IMPACT PROGNOSIS FOR SALT MARSHES FROM SUBSIDENCE BY GAS EXTRACTION IN THE WADDEN SEA

KEES S. DIJKEMA

Made in United States of America
Reprinted from JOURNAL OF COASTAL RESEARCH
Vol. 13, No. 4, Fall 1997

Journal of Coastal Research	13	4	1294–1304	Fort Lauderdale, Florida	Fall 1997

Impact Prognosis for Salt Marshes from Subsidence by Gas Extraction in the Wadden Sea

Kees S. Dijkema

DLO Institute for Forestry and Nature Research (IBN)
P.O. Box 167
NL 1790 AD Den Burg, The Netherlands

ABSTRACT

DIJKEMA, K.S., 1997. Impact Prognosis for Salt Marshes from Subsidence by Gas Extraction in the Wadden Sea. *Journal of Coastal Research*, 13(4), 1294–1304. Fort Lauderdale (Florida), ISSN 0749-0208.

Subsidence will occur as a result of planned gas extraction activities in the Netherlands Wadden Sea (North-west Europe). The effects of subsidence on salt marshes are comparable to the effects of a rise in sea level, which may become a world-wide threat to coastal marshes by affecting the marsh vegetation through an increased number of tidal floodings and an increase in wave energy. Comparison of the prognosis for subsidence with a large dataset on the accretion of various salt marshes over the past 25 years shows that accretion generally is expected to remain positive, even if at the same time sea level should rise by as much as 6 mm per year. In general, the salt marsh zone in the Wadden Sea can cope with subsidence and/or a sea level rise of 5 mm per year for barrier islands and 10 mm for the mainland, which is in the range of future sea level rise. This is an important marsh characteristic when considering its role for nature conservation and coastal protection. An accretional deficit is however expected in the pioneer zone in front of the salt marsh, which is situated on an elevation which is most affected by wave action and currents and lacks the protection of a closed vegetation cover. Vertical erosion in the pioneer zone will lead to horizontal cliff erosion of the salt marsh zone. This might become a general effect of future sea level rise on the world salt marsh resource. Existing management techniques in the pioneer zone of the Wadden Sea salt marshes (brushwood groynes which decrease wave energy and currents) can be optimized to increase sedimentation and vegetation settlement in this pioneer zone. Expectations for the impact of subsidence due to gas extraction on Netherlands salt marshes are in general not negative, if the local accretional balance is made a precondition for the rate of gas extraction. The effects have to be monitored.

ADDITIONAL INDEX WORDS: *Accretion, erosion, management, salt marsh, sea level, subsidence, Wadden Sea.*

INTRODUCTION

Salt marshes are a transitional sedimentary belt between the sea and terrestrial habitats, which were more extensive in former times and provided a continuous landscape along many low-lying coasts (DIJKEMA, 1987a, 1987b). Salt marshes are natural or semi-natural ecosystems, in which plant and animal communities develop in a close interaction with hydrological and geomorphological processes and with human exploitation (BAKKER *et al.*, 1993). Disappearance of the salt-marsh habitats will mean the loss of highly specialized plants and invertebrate animals. Salt marshes also provide resting, breeding and feeding grounds for substantial numbers of birds, many of them migratory. Salt marshes are essential to coastal protection (ERCHINGER, 1995).

Up till now, the areal extent of salt marshes in Europe in general and the Northwest-European Wadden Sea in particular has suffered most from major losses due to embankments (DIJKEMA *et al.*, 1984; DIJKEMA, 1987B; KONIG, 1987). In the future attention must be focused on the effects of enhanced sea level rise, which may become a worldwide threat to coastal marshes by affecting the marsh vegetation through an increased number of tidal floodings and an increase in wave energy. The survival of salt marshes depends on the accretional balances in both the marsh zone itself and the pioneer zone in front of the marsh (DIJKEMA *et al.*, 1990).

Subsidence will occur in the Netherlands Wadden Sea as a result of the proposed gas-extraction from various small reservoirs. The effects of subsidence on salt marshes will be comparable to the effects of a worldwide rise in sea level, except that the subsidence caused by gas extraction is localized and temporary. An impact prognosis for salt marshes from subsidence by gas extraction can therefore provide data on the effects of enhanced sea level rise. This study was carried out in 1993 as a compilation of data and literature of sediment and the sedimentation of salt marshes and tidal flats in the Wadden Sea (OOST and DIJKEMA, 1993).

SALT MARSHES IN THE WADDEN SEA: INTERACTIONS WITH SEDIMENTATION AND SEA LEVEL CHANGES

The Danish-German-Netherlands Wadden Sea harbours substantial areas of salt marsh. With 350 km² a first place in Europe is shared with Great Britain (DIJKEMA, 1990). 85 km² occurs in the Netherlands part of the Wadden Sea (only 3.5% of the total tidal area of 2,500 km²), divided into a barrier-type and a foreland-type of salt marsh (Figure 1). Natural mainland salt marshes have almost completely disap-

95289 received 12 November 1994; accepted in revision 29 October 1995; accepted in 2nd proof 7 July 1997.

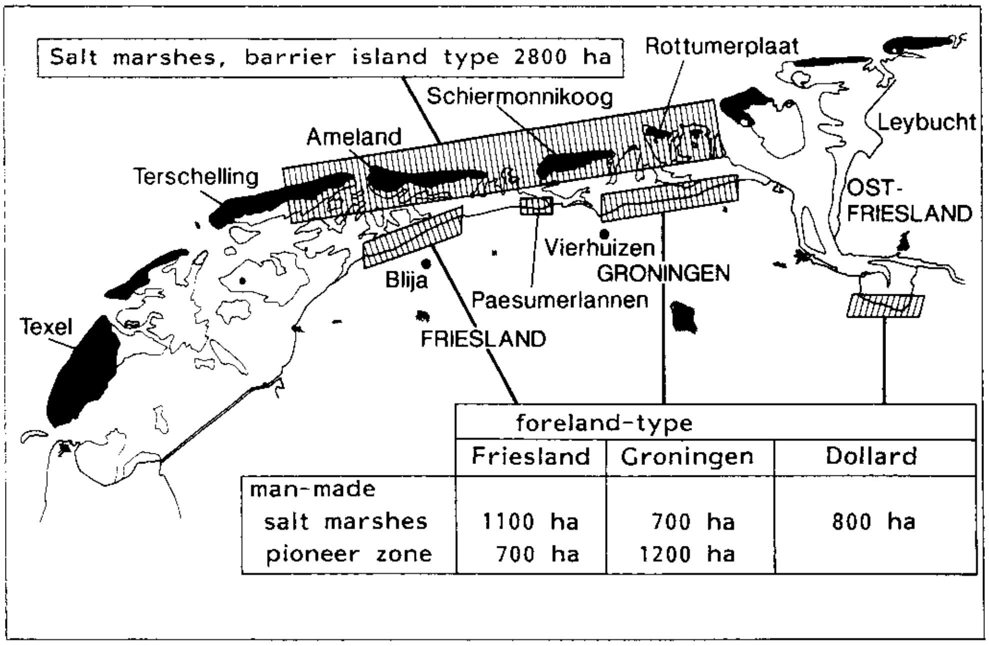

Figure 1. Overview of the salt marshes in the Netherlands Wadden Sea (northwest Europe). The barrier-type occurs at the lea side of the barrier islands and the foreland-type along the mainland sea walls. Marsh types according to DIJKEMA (1987a). Mean tidal range for our salt marshes from 2.00 m for the western sites to 2.40 m for the eastern sites and 3.00 m in the Dollard-estuary.

peared from the international Wadden Sea because the embankments for land reclamation has far exceeded the natural accretion enhancement rate (DIJKEMA, 1987b). Present-day mainland salt marshes in the provinces of Friesland and Groningen are the result of stimulating sedimentation processes through artificial draining and sedimentation fields sheltered by brushwood groynes.

Since salt marshes are subject to tides, sedimentation and erosion take place. If the height is increased by sedimentation, pioneer plants such as *Spartina anglica* and *Salicornia dolichostachya* appear (Figure 2): on the lee-side of the barrier islands they colonize the tidal flats once the surface reaches within 20 cm below mean high tide (MHT) up to MHT level and in the sedimentation fields of the mainland at elevations of 40 to 20 cm below MHT. Characteristics that define whether pioneer plants can become established are the elevation, local wave energy and density of the sediment (KÖNIG, 1948, VAN EERDT, 1985, GROENENDIJK, 1986). At around MHT level, the perennial grass *Puccinellia maritima* provides sufficient cover (1) to produce the fastest accretion in the entire salt marsh development process (WOHLENBERG, 1933; JAKOBSEN, 1954; BOUWSEMA *et al.*, 1986; DIJKEMA *et al.*, 1988; ANDRESEN *et al.*, 1990), (2) to prompt the development of a natural creek system (YAPP *et al.*, 1917, GROTJAHN *et al.*, 1983), and (3) to counteract erosion of the newly formed salt marsh (WOHLENBERG, 1953; KAMPS 1956, 1962; VON WEIHE, 1979). The creation of a creek system provides a major stimulus for the growth of most salt marsh plants by improving drainage (hence the digging of ditches in man-made salt marshes) and it also promotes succession to the next vegetation types in salt marsh development. Salt marsh plants therefore play an essential role in the interaction process of hydrodynamical and biological factors. The maximum in accretion is primarily due to the salt marsh vegetation, because in fact the reduced flooding rate should result in less silt at this height. If the salt marsh is elevated even further, the accretion rate is cut considerably due to this reduced flooding frequency.

Year to year changes in MHT prove to have an impact on the occurrence of plants in the salt marsh zones (BEEFTINK, 1987b; OLFF *et al.*, 1988). The vegetation zones will eventually shift parallel to the trend in water level (apart from possible accretion or erosion). This has already been shown to be the case for land-uplift areas in the Baltic (ERICSON, 1980; CRAMER and HYTTEBORN, 1987). Even a rise in MHT level of 5 to 10 cm in a single year can result in a shift of some plant species. These changes take place in the same year with a lower MHT and can be slowed down by one or more years in the event of higher MHT levels (BEEFTINK, 1987a, 1987b). The vegetation's delayed reaction to higher water levels provides the opportunity for increased accretion in the years with a higher relative water level (sedimentation is then higher and the protective effect of the vegetation is retained; DIJKEMA *et al.*, 1990). In the man-made salt marshes it has been found that the relationship between management to promote accretion and the development of vegetation is not always clear. This is because the changes in MHT levels affect the development of vegetation and can, on short-term, be responsible for major shifts in the salt marsh area. For long-term vegetation development, however, the accretional bal-

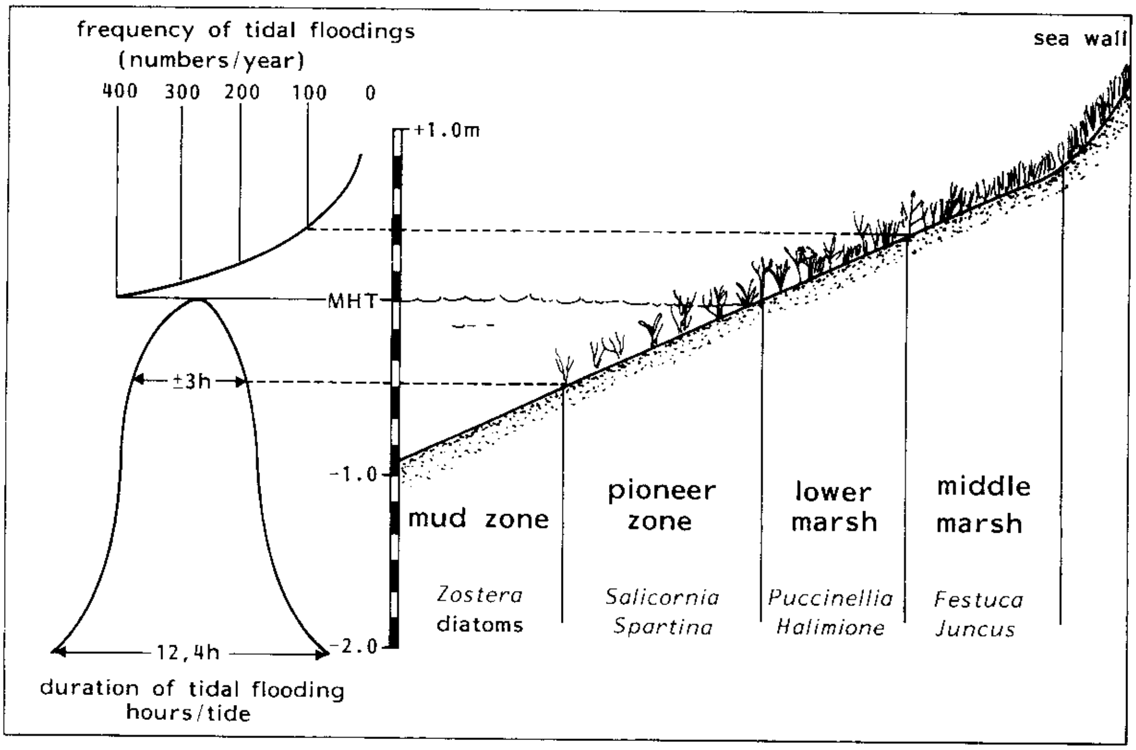

Figure 2. Zonation of salt marshes in the Wadden Sea in relation to duration and frequency of tidal floodings. After ERCHINGER (1985) for the German Wadden Sea.

ance of sedimentation, erosion, sea level rise and soil subsidence is the determining factor (DIJKEMA *et al.*, 1990).

METHODS

Earlier studies (KAMPS, 1958, 1962, GROTJAHN *et al.*, 1983, DIJKEMA *et al.*, 1988) and our present research (unpublished results W. van Duin, EU contract CEE EV EV/CT 92/0098: "The effects of environmental change on European salt marshes") show that the mud supply in no way restricts the rate of accretion of the mainland salt marshes and perhaps even the island salt marshes. This aspect is therefore further disregarded.

The carrying capacity for subsidence is calculated on the basis of a compilation of accretional data. A large dataset on man-made salt marshes collected by the Department of Public Works' Wadden Sea East Unit ("Rijkswaterstaat") between 1937 and 1992 was of major significance. The dataset includes 27 experimental fields (each 50 ha and each including 50 fixed 100 m transects for levellings) along 50 km of the mainland coast. The database is more than 6 megabytes and includes 50,000 records on elevation, accretion, soil composition, vegetation composition, vegetation coverage, vegetation type, yearly average MHT, management, etc. (VAN DEN BERGS *et al.*, 1990; DIJKEMA *et al.*, 1995), probably the oldest and largest monitoring dataset of salt marshes in Europe. For elevation and accretion each record in the database from 1960 on consists of one mean value from 100 levellings in a fixed 100 m transect. In all these years this levelling method has never been changed. The prognosis for subsidence has been tested against the 5-years average for each salt marsh zone (one zone includes about 16 transects) in more than one experimental field; therefore **one** average figure includes at least $5 \times 16 \times 100 = 8{,}000$ levelings.

Basis for the prognosis for subsidence was an agreement on a "possible production scenario" map as produced by the NAM (Dutch Petroleum Company), which indicates calculated subsidence for the new gas fields through to the year 2050 (Figure 3). A worst case estimate for the maximum subsidence rate per year can be calculated by dividing half of NAM's prognosis by 10 years, assuming that half of the subsidence will occur in the first 10 years of extraction, and that all new fields will be in operation simultaneously. After the first ten years, subsidence will reduce sharply. Two scenarios have been added: (1) the maximum subsidence scenario cumulated with a 2 mm per year rise in MHT level (Figure 4; BOSSINADE *et al.*, 1993) or (2) the maximum subsidence scenario cumulated with a hypothetical 6 mm per year rise in sea level (enhancement due to global warming; WARRICK and OERLEMANS, 1990).

CARRYING CAPACITY OF SALT MARSHES FOR SOIL SUBSIDENCE

Pioneer Zone

A cliff is often found in front of high-lying salt marshes as a result of (past) erosion. Cliff erosion leads to backwards

Prospects

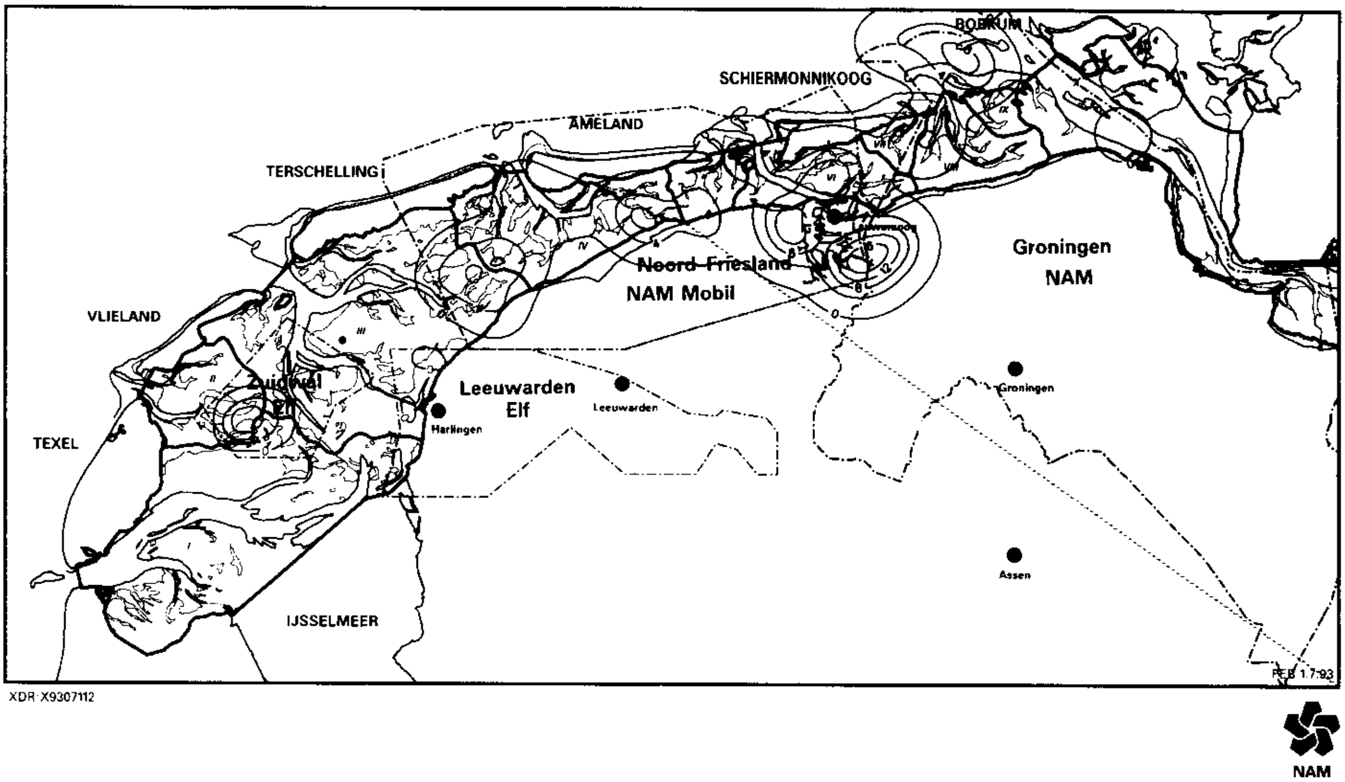

Figure 3. Subsidence prognosis for the Wadden Sea after new gas-extractions (in cm); situation anno 2050 (data NAM).

retreat of the salt marsh (DE GLOPPER, 1981) and is dependent on the accretional balance in the pioneer zone (i.e. the transitional zone towards the mudflats). Therefore the accretion in the pioneer zone is important for marsh survival.

In the pioneer zone of the man-made salt marshes it has been found that temporary erosion and cliff formation occurred as a result of an increase in MHT levels of 18 cm in the period 1976–1983 (Figure 4). Problem areas hereby were the central area of the man-made salt marshes in Friesland (near Blija) and the eastern section of the man-made salt marshes in Groningen (Figure 1; dataset Department of Public Works, in DIJKEMA *et al.*, 1995). Since local wave action and currents have a more significant effect on the accretional balance in the pioneer zone of the man-made salt marshes than the availability of sediment, the rate of accretion will not increase as a reaction to subsidence. Instead, wave action and currents along the mainland salt marshes are artificially regulated by the brushwood groynes of the sedimentation fields.

Control measures are hardly used for the pioneer zone of the barrier-island salt marshes: (1) because erosion is less of a problem, (2) there is a lower supply of muddy sediment and (3) in order to allow a natural development to occur. The morphological processes in the nearby Wadden Sea determine at which locations along the barrier-island salt marshes sedimentation or erosion occurs.

Salt Marsh Zone

The accretion and the vegetation together determine whether the salt marsh is capable of compensating the subsidence (chapter 'Interactions'; REED, 1990). Subsidence could cause a reduction in the elevation of the salt marshes and a reduction in the areal extent because of regression in the salt marsh vegetation towards pioneer vegetation or bare mudflats.

The average rate of accretion of the mainland salt marshes for the lower (including some middle) marsh zones is 13 to 18 mm per year (the large dataset of the Department of Public Works, in DIJKEMA *et al.*, 1995). For the middle and upper marshes the accretion is lower, but in this case any possible accretionary deficit will give rise to a larger number of floodings and thus an increased supply of sediment (CHAPMAN, 1976; DE GLOPPER, 1981; PETHIC, 1981; BOUWSEMA *et al.*, 1986; EYSINK, 1987). Generally speaking, this mechanism ensures that up to a certain extent the accretional rate of the marsh zone responds to the rate at which sea level rises and thus compensates any deficit (STEVENSON *et al.*, 1986; DIJKEMA *et al.*, 1990; FRENCH *et al.*, 1990).

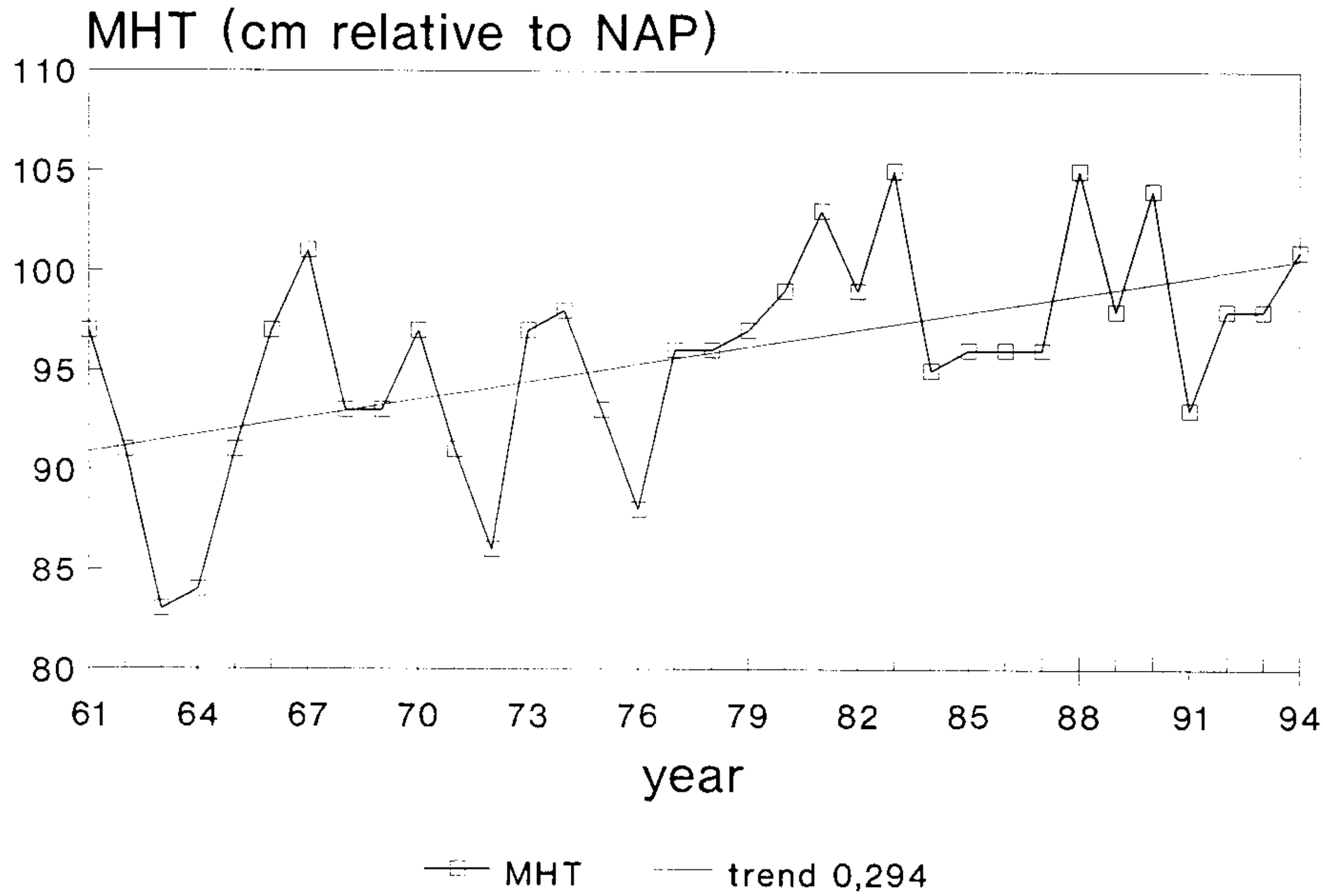

Figure 4. MHT-levels for the period 1961–1994 in the Wadden Sea, based on records of tidal gauges at Harlingen, Holwerd and Schiermonnikoog. Data from J. Bossinade, Department of Public Works. The trend of 2.9 mm per year shown is not significant; a 2 mm per year increase in MHT for the period 1971–1989 has been calculated after corrections for the effects of wind and air pressure (BOSSINADE *et al.*, 1993). The figure for mean sea level rise in this century is also about 2 mm per year.

The mainland salt marshes in the Dollard embayment (Figure 1) have a lower accretion rate (0.5–1.2 cm per year; REENTS, 1994). In the German Wadden Sea, off Ostfriesland, average values of between 1.0 and 2.0 cm per year are found; for the Leybucht this rate is 2.0 cm per year and for Schleswig-Holstein between 0.6 and 2.0 cm per year (DIECKMANN, 1988; ANDRESEN *et al.*, 1990; REENTS, 1994).

Barrier-island salt marshes are formed by relatively low mud deposits on a raised sandbank or beach. On a low salt marsh on the barrier-island of Terschelling the accretion rate between 1958 and 1979 was found to be 12 cm (6 mm per year, ROOZEN, 1985); a special marker technique was used. EYSINK (1987) calculated 1 to 4 mm per year on the barrier-island of Ameland, a somewhat conservative estimate since the clay thickness was divided by the age of the salt marsh (reduced accretion with increased elevation). Since the total inundation depth increases by a factor of 1.5 to 2 as a result of subsidence, EYSINK (1987) calculated for the low salt marsh on Ameland a future accretion rate of 3 to 8 mm per year. For the period 1989–1993 we measured accretion in the subsidence area on Ameland with a fixed-pole technique on 47 sites: 14 mm per year for the pioneer zone, 8 mm per year for the low salt marsh (indeed, the prognosis of EYSINK), 5 mm per year for the middle salt marsh and 2 mm per year for the high marsh zone (in EYSINK *et al.*, 1995). For comparable barrier-island salt marshes in North Norfolk (Great Britain) FRENCH *et al.*, (1990) suggests a limit of 5 mm per year below which the salt marsh can parallel the rise in sea level.

Summary

Table 1 summarizes the carrying capacity for subsidence in the Wadden Sea salt marshes. The highest acceptable level for subsidence in the salt marsh zone of the man-made salt marshes is 13 to 18 mm per year. On the basis of the studies mentioned in this chapter, the safety margin for other mainland salt marshes can be estimated at 10 mm subsidence per year. The margin on the islands is estimated lower at 5 mm per year. These figures also provide an indication for the carrying capacity of Wadden Sea salt marshes for enhanced sea level rise. There is evidence that the accretion rate in the salt

Table 1. *Carrying capacity for subsidence and rise in sea level (in mm per year). Sources discussed in the text.*

	Area	Average Accretion	Safety Limit
Salt marsh zone	Frisian mainland	18	18
	Groningen mainland	13	13
	Mainland, other sites	?	10
	Barrier-islands, low salt marsh	3–8	5
Pioneer zone	Mainland	Dependent on systems of brushwood groynes	
	Barrier-islands	Dependent on processes in the adjacent Wadden Sea	

marsh zone increases in response to subsidence or sea level rise. Yearly fluctuations in MHT levels (as much as 10 cm!) play an important and perhaps even crucial role: luck can be with us or against us.

There is a greater problem on the seaward edge of the salt marshes in the pioneer zone. Accretion in that zone along the mainland coast is currently maintained artificially by means of the traditional management methods for man-made salt marshes. The accretion rate will not increase in response to subsidence. Large-scale external morphological processes determine the sediment balance in the pioneer zone on the islands.

COMPARISON OF THE CARRYING CAPACITY OF SALT MARSHES WITH THE PROGNOSIS FOR SUBSIDENCE

Mainland and Barrier-Island Sites

Table 2 shows a comparison of carrying capacity figures for the salt marsh sites with NAM's maximum prognosis for subsidence at these sites (Figure 3). In separate columns subsidence is cumulated with the present 2 mm per year rise in MHT or a future 6 mm per year world-wide sea level rise respectively. From Table 2 we can deduce the following:

(1) The maximum scenario seems to present no problems for the salt marsh zone in the 1800 ha man-made salt marshes in Friesland and Groningen (Figure 1), not even if subsidence is cumulated with the future global rise in sea level. The following section will consider accretion rates for each zone of these sites, including the pioneer zone.

(2) For the Paesumerlannen site in North-eastern Friesland (Figure 1; 200 ha) the cumulation of maximum subsidence with the present rise in MHT would keep within the expected accretion for a salt marsh of this type (other mainland areas in Table 1). However, cumulation with the future global rise in sea level could prove problematic (under worst case conditions of an unchanged accretion rate of 10 mm per year and during the first ten years of gas-extraction). The edge of this site is protected by a broken seawall. For this reason there is no gradual transition towards the tidal flat and problems in a pioneer zone cannot occur.

(3) For the barrier-island salt marshes on Schiermonnikoog (700 ha) and the Rottumerplaat (100 ha), the maximum subsidence is lower than the rate of accretion for this type of salt marsh (Table 1), and that also applies in the case of cumulation of subsidence with the present rise in MHT. The future global rise in sea level of 6 mm per year on its own is 1 mm per year greater than the carrying capacity for the island salt marshes. Thus the cumulation of the relatively low subsidence with this future climatic effect exceeds the carrying capacity for the islands too (under worst case conditions of an unchanged accretion rate of 5 mm per year and during the first ten years of gas-extraction).

Specific Sites

It is possible to make a detailed comparison of the specific sites and zones of the mainland salt marshes on the basis of the large dataset from the Department of Public Works. The years before 1968 have been excluded from the database since this was the period when the brushwood groynes were being constructed, resulting in extraordinary high accretion rates. The annual rise in MHT is taken to be 2 mm, the result for

Table 2. *The carrying capacity for the salt marsh sites (Table 1) compared with NAM's 'worst case prognosis' for subsidence (half the subsidence during the first ten years of production) and cumulated with sea level rise (slr). All figures in mm per year. ( ) = resulting accretional balance. Sources discussed in the text.*

	Carr. Capacity Salt Marsh Zone	Maximum Subsidence	Subsidence + Present slr	Subsidence + Future slr
Mainland				
Frisian man-made salt marshes (east)	18	1–4 (+)	3–6 (+)	7–10 (+)
Groningen man-made salt marshes (west)	13	1–2 (+)	3–4 (+)	7–8 (+)
Paesumerlannen (natural salt marsh)	10	4–6 (+)	6–8 (+)	10–12 (−)
Barrier Islands				
Schiermonnikoog	5	0–1 (+)	2–3 (+)	6–7 (−)
Rottumerplaat	5	1–2 (+)	3–4 (+)	7–8 (−)

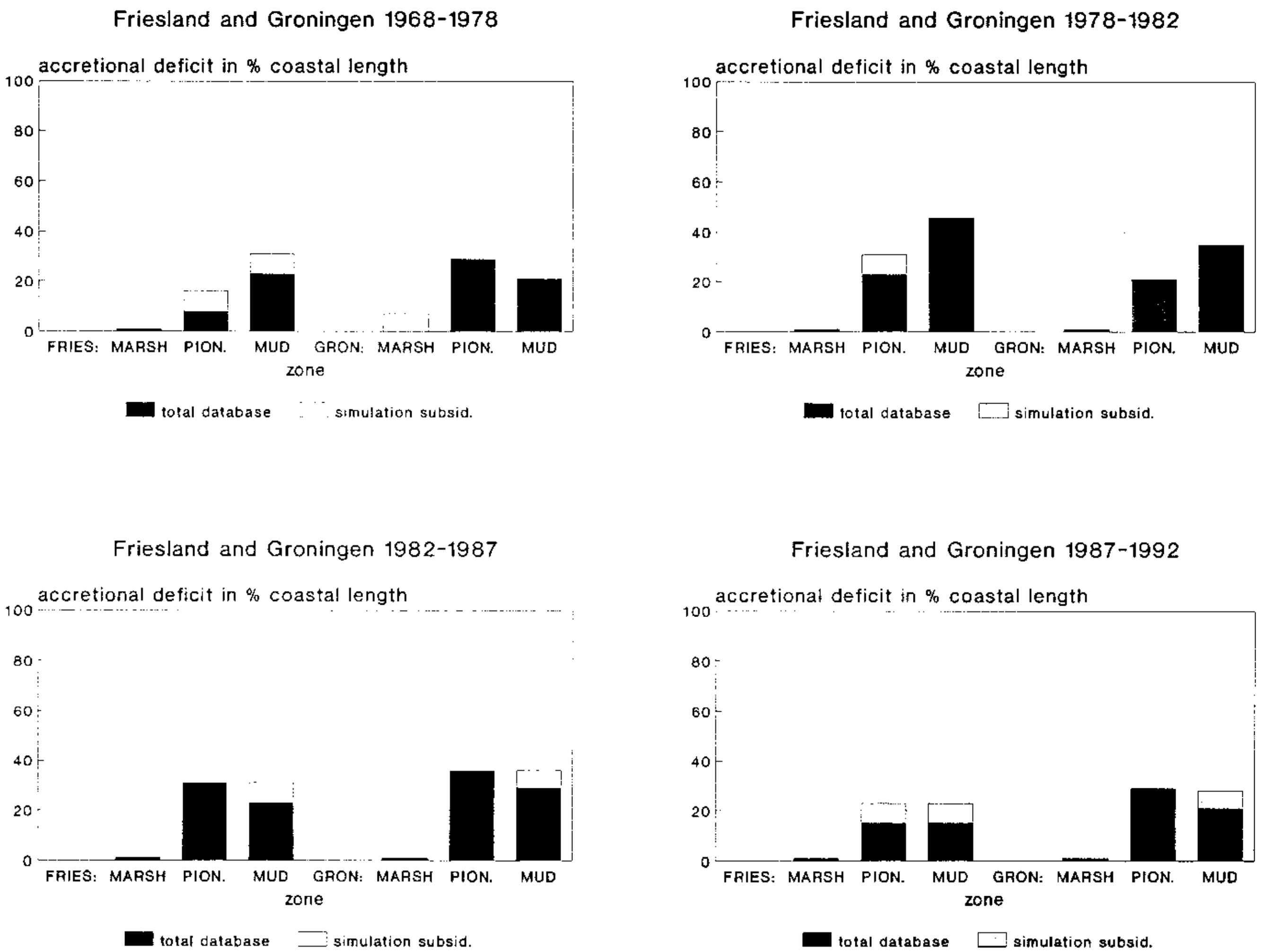

Figure 5. Accretional deficit (as percentage of coast showing a deficit) for the Friesland and Groningen sections of the mainland salt marshes in the years 1968–1992, from measured accretion ("database 27 fields", relative to 2 mm trend in sea level rise) with superimposed simulated subsidence.

the period 1971–1989 after correction for the effects of wind and air pressure (BOSSINADE *et al.*, 1993). Subsequently, the maximum prognosis for subsidence is added to these figures. It is then possible to simulate what the accretional balance would have been over the course of 25 years, divided into four time slots, if worst case subsidence had actually occurred during that period.

Figure 5 gives a qualitative indication of the accretional deficit scores of the 27 experimental fields in the salt marshes, with and without the simulated subsidence. Without subsidence there are no cases of accretional deficit in the salt marsh zone (the 2 mm per year increase in MHT included). With the hypothetical subsidence one of the 27 experimental fields shows an accretionary deficit in the period 1968–1978. This field has a very heavy grazing, which serves to slow down the accretion rate. The simulation does not take account of any possible self-regulatory increase in the rate of accretion after subsidence in the salt marsh zone. The former conclusion that the salt marshes would not be directly affected by subsidence due to gas-extraction is confirmed by this simulation.

Simulation of the maximum subsidence for the pioneer zone and the mud zone in the experimental fields has been shown to result in a 20–30% increase in the length of coast showing an accretional deficit (Figure 5). The accretional deficit will notably increase in the mud zone and the pioneer zone of the Frisian mainland salt marshes (central section near Blija), which have already been indicated as a problem area in the previous chapter on carrying capacity. In addition, the outer sedimentation field in one of the Groningen experimental fields (Vierhuizen) gives rise to problems.

Figures 6 and 7 show the accretional balance quantitatively, without and with simulation of the maximum subsidence. For four time periods, the sediment balance remains positive for all blocks of salt marshes. Significant quantitative effects are found in the pioneer zone and the mud zone. These effects occur in the Frisian central section (near Blija), the poor accretion area known from the previous chapter, which almost

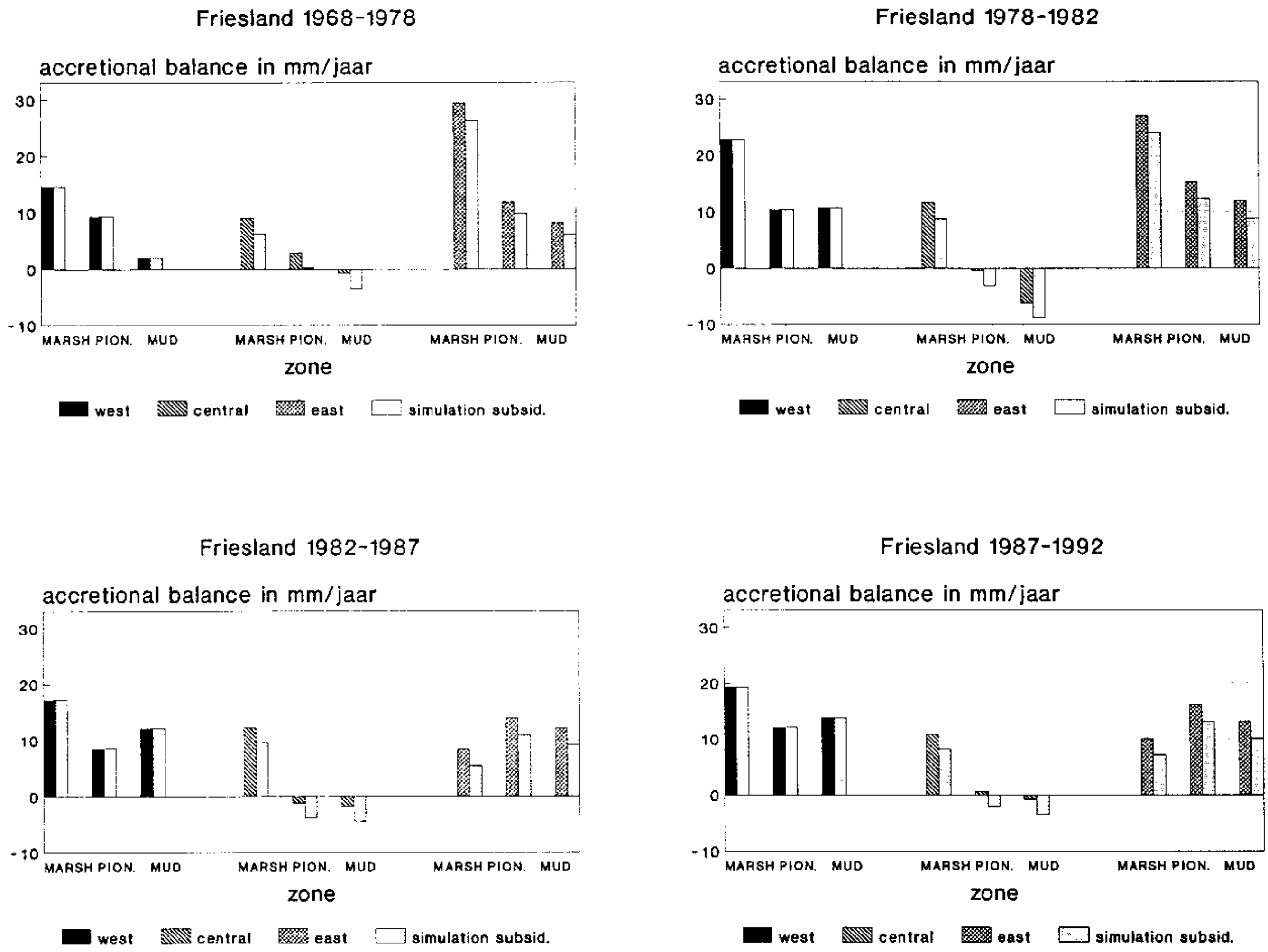

Figure 6. Accretional balance for different sections of the mainland salt marshes in Friesland in the years 1968–1992, from measured accretion (relative to 2 mm trend in sea level rise) with superimposed simulated subsidence.

entirely coincides with the highest prognosis for subsidence. Simulation shows that this area will be subject to hypothetical erosion in all time periods, or existing erosion will be increased, even in the period from 1987–1992 in which accretion was improved.

DISCUSSION

Screening of the various salt marsh sites in the Netherlands Wadden Sea has shown that, generally speaking, soil subsidence due to gas-extraction will not result in problems with the accretional balance in the salt marshes proper. However, if cumulation with a 6 mm per year enhanced rise in sea level will come true and with a conservative estimate for accretion, there would be a slight accretional deficit in one mainland site (Paesumerlannen) and on both barrier islands (Schiermonnikoog and Rottumerplaat; Figure 1). The total deficit for the first ten years of gas extraction would amount to 20, 20 and 30 mm respectively. After that period subsidence will reduce sharply.

Simulation of half the subsidence in ten years for specific sites and zones of the mainland salt marsh results in negative impact for the pioneer zone and the mud zone for the central part of the mainland salt marshes in Friesland, but the subsidence is not expected to affect the salt marsh zone. The elevation of the mud zone may adjust as a result of subsidence comparably to that of the adjacent tidal flats (Oost and Dijkema, 1993). An accretional deficit in the pioneer zone will, in time, lead to cliff erosion and marsh erosion from the seaward edge. The pioneer zone, which is transitional to the tidal flats, is situated on a level which is most affected by wave action and currents. In the pioneer zone there will be no self-regulation of the accretion rate since the brushwood groynes in that zone are the regulating factor. Moreover, it lacks the protection of a closed vegetation cover. In the Netherlands Wadden Sea more than half of the mainland salt marshes (which are man-made) showed an accretional deficit in this pioneer zone during a 7 year period with rising high-tide levels (Dijkema *et al.*, 1990).

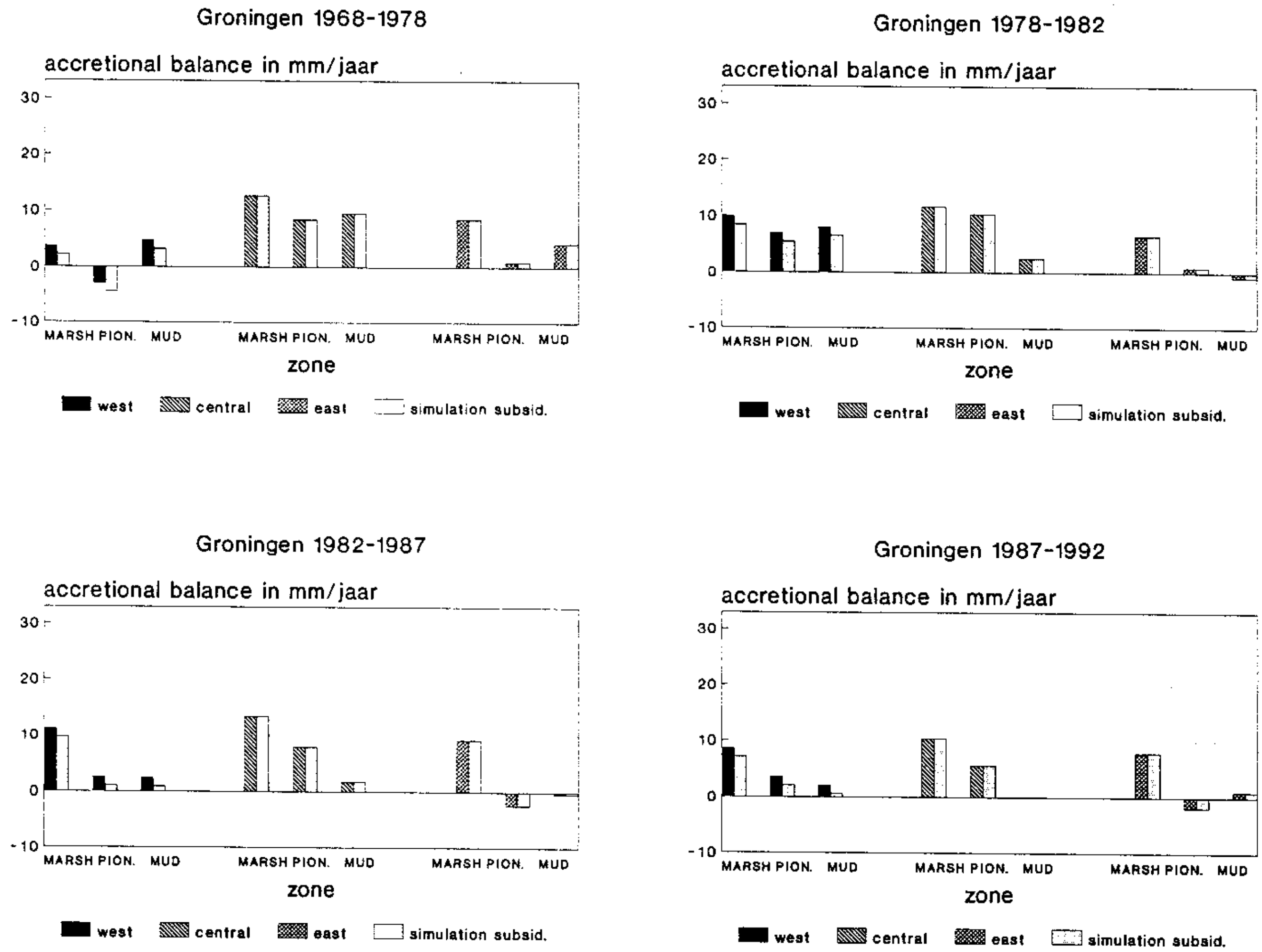

Figure 7. Accretional balance for different sections of the mainland salt marshes in Groningen in the years 1968–1992, from measured accretion (relative to 2 mm trend in sea level rise) with superimposed simulated subsidence.

When considering the role of salt marshes for nature conservation and coastal protection important marsh characteristics are: (1) in the salt marsh zone itself, generally a positive accretional balance due to the effect of the vegetation cover on sedimentation and erosion protection (DIJKEMA *et al.*, 1990), (2) the mainland salt marshes in the Wadden Sea can compensate for a future sea level rise of about 10 mm per year and the barrier-island salt marshes for about 5 mm per year, which is within the range of future sea level rise; (3) however, vertical erosion in the pioneer zones will lead to horizontal cliff erosion of the salt marsh zone proper, which might become a general effect of future sea level rise on the world salt marsh resource.

CONCLUSION

Prevention

A general conclusion is that management techniques to prevent negative effects of soil subsidence or sea level rise have to direct most attention to the pioneer zone at the seawards edge of the marsh. Secondly, it is hypothesed that for the salt marsh zone the accretion rate responds to the rate of soil subsidence or sea level rise and thus compensates any deficit, up to a certain limit. The role of vegetation in this mechanism is substantial, thus leading to the third conclusion that marsh management should be optimal for vegetation development.

Previous research (DIJKEMA *et al.*, 1988) has indicated that the accretional balance in the pioneer zone of mainland salt marshes is mainly determined by the hydrodynamical conditions for sedimentation. In the Wadden Sea there is no lack of mud, and the main regulating factor for salt marsh growth is protection against wave energy and currents. After extensive land reclamation of past centuries, accretion along the mainland of the Wadden Sea is mainly limited to the sedimentation fields of the man-made salt marshes. For the last 60 years simple brushwood groynes have been effective in reducing wave energy and currents. Since locally generated

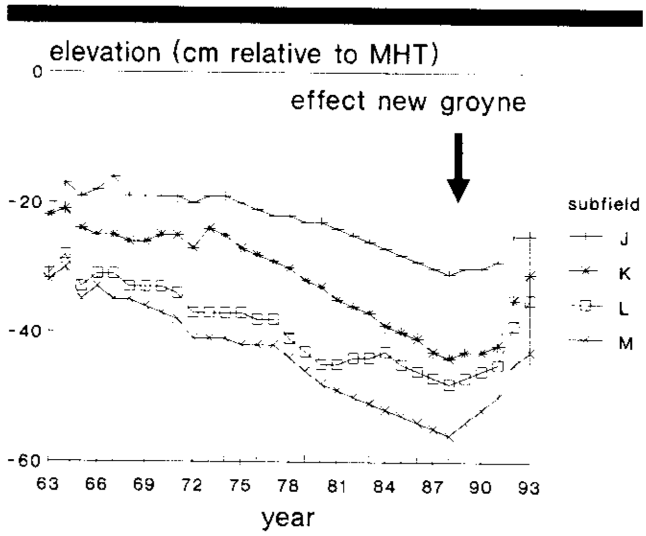

Figure 8. Effect of halving one sedimentation field in the pioneer zone (Friesland, field 101 in the central section) from 400 × 400 m to 200 × 400 m.

small waves and currents can cause erosion within the sedimentation fields, a fetch between the groynes of 200 m at the most appears necessary to prevent erosion in poor accretional areas. For this reason, the Department of Public Works is currently being constructing extra brushwood groynes (N–S orientation) in the poor accretional areas, thus halving the size of the sedimentation fields to 200 × 400 m. The method has proved to be very successful (Figure 8).

Sedimentation fields of 400 × 400 m produce an initial accretion of about 10–30 cm in approx. four years (DIJKEMA *et al.*, 1988). Accretion subsequently continues at the normal rate. In Germany it was found that halving the size of such a sedimentation field produced 10–20 cm extra accretion, and a second halving (i.e. to 200 × 200 m) repeated the increase (ERCHINGER, pers. comm.). This means that for preventing ecological effects from soil subsidence or enhanced sea level rise the accretion in the mainland pioneer zone can be optimized by reducing the size of the sedimentation fields from the current 200 × 400 m to 200 × 200 m.

Monitoring

On the barrier island of Ameland (a present subsidence area) and along the mainland coast (man-made salt marshes), monitoring systems have provided satisfactory data. With the help of the system it is possible to monitor the developments of salt marsh area, elevation, accretion and vegetation. In this way any developments which have not been foreseen in this impact prognosis will be brought to light and steps can be taken to adjust the rate of subsidence or to optimize the management-techniques of the man-made salt marshes.

The response of marsh vegetation and sedimentation to year to year changes in MHT levels complicates the effects of a long-term sea level rise. Fundamental research into the interactions between sediments, waves and currents, plant settlement and -growth, creek formation and sea level changes increases the chances of more effective and probably more natural management-techniques for the mainland coast in the northwest European Wadden Sea, the most important estuarine area in Europe.

ACKNOWLEDGEMENTS

I dedicate this paper to the late Piet Bouwsema for his friendship, for educating me the secrets of marsh accretion techniques and for his never ending efforts to continue **his** monitoring system (**the** "large dataset" of the Department of Public Works). Thanks are due to Jappie van den Bergs, Jaap Bossinade, Rob de Glopper, Trineke Kroeze and all the others from the Department of Public Works for their cooperation and great interest concerning the monitoring of salt marshes and salt marsh management in particular. From my own DLO-Institute for Forestry and Nature Research (IBN) Michaela Scholl helped with text processing and Willem van Duin with stimulating discussions. The second reviewer showed me how to improve clarity and brevity of the final paper and encouraged me to go on. Thanks also to a Steering Committee for the basic study with dr. N. Dankers, IBN, ir. W.D. Eysink, Delft Hydraulics, dr. P.L. de Boer and dr. A.P. Oost, Geological Department of Utrecht University and drs. M.A.U. de Boer, H.J. Gussinklo and drs. J.J. Verburgh from the NAM (Dutch Petroleum Company).

LITERATURE CITED

ANDRESEN, H.; BAKKER, J.P.; BRONGERS, M.; HEYDEMANN, B., and IRMLER, U., 1990. Long-term changes of salt-marsh communities by cattle grazing. *Vegetatio*, 89, 137–148.

BAKKER, J.P.; DE LEEUW, J.; DIJKEMA, K.S.; LEENDERTSE, P.C.; PRINS, H.H.T., and ROZEMA, J., 1993. Salt marshes along the coast of The Netherlands. *Hydrobiologia* 265, 73–95.

BEEFTINK, W.G., 1987a. Vegetation responses to changes in tidal inundation of salt marshes. *In:* VAN ANDEL, J.; BAKKER, J.P., and SNAYDON, R.W. (eds.), *Disturbance in grasslands.* Dordrecht: Junk, pp. 97–117.

BEEFTINK, W.G., 1987b. De betekenis van de factor getij voor de schorrevegetatie. *In:* ROZEMA, J. (ed.), *Oecologie van estuariene vegetatie.* Amsterdam, Yerseke: Vrije Universiteit Amsterdam, Delta Instituut voor Hydrobiologisch Onderzoek, pp. 1–45.

BOSSINADE, J.H.; VAN DEN BERGS, J., and DIJKEMA, K.S., 1993. *De invloed van wind op het jaargemiddelde hoogwater langs de Friese en Groninger Waddenkust.* Nota GRAN 1993–2009 and IBN-rapport 049. Groningen, Texel: Rijkswaterstaat Directie Groningen + DLO Instituut voor Bos-en Natuuronderzoek, 22p.

BOUWSEMA, P.; BOSSINADE, J.H.; DIJKEMA, K.S. (ED.); VAN MEEGEN, J.W.TH.M.; REENDERS, R., and VRIELING, W., 1986. *De ontwikkeling van de hoogte en van de omvang van de kwelders in de landaanwinningswerken in Friesland en Groningen.* Nota ANA-86.05, RIN-rapport 86/3. Groningen, Texel: Rijkswaterstaat and Rijksinstituut voor Natuurbeheer, 58 p.

CHAPMAN, V.J., 1976. *Coastal Vegetation.* Oxford: Pergamon, 292p.

CRAMER, W. and HYTTEBORN, H., 1987. The separation of fluctuation and long-term change in vegetation dynamics of a rising seashore. *Vegetatio*, 69, 157–167.

DE GLOPPER, R.J., 1981. De snelheid van de opslibbing en van de terugschrijdende erosie op de kwelders langs de noordkust van Friesland en Groningen. *In: 50 jaar onderzoek.* Flevobericht 163. Lelystad: Rijksdienst voor de IJsselmeerpolders, pp. 43–51.

DIECKMANN, R., 1988. Entwicklung der Vorländer an der nordfriesischen Festlandküste. *Wasser und Boden*, 1988/3, 146–150.

DIJKEMA, K.S.; BEEFTINK, W.G.; DOODY, J.P.; GEHU, J.M.; HEY-

DEMANN, B., and RIVAS MARTINEZ, S., 1984. *Salt marshes in Europe.* Strasbourg: Council of Europe, Nature and Environment Series 30, 178p.

DIJKEMA, K.S., 1987a. Geography of salt marshes in Europe. *Zeitschrift für Geomorph. N.F.*, 31(4), 489–499.

DIJKEMA, K.S., 1987b. Changes in salt-marsh area in the Netherlands Wadden Sea after 1600. *In*: HUISKES, A.H.L.; BLOM, C.W.P.M., and ROZEMA, J. (eds.), *Vegetation Between Land and Sea.* Dordrecht: Junk, pp. 42–49.

DIJKEMA, K.S.; VAN DEN BERGS, J.; BOSSINADE, J.H.; BOUWSEMA, P.; DE GLOPPER, J.R., and VAN MEEGEN, J.W.TH.M., 1988. *Effecten van rijzendammen op de opslibbing en de omvang van de vegetatiezones in de Friese en Groninger landaanwinningswerken.* Nota GRAN 1988–2010, RIN-rapport 88/66, RIJP-rapport 1988–33 Cbw. Groningen, Texel, Lelystad: Rijkswaterstaat and Rijksinstituut voor Natuurbeheer and Rijksdienst voor de IJsselmeerpolders, 119p.

DIJKEMA, K.S.; BOSSINADE, J.H.; BOUWSEMA P., and DE GLOPPER, R.J., 1990. Salt marshes in the Netherlands Wadden Sea: rising high-tide levels and accretion enhancement. *In*: BEUKEMA, J.L.; WOLFF, W.J. and BROUNS, J.J.W.M. (eds), *Expected Effects of Climatic Change on Marine Coastal Ecosystems.* Dordrecht: Kluwer, pp. 173–188.

DIJKEMA, K.S., 1990. Salt and brackish marshes around the Baltic Sea and adjacent parts of the North Sea: their vegetation and management. *Biological Conservation*, 51, 191–209.

DIJKEMA, K.S.; VAN DEN BERGS, J.; BOSSINADE, J., and KROEZE, T.A.G., 1995. *Monitoring kwelderwerken in Groningen en Friesland. Evaluatie medio 1992–1995.* Groningen, Texel: Rijkswaterstaat and DLO-Instituut voor Bos-en Natuuronderzoek, 34p.

ERCHINGER, H.F., 1985. *Dünen, Watt und Salzwiesen.* Hannover: Der Niedersächsische Minister für Ernährung, Landwirtschaft und Forsten, 59p.

ERCHINGER, H.F. 1995. Intaktes Deichvorland für Küstenschutz unverzichtbar. *Wasser und Boden*, 47(2), 48–53.

ERICSON, L., 1980. The downward migration of plants on a rising Bothnian seashore. *Acta Phytogeographica Suecica*, 68, 61–72.

EYSINK, W.D., 1987. *Gaswinning op Ameland-oost, effecten van de bodemdaling.* Report H114. Delft: Delft Hydraulics Laboratory, 53p.

EYSINK, W.D.; DANKERS, N.; DIJKEMA, K.S.; VAN DOBBEN, H.F.; SMIT, C.J., and DE VLAS, J., 1995. Monitoring effecten van bodemdaling op Ameland-Oost. Delft Hydraulics. DLO-Institute for Forestry and Nature Research, Wageningen, Texel, 62p.

FRENCH, J.; SPENCER T., and STODDART, D., 1990. Backbarrier salt marshes of the North Norfolk coast: geomorphic development and response to rising sea-levels. Discussion papers. *Conservation* 54, Ecology and Conservation Unit, University College, London, 35 p.

GROENENDIJK, A.M., 1986. Establishment of a Spartina anglica population on a tidal mudflat: a field experiment. *Journal of Environmental Management*, 22, 1–12.

GROTJAHN, M., MICHAELIS, M.; OBERT, B., and STEPHAN, H.W., 1983. Höhenentwicklung, Sediment, Vegetetion und Bodenfauna in den Landgewinnungsgebieten beiderseits des Capeller Tiefs. *Forsch.-Stelle f. Insel-u. Küstenschutz* (Nordeney), 34, 63–94.

JACOBSEN, B., 1954. The tidal area in south-western Jutland and the process of the salt marsh formation. *Geografisk Tidsskrift*, 53, 49–61.

KAMPS, L.F., 1956. *Slibhuishouding en landaanwinning in het oostelijk waddengebied.* Baflo: Rijkswaterstaat Directie Landaanwinning, 93p.

KAMPS, L.F., 1962. *Mud distribution and land reclamation in the eastern wadden shallows.* Den Haag: Rijkswaterstaat Comm., 4, 73p.

KÖNIG, D., 1948. Spartina townsendii an der Westküste von Schleswig-Holstein. *Planta* 36, 34–70.

KÖNIG, D., 1987. Historisches über Wattenmeer-Salzwiesen. *In*: N. KEMPF, J. LAMP and P. PROKOSCH, *Salzwiesen: Geformt von Küstenschutz, Landwirtschaft oder Natur?* Tagungsbericht 1. Husum: WWF-Deutschland, pp. 31–70.

OLFF, H.; BAKKER, J.P., and FRESCO, L.F.M., 1988. The effect of fluctuations in tidal inundation frequency on a salt-marsh vegetation. *Vegetatio*, 78, 13–19.

OOST, A.P. and DIJKEMA, K.S., 1993. *Effecten van bodemdaling door gaswinning in de Waddenzee.* IBN-rapport 025. Texel, Utrecht: DLO-Instituut voor Bos-en Natuuronderzoek + Universiteit Utrecht, fac. Aardwetenschappen, 134p.

PETHIC, J.S., 1981. Long-term accretion rates on tidal salt marshes. *Journal Sediment Petrology*, 51, 571–577.

REED, D.J., 1990. The impact of sea-level rise on coastal salt marshes. *Progress in Physical Geography*, 14(4), 465–481.

REENTS, S., 1994. *Vertical accretion in the salt marshes of the Dollard.* Intern Rapport 94/1. Stichting Het Groninger Landschap, 81p.

ROOZEN, A.J.M., 1985. Een kwart eeuw onderzoek aan vegetatiesuccessie op de Boschplaat van Terschelling. *De Levende Natuur*, 86, 74–80.

VAN DEN BERGS, J.; BOUWSEMA, P., and DIJKEMA, K.S., 1990. Management of mainland salt marshes and accretion works in relation to coastal protection. *In*: C. HELWEG OVESEN. *Saltmarsh management in the Wadden Sea region.* Hørsholm, Denmark: Ministry of the Environment, pp. 85–95.

VAN EERDT, M.M., 1985. The influence of vegetation on erosion and accretion in salt marshes of the Oosterschelde, The Netherlands. *Vegetatio*, 62, 367–373.

VON WEIHE, K., 1979. Morphologische und ökologische Grundlagen der Vorlandsicherung durch Puccinellia maritima (Gramineae). *Helgol. Wiss. Meeresunters*, 32, 239–254.

WARRICK, R. and OERLEMANS, J., 1990. Sea-level rise. *In*: HOUGHTON, J.T., JENKINS, G.J., and EPHRAUMS, J.J. (eds.), *Climate Change, the IPCC Scientific Assessment.* Cambridge University Press, pp. 260–281.

WOHLENBERG, E., 1933. Das Andelpolster und die Entstehung einer charakteristischen Abrasionsform im Wattenmeer. *Wiss. Meeresunters. NF. Abt. Helgoland*, 19(4), 1–3.

WOHLENBERG, E., 1953. Sinkstoff, Sediment und Anwachs am Hindenbrugdam. *Die Küste*, 2, 31–94.

YAPP, R.H.; JOHNS, D., and JONES, O.T., 1917. The salt marshes of the Dover estuary. *Journal of Ecology* 5 (2), 65–103.