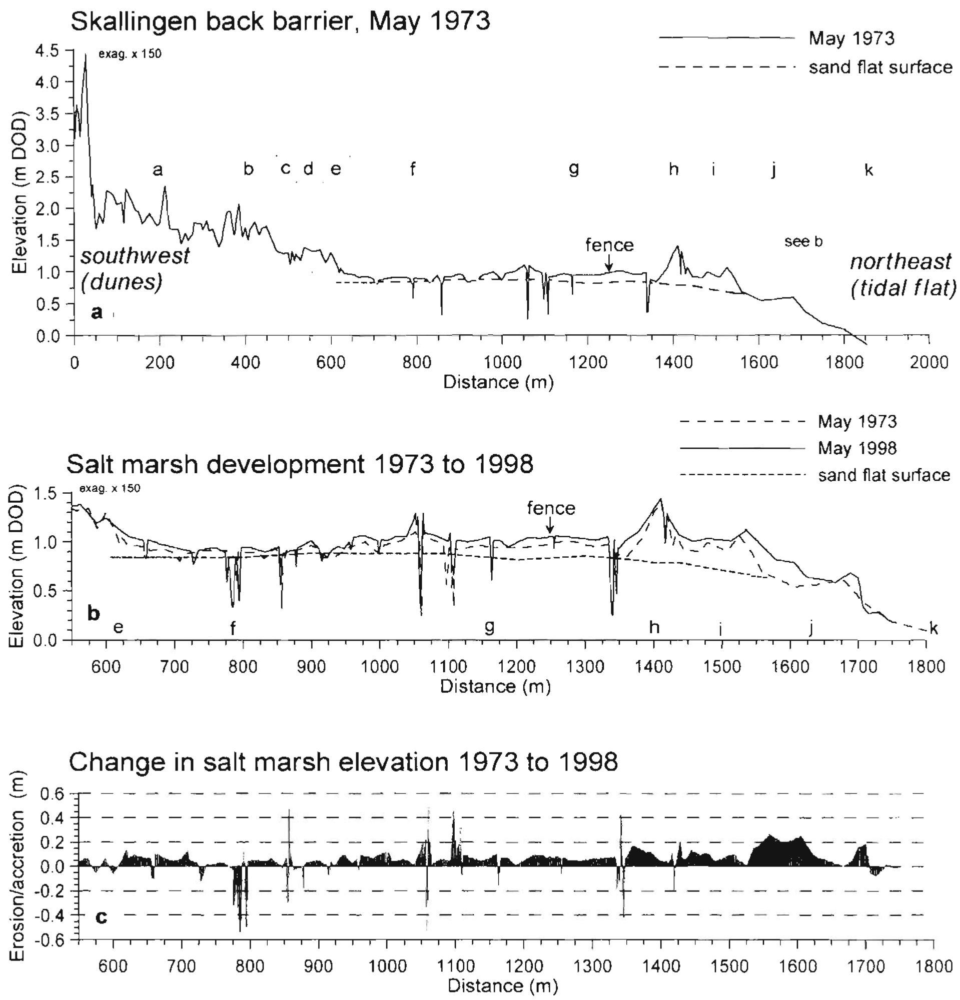

Figure 5. a. The profile surveyed in 1973. The different marsh-zones and the cattle fence discussed in the text are indicated. b. 25-year profile development. c. Change in salt marsh elevation from 1973 to 1998. Spikes are due to levee formation (positive) or creek erosion (negative).

Since 1973 the salt marsh has grown laterally about 61 m (almost 2.4 m a^{-1}) out onto the tidal flat and the overall elevation has increased from 0.94 m to 0.99 m DOD in average, which corresponds to a mean sediment accumulation of 2.51 mm a^{-1}. However, this growth includes substantial variations regarding the different zones. There is a significant difference in the accretion rate between the lower and higher part of the marsh. The rates on the inner and outer marsh (creek erosion excluded) are around 3 mm a^{-1} with maximum values of 3.3 to 3.5 mm a^{-1} for the highest part of the outer marsh. The low inner-wadden only shows an accretion rate about the half (1.7 mm a^{-1}).

The accretion rate in section (h)—the sand ridge—only occurs on the flanks of the ridge while the crest height itself is almost unaffected, presumably as a result of fewer inundations (Figures 5b and c).

The vegetational influence of the marsh growth is studied around the cattle fence (Figure 6), 1254 m from the starting point of the profile (Figure 2), and by comparing the inner wadden to the early established marsh area at the outer marsh. During periods with inundation in the summer time Puccinellia is supposed to be most efficient in trapping suspended sediment because of the density of its fine leaves. During the winter the leaves are still fixed to the roots, and become included in the marsh sediment. Its effectiveness as sediment catcher, however, is at a minimum as the withered leaves lie flat on the ground. Furthermore, the Puccinellia is situated where the cattle grazes. This cropping reduces the capability to restrain the sediment and lesser amount of biomass is available for marsh building. East of the fence, where cattle is prevented, Halimione dominates. It is a bushy plant, approximately 30 cm high, which all the year round is very effective as shelter for suspended sediment during periods with inundation. However, as the plant is deciduous the

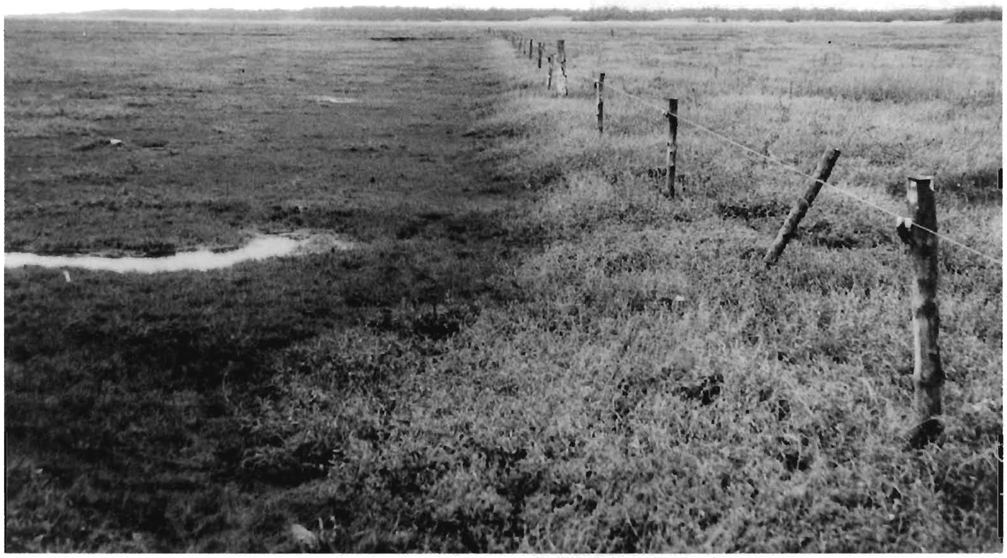

Figure 6. The cattle fence on the outer marsh separates two different types of vegetation, dominated by Puccinellia and Halimione west (left on the photo) and east of the fence, respectively (see ·: b on Fig. 2). (Photo N.Nielsen)

leaves are swept away during high waters why they only contribute to a minor degree as an organic element in the marsh growth.

For the reasons mentioned above, it might be expected that the rate of accretion are different in the two types of vegetation. The areas within 50 m on each side of the fence are comparable as they are homogeneous concerning the geomorphology (*i.e.* no creeks) and sediments. The observed mean increase of the marsh elevation within the two areas from 1973–1998 were 0.054 m and 0.079 m (Std. Dev. 0.01) east and west of the fence respectively (Figure 7). However, the mean elevations in 1973 east and west of the fence were 0.989 m DOD and 0.955 m DOD respectively both with a Std. Dev. of 0.01 m., which means that the difference in levels between the two areas is reduced from 0.034 m in 1973 to 0.008 m in 1998.

Hydrography and Wind Conditions

A tide gauge in the Esbjerg harbour (Figure 1) has been operating since 1890 (Figure 8). Despite a large fluctuation of annual mean sea-levels, the average rise of the sea-level from 1890 to 1998 can be calculated to 1.26 mm a^{-1}, which correspond to the global sea-level rise proposed by GORNITZ and LEBEDEFF (1987) and GORNITZ (1995). A 19-year moving average of the annual sea-levels indicates that the rise of the sea-level is of the same order until 1960 after which the rate decreases to 0.7 mm a^{-1} until 1980. Then the mean sea wa-

Table 1. *Development of the surface eevation and accretion rates from 1973 to 1998, using the selected zone borders frrom the 1973-profile (see Fig. 5).*

Salt Marsh Zone (see Fig. 5)	1973 Mean Level m (DOD)	Total (all values) 1998: Mean Level m (DOD)	Total (all values) 1998: Mean Accre. mm a^{-1} 1973–1998	Only Values > = 0, 1998: Mean Level m (DOD)	Only Values > = 0, 1998: Mean Accre. mm a^{-1} 1973–1998
(e) inner marsh 580–645 m	0.97	1.04	2.68	1.06	3.16
(f) inner wadden 645–950 m	0.89	0.95	0.23	0.93	1.73
(g) (west of fence) outer marsh 950–1250 m	0.95	1.01	2.69	1.03	2.98
(g) (east of fence) outer marsh 1250–1395 m	0.94	1.01	2.75	1.05	3.47
(h) sand ridge 1395–1420 m	1.28	1.31	1.26	1.32	1.90
(i) outer marsh 1420–1535 m	0.97	1.05	3.25	1.05	3.25
(j) new marsh 1535–1610 m	0.68	0.90	8.64	0.90	8.64

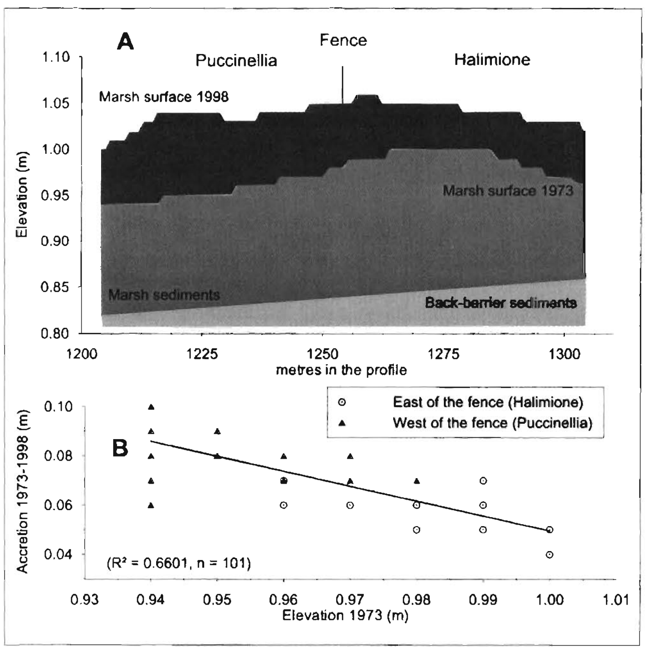

Figure 7. A. Deposition of sediment during the last 25 years in a 50 m section on both side of the fence. B. The development shows a significant correlation between the elevation and accretion in spite of differences of the vegetation and initial levels.

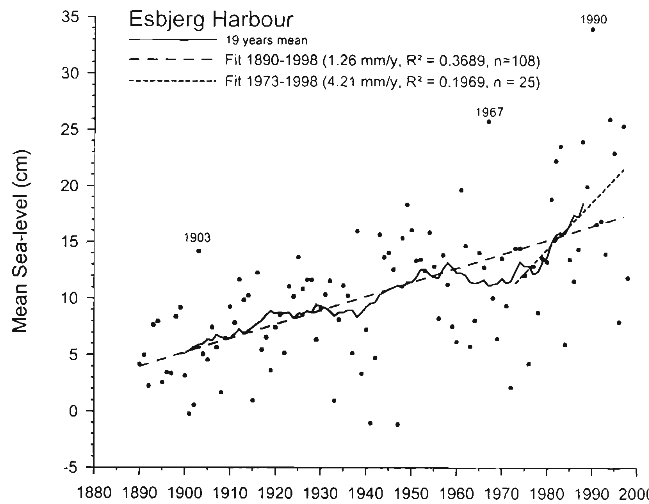

Figure 8. Yearly mean sea-level since 1890 (Esbjerg Harbour) and the mean trend during the last century. The mean sea-level rise during the last 25 years is also indicated.

ter-level increases again, but now at a much higher rate—indicated by 4.21 mm a^{-1} (1973–1998). Looking into details, the sea-level shows alternating periods of rises (1890–1920 and 1940–1960) and stabilisations (1920–1940 and 1960–1980). In spite that the Esbjerg sea-level record covers a period of more than one hundred years the mean sea-level rise is strongly affected by extraordinary high sea-levels. If calculating the mean sea-level rise between 1890 and 1990 the rate has been 1.11 mm a^{-1}; choosing 1890 to 1997 the rate is 1.26 mm a^{-1}.

A German investigation from 1990 indicated that the tidal range along the German North Sea coast has increased since the mid 1950s, mostly in the southern part and less toward the north (FÜHRBÖTER *et al.*, 1990). Similar studies, but not as systematic, have been conducted concerning tidal data from Esbjerg and also here increasing tidal harmonic constants have been observed (LUNDBAK, 1945; HVIDBJERG-KNUDSEN *et al.*, 1998). Since 1874 all storm surges have been recorded at Esbjerg concerning both the development of the sea level and the wind condition during each surge (Figure 9). In this part of the Denmark a sea-level more than 3.00 m DOD is regarded as a storm surge. This level corresponds to the elevation of the toe of the frontal dunes on the barrier. Storm surge frequencies vary a lot during the period, but with a tendency towards an increasing rate in the last 20 years. It is important to notice that wind directions from southwest and west southwest are responsible for most storm surges and the most intense ones. The reason for that may be explained as a consequence of geomorphic outline of the northern part of the barrier chain in the Danish Wadden Sea.

An examination of the extreme sea levels at Esbjerg indicates that both the extreme high and low water levels have increased by HW: + 6.8 mm and LW: − 3.3 mm per year respectively during the last 125 years (DUUN-CHRISTENSEN, 1990).

On the basis of wind recordings from Vyl lightship outside Grådyb (1921–1938 and 1946–1978), Sædden Strand lighthouse at Esbjerg (1968–1991) and Blåvand lighthouse since 1982 it is possible to describe the wind conditions until now affecting Skallingen since the 1930s. It is characteristic that the wind energy has increased and from the last part of the 1970s the prevailing wind direction has changed from northwest to west and even to west-southwest. This change may be the explanation of the increased extreme sea water-levels and storm surges at Esbjerg (AAGAARD *et al.*, 1995)

Since 1976 the Esbjerg Harbour authority has monitored sea-levels at every 15 min. Based on these data, which include both the increasing mean sea level and the increasing tidal range, inundation frequencies have been calculated in hours per year for two significant levels: 0.90 m and 1.10 m DOD, (Figure 10). However, the increase of duration should be regarded with cautions as high wind speeds from a westerly direction generate a sea-level at Esbjerg, which is higher than at Skallingen because of local wind set-up and this difference growths with increasing wind speed. In the 1990-storm surge the maximum sea level at Esbjerg was 0.41 m higher than at Skallingen. During periods with moderate wind conditions the sea-level is almost identical at the two sites.

DISCUSSION

A fundamental prerequisite of salt marsh growth is that the marsh is inundated from time to time allowing sediments to be transported onto surfaces covered by vegetation. Comprehensive investigations by FRENCH and STODDART (1992)

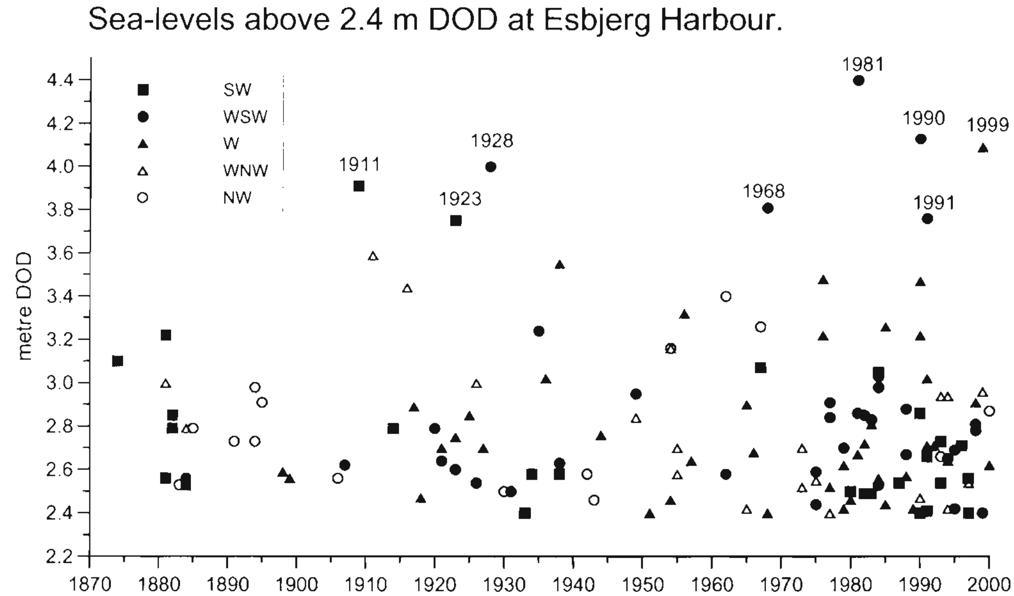

Figure 9. Storm surge occurrences since 1874 at Esbjerg and coincident wind directions. Only the highest sea-level during each event is indicated. Notice that the most extreme sea levels occur during winds from west-southwest. The storm surge frequencies have increased during the last 25 years. Sea-level above 3.00 m DOD is locally regarded as storm surge level.

from an even sloping salt marsh indicated that about 60 % of the sea water exchange during extraordinary high water conditions happened through the creeks, while 40 % took place as sheet flow. Consequently the rate of accretion is inversely proportional to the distance from the creeks and the edge of the marsh and directly proportional to the frequency of inundation, *i.e.* largest in the lowest part of the marsh (FRENCH and SPENCER, 1993).

The marsh profile on Skallingen is, however, somewhat different from the one described at Hut Marsh, Norfolk (FRENCH and SPENCER, 1993) because of the low sand ridge in the outer marsh area. The profile studied is located so that it does not intersect major creeks. Therefore, the profile section east of the low sand ridge slopes rather gently toward the marsh edge (Figure 5). This part of the profile is consequently dominated by sheet flow and the sediment is mainly clay and silt. West of the low sand ridge the profile is characterized by a more heterogeneous surface morphology and sediments as the line cuts several minor creeks some with well-developed levees.

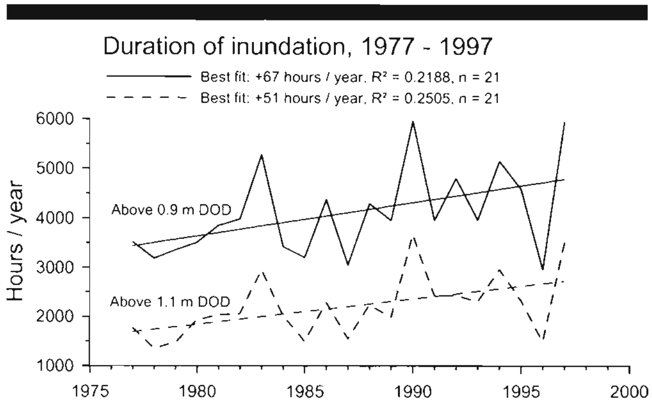

Figure 10. Inundation frequencies calculated in percent per year for every 10 cm exceeding 0.90 m DOD. 0.90 m and 1.10 m DOD are typical values for the inner and outer marsh respectively.

Our investigation indicates that during the last 25 years the overall rate of sedimentation in the profile line is amazingly homogeneous. When calculating mean values for longer profile sections of marsh surfaces, which have been covered by vegetation all through the observation period, it has been about 3 mm a^{-1}, Table 2. Since 1973 new salt marsh formation has occurred in section (j) (Figure 5) with an average sedimentation rate of about 8 mm a^{-1}. It is not known if this high value is a result of the higher accretion potential because of the lower elevation or other mechanisms of sedimentation are involved. According to field observations, sediments rafted by sea ice may be important (ANDERSON, 1983; DIONNE, 1984, 1988; PEJRUP and ANDERSEN, 2000). During winters, the North Sea never or very seldom freezes up, but when the intertidal mud flats is covered by a thin sheet of sea water it may cool down quickly and freeze. At low water, the sea ice or ice floes may come to rest on the sediment which may freeze to the ice. If this process repeats, a sandwich of ice and sediment gradually develops. Frequently, but not every spring, sediment cakes up to 1–2 m in diameter and 5–7 cm thick, often containing mussels *(Mytilus edulis and Cardium edule)*, are seen on top of the vegetation 100–200 m from the marsh edge. After one or two growing season the vegetation penetrates and hide the cakes. Sediment transported by sea ice may explain the heaps in section (i) on the profile (Figure 5).

Table 2. *Total thicknesses of salt marsh layer in different profile section measured by digging into the sand flat. Accretions rates found by different methods are listed.*

Digging Point On The Salt Marsh (see Fig. 5)	Appearance Of Salt Marsh Development Year	Total Thickness Of Salt Marsh mm		Accretion Rate mm a^{-1}		Accretion Rate (surveyed) mm a^{-1} 1973–1998	Accretion Rate Since 1980 Dated by ^{210}Pb mm a^{-1}
		1973	1998	1973	1998		
(e) inner-marsh 600 m	1940	85		2.6		3.2	3.1
(f) inner-wadden 800 m	1950	50	100	2.2	2.1	1.7	
(g) outer marsh (west) 1300 m	1940	110	160	3.3	2.8	3.5	1.6
(i) outer marsh (east) 1500 m	1900	220	290	3.0	3.0	3.3	3.8
(j) outer marsh (east) 1600 m	1973		170		6.8	8.6	

West of the low sand ridge in section (g) on Figure 5 remnants of ice rafted sediment have not been found, presumably because of the low sand ridge. During high water situations inundation occurs primarily through the dendritic creek system, and deposited sediments vary from fine sand on the levees to silt and clay on the marsh surfaces. In general, it has not been possible to demonstrate a correlation between elevation and accretion over longer distances, partly because the levels only vary about 10 cm, and partly because the highest sedimentation rates are connected to the levees, which also represent the highest elevations (Figure 5).

There is a significant correlation between the elevation of the marsh in the 100 m profile section around the fence in 1973 and the accretion during the following 25 years (Figure 7). Evidently there is only a small change in the trend of the relationship from one side of the fence to the other. Furthermore the duration of inundation estimated from sea water-level records in Esbjerg (from 1977) reduced with the mean increase of marsh surface level, indicate that in spite of the small difference of the initial surface levels the western part (Pucinellia-covered) of the profile has been inundated about 100 hours more than the eastern part (Halimione-covered) (Figure 10). Consequently this study shows that the actual levels, and therefore the inundation frequency, is more important for the marsh growth than differences in vegetation.

In spite of the fact that the inner wadden, section (f) in Figure 5, is today covered by vegetation, its appearance is still distinct from the surrounding marsh areas in respect of density and species of vegetation. The surface here is less consolidated (firm), and has been broken by cattle treads and appears as a tufted field (Figure 11). The incoherent vegetation cover reduces the ability to catch sediment when inundated. An additional explanation of the lower accretion rate (less than 2 mm a^{-1}) on this relatively low area, is that

Figure 11. Typical surface of the inner-wadden (see < c on Fig. 2). The cover of vegetation is less consolidated (firm), and has been broken by cattle treads and appears as a tufted field. (Photo N.Nielsen)

the small creek branches which now penetrate the area only have limited capacity to transport sediment to the area.

By comparing the studies 1973–1998 with evidences on topographical maps from 1870 and 1910 and field studies in 1933–1953 (JAKOBSEN, 1954), it is possible to estimate the rate of sedimentation from the initial phases of the Skallingen salt marsh development (Table 2). In all sections, apart from (f), the inner wadden, the average rates of sedimentation are slightly lower compared to the last 25 years. The difference may, however, be explained by differences in measuring methods and/or compaction, dewatering and digestion of organic matters. Rates before 1973 have been estimated from digging in single points, and the time when the marsh development started is estimated. The profile method, on the other hand, gives average values in selected zones over a well defined period of time. Results from different methods used become further pronounced where the surface morphology is heterogeneous as in young marsh areas (f and g) west of the low sand ridge. In the profile method, the formation of levees provides a positive contribution to the increase in elevation; the measuring in point may not includes this. Within the inner wadden (f) the micro relief variates more than 10 cm, which also may increase the possibility of misinterpretation. It may therefore be concluded that no significant difference of the accretion rate has happened during the history of the Skallingen salt marsh development.

In 1931 marker layers of coloured sand were established at several locations on the eastern part of Skallingen (NIELSEN, 1935). Salt marsh accretion upon these layers were recorded every year until 1954 (JAKOBSEN, 1954)—and subsequently forgotten. In 1998 some of the marker layers were discovered on the easternmost part of the marsh, about 200 m south of our line. Analyses and dating of the sediment columns on top of the old marker layer indicate that the accretion rate from 1931 to 1939 has been 7 mm a^{-1} and during the total period, 1931–1998, 3 mm a^{-1} (CHRISTIANSEN *et al.*, 2001—in press). The results correspond closely to our observations 1973–1998, where the accretion rate during the first years after salt marsh colonization, was recorded to about 8 mm a^{-1} simultaneously with 3 mm a^{-1} on already established marsh areas (Table 1).

An investigation in 1980 of heavy metal pollution conducted in the described profile (MADSEN, 1981; BARTHOLDY and MADSEN, 1985) included dating by the ^{210}Pb-method of the sediment 3 cm below the marsh surface at three locations, (Table 2). The ages were close to 10 years, which correspond to a sedimentation rate of about 3 mm a^{-1}, both at the innermarsh and at the outer marsh east of the low sand ridge. This equals our values. At one location, west of the low sand ridge, the value was found to be only the half (1.6 mm a^{-1}), which might be explained by the point-sampling.

To sum up about the accretion rates on the Skallingen marsh it may be concluded that 3 mm a^{-1} seems to be characteristic for the established salt marsh areas, 1–2 mm a^{-1} in the low and central part, and about 8 mm a^{-1} in newly developed areas at the edge of the marsh.

An important question is if the relation between the frequency of inundation and the marsh growth can keep pace with an accelerating sea level rise. When looking at the sea-level curve (Figure 8), and especially its large fluctuations, it is interesting that the values of the different accretion rates do not change significantly when they are calculated for different periods and by different methods. During the last 100 years the average rate of sedimentation has been 3 mm a^{-1}. In fact this is faster than the sea level rise for this part of the North Sea, which averagely has been 1.3 mm a^{-1} during the same period (Figure 8). If, however, the same figures are compared during the past 25 years the relationship has become different. The rate of accretion has stayed similar to the 100-year rate, 3 mm a^{-1}, while the sea level rise has increased to 4.2 mm a^{-1}. If this tendency continues for a longer period of time, the scenery turns a bit more gloomy. Today no stagnation or degradation of the salt marsh is visible in any of the subzones of the profile studied.

CONCLUSION

(1) Both during the last 25 years and since the marsh formation began in the beginning of the last century the overall vertical rate of sedimentation in the Skallingen marsh has been amazingly homogeneous. Measurements of vertical accretion from profiling, layer marker observations and ^{210}Pb dating all show a value of about 3 mm a^{-1}. An exception was found along the edge of the marsh, where new marsh has developed. Here the accretion rate was about 8 mm a^{-1}.

(2) There was no significant difference in the accretion rate in two neighbouring areas covered by Halimione and Puccinellia respectively. The correlation between the elevation of the salt marsh surfaces and the rate of sedimentation is more evident.

(3) The study indicate that the rate of sedimentation since 1931 has been almost uniform at 3 mm a^{-1}, and is relatively insensitive to decadal-scale variations in mean sea-level and/or storminess.

(4) The average rate of sedimentation is well above the average sea-level rise of 1.3 mm a^{-1} during the last century. Concerning the last 25 years the accretion rate is still 3 mm a^{-1}, while the sea-level rise has increased to 4.2 mm a^{-1}.

(5) In spite of 3) no degeneration of salt marsh on Skallingen has been observed.

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LITERATURE CITED

AAGAARD, T.; NIELSEN, N., and NIELSEN, J., 1995. Skallingen—origin and evolution of a barrier spit. *Meddelelser fra Skalling Laboratoriet*, XXXV, 85p.

ALLEN, J.R.L., 1990. Salt marsh growth and stratification: a numerical model with special reference to the Severn Estuary, S. W Britain. *Marine Geology* 95, 77–96.

ALLEN, J.R.L. and PYE, K., 1992. Coastal salt marsh: their nature and importance. *In:* ALLEN, J.R.L. and PYE, K. (eds.), *Salt Marshes:*

Morphodynamics, Conservation and Engineering Significance, Cambridge University Press, pp. 1–18.

ALLEN, J.R.L. and DUFFY, M.J., 1998. Temporal and spatial depositional patterns in the Severn Estuary, Southwest Britania; Intertidal Studies at spring-neap and seasonal scales, 1991–1993. *Marine Geology*, 146, 147–171.

ANDERSON, F.E., 1983. The northern muddy intertidal: seasonal factors controlling erosion and deposition—a review. *Canadian Journal of Fisheries and Aquatic Science*, 40 (1), 1–72.

BARTHOLDY, J., 1997. The back barrier sediments of Skallingen Peninsula, Denmark. *Danish Journal of Geography*, 97, 11–32.

BARTHOLDY, J. and MADSEN, P.P., 1985. Accumulation of fine-grained material in a Danish tidal area. *Marine Geology*, 67, 121–137.

BARTHOLDY, J. and PEJRUP, M., 1994. Holocene evolution of the Danish Wadden Sea. *Senkenbergiana Maritima*, 24, 187–209.

BIRD, E.C.F., 1993. *Submerging Coasts*. New York: Wiley. 184p.

CARLING, P.A., 1982. Temporal and spatial variation in intertidal sedimentation rates. *Sedimentology*, 29, 17–23.

CHRISTIANSEN, C.; BARTHOLDY, J., and KUNZENDORF, 2001. Effect of morphological changes on metal accumulation in a salt marsh sediment of the Skallingen peninsula, Denmark. *Wetland Ecology and Management*. In press.

CRAFT, C.B.; SENECA, E.D., and BROOME, S.W., 1993. Vertical accretion in microtidal regularly and irregularly flooded estuarine marshes. *Estuarine and Coastal Shelf Science*, 37, 371–86.

DAVIS, J.L., 1964. A morphogenetic approach to World shorelines. *Zeitschift für Geomorphologie*, 8, 127–142.

DAVIS, R.A.; BARTHOLDY, J.; PEJRUP, M., and NIELSEN, N., 1997. Stratigraphy of Skallingen—a Holocene Barrier in the Danish Wadden Sea. *Aarhus Geoscience*, 7, 35–48.

DIONNE, J.C., 1984. An estimate of ice-drifted sediments based on mud content of the ice cover at Montagny, St. Lawrence Estuary. *Marine Geology*, 54, (1/4), 149–166.

DIONNE, J.C., 1988. Characteristic features of modern tidal flats in cold regions. *In:* DE BOER, P.L.; VAN GELDER, A., and NIO, S.D. (eds), *Tide-influenced Sedimentary Environments and Facies*. Dordrecht: Reidel, pp. 301–332.

DMI, 1970. Middelvandstand og dens ændringer ved de danske kyster, *DMI*, 23, 24p.

DUNN-CHRISTENSEN, J.T., 1990. Langtidsvariationer af havspejlet ved de danske kyster. *Præsentationer Ved Det Sjette Danske Havforskermøde*, 37–47.

ESSELINK, P.; DIJKEMA, K.S.; RENTS, S., and HAGEMAN, G., 1998. Vertical accretion and profile changes in abandoned man-made tidal marshes in the Dollard Estuary, The Netherlands. *Journal of Coastal Research*, 14, 570–582.

FRENCH, J.R., 1991. Eustatic and neotectonic controls on salt marsh sedimentation. *In:* KNAUS, N.C.; GINGERICH, K.J., and KRIEBLE, D.L. (eds.), *Coastal Sediments '91*. New York: American Society of Civil Engineers, pp. 1223–36.

FRENCH, J.R., 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated sea level rise, North Norfolk, UK. *Earth Surface Processes and Landforms* 18, 63–81.

FRENCH, J.R., 1994. Tide-dominated coastal wetlands and accelerated sea-level rise: a NW European perspective. *In:* (ed.), *Journal of Coastal Research, Special Issue*, pp. 22,

FRENCH, J.R. and SPENCER, T., 1993. Dynamics of sedimentation in a tide-dominated back barrier salt marsh, Norfolk, UK. *Marine Geology*, 110, 315–31.

FRENCH, J.R.; SPENCER, T., and REED, D.J., 1994a. Geomorphic response to sea level rise: existing evidence and further impacts. *Earth Surface Processes and Landforms*, 20, 1–6.

FRENCH, J.R., and STODDART, D.R., 1992. Hydrodymanics of salt marsh creek systems: implications for salt marsh morphological development and material exchange. *Earth Surface Processes and Landforms*, 17, 235–252.

FÜHRBÖTER, A.; DETTE, H.H., and TÖPPE, A., 1990. Recent change in the sea level. *Proceedings Skagen Symposium*, pp. 146–159.

GORNITZ, V., 1995. Sea-level rise. A review of recent past and near-future trends. *Earth Surface Processes and Landforms*, 20, 7–20.

GORNITZ, V. and LEBEDEFF, S., 1987. Global sea level changes during the past century. *In:* NUMMEDAL, D.; PILKEY, O.H., and HOWARD, J.D. (eds.), *Sea Level Fluctuation and Coastal Evolution*, SEPM Spec. Publ. 41, pp. 3–16.

HARRISON, E.Z. and BLOOM, A.L., 1977. Sedimentation rates on tidal salt marshes in Connecticut. *Journal of Sedimentary Petrology*, 47, 1484–1490.

HVIDBJERG-KNUDSEN, M.; BOLDING, K.; NIELSEN, J.W., and BRINKKJÆR, O., 1998. Analyse af tidevand i Esbjerg, *Dansk Hydraulisk Institut*, 49p.

IVERSEN, J., 1954. The zonation of the salt marsh vegetation of Skallingen in 1931–34 and 1952. *Meddelelser fra Skalling-Laboratoriet*, XIV, 113–118.

JACOBSEN, N.K., 1969. Landformerne. *Meddelelser fra Skalling-laboratoriet*, 22, 1–23.

JAKOBSEN, B., 1953. Landskabsudviklingen i Skallingmarsken. *Danish Journal of Geography*, 52, 147–158.

JAKOBSEN, B., 1954. The tidal area in south-western Jutland and the processes of salt marsh formation. *Danish Journal of Geography* 53, 49–61.

JAKOBSEN, B., 1964. Vadehavets morfologi. *Folia Geographica Danica*, Tom XI, 176 p.

KIRCHNER, G. and EHLERS, H., 1998. Sediment geochronology in changing coastal environments: potentials and limitations of 137Cs and 210Pb methods. *Journal of Coastal Research*, 14, 483–492.

LARSEN, E., 1951. Studies on the soil fauna of Skallingen. *Oikos*, 3 (2), 166–192.

LETZSCH, W.S., 1983. Seven year's measurement of deposition and erosion. Holocene salt marsh, Sapelo Island, Georgia. *Senckenbergiana Maritima*, 15, 157–165.

LUNDBAK A., 1945. Vadehavets Hydrografi. Unpubl. report. Copenhagen, 87p.

MADSEN, P.P., 1981. Accumulation rates of heavy metals determined by ^{210}Pb dating: Experience from a marsh area in Ho Bay. *Rapport Procés-Verbaux de Réunion. Conseil International l'Exploration de la Mer*, 181, pp. 59–63.

MARKER, M.E., 1967. The Dee Estuary: its progressive silting and salt marsh development. *Transaction Instititute British Geographus*, 41, 65–71

MØLLER, J.T., 1964. Morphological elements of river and flat coast in a tidal landscape with special reference to the hydrography and the influence of the vegetation. *Meddelelser fra Skalling-laboratoriet*, 10, 148p.

NEUHAUS, R.; STELTER, T., and KIEHL, K., 1999. Sedimentation in Salt Marshes Affected by Grazing Regime, Topographical Patterns and Regional Differences. *Senckenbergiana*, 29, 113–116.

NIELSEN, J. and NIELSEN, N., 1973. Skallingen, Niveauforholdene på det marine forland. *Geo-Noter*, 2, 27–30.

NIELSEN, N., 1935. Eine Methode zur exacten Sedimentatonsmessung. *Meddelelser fra Skalling-Laboratoriet*, I, 97p.

ORSON, R.; PANAGEOTOU, W., and LEATHERMAN, S.P., 1985. Response of tidal salt marshes of the U.S. Atlantic and Gulf coast to rising sea level. *Journal of Coastal Research*, 1, 29–37.

PEJRUP, M., 1981. Bottom sediments in Ho Bugt—a Wadden Sea environment. *Danish Journal of Geograpy*, 81, 11–16.

PEJRUP, M. and ANDERSEN, T.J., 2000. The influence of ice on sediment transport, deposition and reworking in a temperate mudflat area, the Danish Wadden Sea. *Continental Shelf Research*, 20, 1621–1634.

PETHICK, J.S., 1981. Long term accretion rates on tidal salt marshes. *Journal of Sedimentary Petrology* 51, 571–77.

REED, D.J., 1988. Sediment dynamics and deposition on a retreating coastal salt marsh. *Eustarine, Coastal and Shelf Science*, 26, 67–79.

REED, D.J., 1990. The impact of sea level rise on coastal salt marshes. *Progress in Physical Geography*, 14, 465–81.

RICHARD, G.A., 1978. Seasonal and environmental variations in sediment accretion in a Long Island salt marsh. *Estuaries*, 1, 29–35.

ROMAN, C.T.; PECK, J.A.; ALLEN, J.R.; KING, J.W., and APPLEBY, P.G., 1997. Accretion of a New England (U.S.A.) salt marsh to inlet migration, storms, and sea level rise. *Estuarine, Coastal and Shelf Science*, 45, 717–727.

STEERS, J.A., 1938. The rate of sedimentation on salt marshes on Scolt Head Island, Norfolk. *Geological Magazine*, 75, 26–39.

STEVENSON, R.E. and EMERY, K.O., 1958. Marshlands at Newport Bay, California. *Occasional Papers Allen Hancock Foundation* 20, 1–109.

STEVENSON, J.C.; WARD, L.G., and KEARNEY, M.S., 1986. Vertical accretion in marshes with varying rates of sea level rise. *In:* WOLFE, D.A. (ed.): *Estuarine Variability*. Orlando: Academic, pp. 241–260.

VILES, H. and SPENCER, T., 1995. *Coastal Problems, Geomorphology, Ecology and Society at the Coast.* London: Edward Arnold, 350p.