6 SALT MARSH DEVELOPMENT ALONG THE MAINLAND COAST OF THE DUTCH WADDEN SEA FROM 1965 UNTIL PRESENT

6.1 Introduction

6.1.1 General introduction
Quantitative analyses of long-term salt marsh behaviour can contribute to a better understanding of the behaviour. Thereby, an understanding of the processes at a smaller scale is needed and therefore the process knowledge of Chapters 4 and 5 is integrated in this chapter. In the long-term analysis, data concerning the entire salt marsh, the pioneer zone and part of the upper mudflats is studied. A temporal and spatial variation in erosion and sedimentation patterns and salt marsh growth curves are used to describe salt marsh development. Temporal and spatial variation in wind, water level, wave height and morphology determine salt marsh development and can therefore be used to explain the salt marsh development. Long-term data sets of Rijkswaterstaat (Department of Public Works and Water Management) were used to study salt marsh behaviour along the Dutch mainland salt marshes from 1965 until present.

The main objective of this chapter is to explain past decadal salt marsh behaviour along the mainland coast of the Dutch Wadden Sea in order to gain knowledge about long-term salt marsh behaviour.

6.1.2 Development of the study area
Land reclamation over the last four centuries and enclosures have straightened the mainland coast of the provinces of Friesland and Groningen in the eastern Dutch Wadden Sea. Most of the natural embayments are closed and the natural development of the salt marshes has stagnated. Presently, the growth of the salt marshes is slow and only occurs under controlled conditions in several areas along the mainland coast, especially in the north of the provinces Friesland and Groningen (Figure 1). Before 1900, small dams and drainage channels were constructed to stimulate salt marsh accretion in order to reclaim land along the mainland coast of the Dutch Wadden Sea. However, at the beginning of the 20th century this method hardly resulted in new marshes (Dijkema, 1987). Around 1935, the government started constructing brushwood groins and subsequently created sedimentation fields to stimulate salt marsh development along the mainland coast on a large scale (tens of km). Most of the present mainland salt marshes are the result of these activities (Dijkema, 1987b). The location of sedimentation fields is shown in Figure 1. Channels were dug in the vegetated part of the salt marsh and the pioneer zone to regulate the drainage (Kamps, 1962; Dijkema et al., 1990). Initially, in the first four years after the completion of the construction of sedimentation fields, high sedimentation rates occurred. Afterwards accretion rates decreased and from 1978 on, the seaward extension of the salt marshes has stopped. This development can probably be ascribed to a rise in the mean high water level from 1978 to 1983 of 0.44 cm/y (Dijkema et al., 1990; Dijkema et al., 1995). Presently, despite a continuing rise in sea-level, the extent of the salt marsh area is steady due to stabilisation in mean high water level, a better maintenance of the brushwood groins, and a decrease in size of the sedimentation fields (Chapter 3.2).
6.2 Methods

The long-term height data set of Rijkswaterstaat consists of elevation data collected from 1965 until present. The data is collected in 27 locations along the mainland coast with the dike as a landward boundary and the most seaward brushwood groin as the seaward boundary. This means that the entire salt marsh, the pioneer zone and part of the upper tidal mudflat are included in the data set. This data set was used for interpolation in PRCraster (see Chapter 3.5.2). In the dynamic modelling module of PRCraster, elevation maps of subsequent years were subtracted to calculate temporal and spatial accretion and erosion surfaces (m²), volume changes (m³) and seaward extension (% of total measured area). With PRCraster, maps with areas above and below 0 m NAP (Dutch Ordinance Level) of the height difference maps were calculated to determine the size of the erosion and accretion surfaces per 5 years. Volume changes were calculated by multiplying the erosion and accretion surfaces with the average height change of these surfaces. Erosion volumes were subtracted from accretion volumes to attain net changes of volume over the area. The area above 1 m NAP (Dutch Ordinance Level) was used to calculate the seaward extension of the vegetated salt marsh. According to Dijkema et al., 1990, the 5% cover of Puccinellia maritima determines the salt marsh edge. In general, this corresponds with a height of NAP + 1 m.

Two digital hydrographic maps were available to calculate changes in morphology of the Wadden Sea in time. The first map comprises data from 1986-1990 and the second map includes data from 1992-1995. By subtracting these maps in PRCraster a map of differences was calculated and changes in morphology were analysed.

Wind and water level data were available from a station in Lauwersoog (Figure 1.1) from 1971-1998. From these wind data the average wind speed was calculated for each measuring year. Furthermore, the top 10% of the wind speed was used as a measure for storm frequency and strength. From the high water level data the average, maximum and top 10% were calculated for each measuring year. Moreover, the high water levels during the storm days (determined by the wind data, see Chapter 6.3.1) were calculated and used as a measure for storm surge levels.

A wave model (SWAN) was used to calculate water depths and wave patterns during a storm along the salt marsh coast. At the sea dike of the mainland coast of the Wadden Sea, the spectral parameters (e.g. water depth, significant wave height and wave period) were calculated during a storm.

6.3 Results

6.3.1 Morphological development of the mainland salt marsh coast between 1965 and 1995

Accretion and erosion patterns

For the Friesland and Groningen salt marsh areas surface changes (m²) and volume changes (m³) between 1965 and 1995 from the sea dike up to the seaward side of the brushwood groynes are shown in Figure 6.1. The values shown are instantaneous values. For both locations the figures show that the surface where accretion occurs is always larger than the surface where erosion occurs. This implies that the total salt marsh area (including the pioneer zone) has been growing since 1965. For the Friesland salt marshes the figures show that from 1965-1975 and from 1985-1995 the accretion surface was
approximately 15 km². The erosion surface was smaller than 4 km² over the same periods. Between 1975 and 1985 there was a decrease in accretion surface to 12 km² and an increase in erosion surface to 8 km². For the Groningen salt marshes the figures show that from 1965-1980 the accretion surface was approximately 24 km² and the erosion surface was around 4 km². After 1980 the accretion surface decreased to 19 km² and the erosion surface increased to 9 km².

The volume of the salt marshes has increased between 1965 and 1995 (Figure 6.1). In the Friesland salt marshes the accretion (volume change) was decreasing from 1965 until 1985 and was especially low between 1970 and 1985. After 1985 the accretion increased. For the Groningen salt marshes the accretion decreased in the period 1965-1975. Afterwards the accretion recovered but from 1980-1990 the accretion decreased again. By 1995 a small increase in volume change occurred.

The area of the vegetated salt marsh is shown in Figure 6.2 as a percentage of the total measurement area. The measured area extends in seaward direction as far as the most seaward brushwood groin that borders the area of sedimentation fields. The boundary of the vegetated area corresponds with a height of NAP + 1m. From Figure 6.2 it appears that the vegetated salt marsh area of Friesland almost linearly grows in time. The Groningen vegetated salt marshes show an asymptotic growth. A second-degree polynomial trend was fitted through the data of Groningen and those of Friesland to calculate the following growth curves:

Figure 6.1 - Erosion and accretion surfaces (top) and net volume changes (bottom) between 1965 and 1995.
Friesland: \[ y = -0.006x^2 + 1.69x - 71.2 \quad (R^2 = 0.990) \]
Groningen: \[ y = -0.025x^2 + 4.66x - 186.1 \quad (R^2 = 0.995) \]

In the Friesland salt marsh area, accretion surface and accretion volume have recovered over the last ten years whereas in the Groningen salt marsh area, accretion surface and volume changes have remained stable. Similar conclusions can be drawn upon the salt marsh growth results. The salt marsh surface is still growing almost linearly in Friesland whereas the salt marshes grow asymptotically and show growth stagnation after 1985 in Groningen.

![Development of vegetated salt marsh](image_url)  
**Figure 6.2** - Development of the Friesland and Groningen vegetated salt marsh areas (above NAP + 1m) between 1965 and 1995.

**Wind and water levels**

In Figure 6.3 the average and top 10% of the wind speed from southwest to northeast is shown for the period 1971-1998. Until the mid eighties there is a small increase in wind speed. Despite this increase there are no large standard deviations in the average top 10% wind speed (11.3 ± 0.7 m/s). All measuring days with a wind speed over 11.3 m/s were selected to calculate the number of storm days per year. This is also shown in Figure 6.3. A trend of an increase in number of storm days through time is visible until 1983, despite the large variation in number of storm days between 1971 and 1998.

![Wind speed and storm days](image_url)  
**Figure 6.3** - Average and top 10% wind speed (A) and number of storm days (B) between 1971 and 1998 in Lauwersoog. 1990 is defined as the storm year.
The average and top 10% of the high water levels for the period of 1971-1998 are shown in Figure 6.4. There is an increasing trend in high water level over the period of 1971-1983. Despite the increase in the first period, the top 10% of the high water levels for the entire period does not show high standard deviations. The average of the top 10% high water levels of all measuring years is $1.40 \pm 0.07\text{m}$.

The combination of high wind speeds and high water levels defines a storm surge. Comparable trends appear in wind speed from a southwest to northeastern direction and high water level variations. Winds induce a set-up of the water level almost instantaneously due to the shallowness of the Wadden Sea. The correlation between the top 10% of the wind speed and high water levels was calculated and is shown in Figure 6.5. When the top 10% of the wind speed increases the top 10% of the high water levels also increase. The correlation $R^2=0.63$ is significant at a 5% confidence interval. The correlation coefficient is only 0.63 due to the fact that average values per year of the top 10% of the wind and high water levels were used, instead of time series.

Long term effects of storm surges on salt marsh development

An increase in storm surge levels characterises the period from 1971 until 1983 (Figure 6.3B and 6.4). This coincides with a period in which the erosion surface increases, the accretion

![Figure 6.4 - Average and top 10% of the high water levels between 1971 and 1998 in Lauwersoog. 1990 is defined as the storm year.](image)

![Figure 6.5 - Correlation between the top 10% wind speed and top 10% high water levels.](image)
surface decreases and the changes in volume decrease in the Friesland salt marshes (Figure 6.1). When the storm surge levels increase, the salt marshes are flooded more often and due to the high turbulence in the water, less of the supplied sediment can be deposited or even erosion can occur. No net erosion takes place, shown by an increasing salt marsh volume, but accretion occurs at a lower rate. In Groningen the same effect is recognised with a delay in time of five years relative to Friesland.

The storm surge levels decrease and stabilise after 1983. This coincides with a recovery of the accretion surface and the volume changes and a decrease in erosion surface in the Friesland salt marshes. When the storm surge levels decrease, the turbulence during the flooding of the salt marshes decreases and more sediment can settle. This results in an increase in net accretion rate. In the Groningen salt marshes the size of accretion and erosion surfaces stabilises after 1983 but does not recover. The volume changes keep decreasing until 1990.

In summary, the results show different effects of storm surges on the long-term salt marsh development in Friesland and Groningen. The causes of this different salt marsh behaviour along the mainland coast of the Wadden Sea will be treated in the discussion of this chapter.

Short term effects of storm surges on salt marsh development

The effects of specific calendar years with high storm surge levels on salt marsh development were studied. The water levels during the storm days were averaged for each measuring year (Figure 6.6). Five years with high storm surge levels were selected as storm years and shown in Table 6.1. Effects of these storm years, followed by calm years (see Figure 6.4), on the salt marsh morphology were analysed and the same patterns appear. The year 1990 is used as an example to treat these patterns. In this year, 31 storm days occurred with an average wind speed of 12.2 m/s in combination with an average high water level during the storm days of 2.06 m. These values are high compared to the average amount of 16 storm days per year, the average top 10% of the wind speed of 11.3 m/s and the average high water level of 1.75 m during storm days for all years.

![Figure 6.6](image)

Figure 6.6 - Average and maximum water levels during storm days between 1971 and 1998. 1990 is defined as the storm year.
In Figure 6.7 the accretion and erosion surfaces are shown before, during and after the storm year of 1990. Both salt marsh areas of Friesland and Groningen showed the same patterns. At the beginning of the storm year the accretion surface decreased and the erosion surface increased. The decrease in accretion surface is 8.7% in Friesland and 3.1% in Groningen. The increase in erosion surface is 139.2% in Friesland and 4.0% in Groningen. During and at the end of the storm year the accretion surface started to increase and the erosion surface started to decrease. The increase in accretion surface was 6.7% in Friesland and 14.6% in Groningen. The decrease in erosion surface is 17.7% in Friesland and 17.8% in Groningen. Two years after the storm year the accretion and erosion surfaces approximately returned to the state prior to the storm year. For Friesland

Table 6.1 - Five years with a large number of storm days, high average wind speed and high average high water levels during the storm days

<table>
<thead>
<tr>
<th>Number of storm days</th>
<th>Top 10% wind speed</th>
<th>Average high water level during storm days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>20</td>
<td>11.8</td>
</tr>
<tr>
<td>1981</td>
<td>22</td>
<td>11.5</td>
</tr>
<tr>
<td>1983</td>
<td>27</td>
<td>12.2</td>
</tr>
<tr>
<td>1990</td>
<td>31</td>
<td>12.2</td>
</tr>
<tr>
<td>1994</td>
<td>22</td>
<td>12.1</td>
</tr>
</tbody>
</table>

In Figure 6.7 the accretion and erosion surfaces are shown before, during and after the storm year of 1990. Both salt marsh areas of Friesland and Groningen showed the same patterns. At the beginning of the storm year the accretion surface decreased and the erosion surface increased. The decrease in accretion surface is 8.7% in Friesland and 3.1% in Groningen. The increase in erosion surface is 139.2% in Friesland and 4.0% in Groningen. During and at the end of the storm year the accretion surface started to increase and the erosion surface started to decrease. The increase in accretion surface was 6.7% in Friesland and 14.6% in Groningen. The decrease in erosion surface is 17.7% in Friesland and 17.8% in Groningen. Two years after the storm year the accretion and erosion surfaces approximately returned to the state prior to the storm year. For Friesland
The accretion surface was 16 km² and the erosion surface was 4 km² and for Groningen the accretion surface was 19 km² and the erosion surface was 12 km².

The net changes of the volume also showed the same pattern for the Friesland and Groningen salt marshes (Figure 6.7). At the start of the storm year there was a decrease in volume change. This means that there was less accretion than before the storm year. The decrease in accretion is 25.5% in Friesland and 45.5% in Groningen. During the storm year there was an increase in volume change, so more accretion took place. This accretion is almost twice as high as before the storm year. The year after the storm year, there is a decrease in volume change resulting in less accretion. The decrease is 62.9% in Friesland and 76.3% in Groningen. Two years after the storm year there is another increase in volume change, resulting in more accretion. This accretion is more than twice as high as before the storm year in Friesland and even almost three times as high in Groningen. Two years after the storm both salt marsh areas have been recovered. The above-described patterns of volume changes are comparable but there is an important difference between the development of the Friesland and Groningen salt marsh areas as a result of a storm year. In the Friesland salt marshes, there is a decrease in volume change but negative values are never reached, whereas in the Groningen salt marshes from the start of the storm year and in the year after the storm year show negative volume changes. This means that in the Friesland salt marshes net accretion continues despite of a storm year whereas in the Groningen salt marshes net erosion occurs.

The results show that a storm year has a temporarily negative influence on salt marsh development, because it causes a decrease in accretion or even erosion at the start and in the year after the storm year. In the Groningen salt marshes there is a delicate balance between the accretion volume and the erosion volume. As a result of a storm year this balance becomes negative and erosion occurs. The Friesland salt marshes, which have a more stable positive accretion balance, show continuous accretion despite the storms in 1990. Both salt marsh areas return to the initial state after some years, which has a positive accretion balance.

The development of the vegetated salt marsh is shown in Figure 6.8. The storm year 1990 lead to net growth of the vegetated salt marsh in the Friesland salt marsh area. There is no
net effect of storm year on the vegetated salt marsh in the Groningen salt marshes. These patterns agree with the almost linearly growth of the vegetated salt marsh in Friesland and the growth stagnation after 1985 in Groningen (Figure 6.2). It is remarkable that the long-term trend of accretion is not permanently disturbed by periods of stormy years.

6.3.2 Morphological development within the Friesland and Groningen part of the salt marsh coast between 1965 and 1995

Accretion and erosion patterns
Besides general temporal changes in accretion and erosion surfaces and volumes, variation in salt marsh development occurs within the study areas of Friesland and Groningen. The height development within the Friesland salt marshes between 1965 and 1995 is shown in Figure 6.9. The net erosion and accretion patterns that appear showed hardly any net

Figure 6.9 - Height development of the Friesland salt marshes 1965-1995. See Figure 1.1 for location of the area.

Figure 6.10 - Height development of the Groningen salt marshes 1965-1990. See Figure 1.1 for the location of the area.
erosion in this period for the Friesland salt marshes. Furthermore, the accretion increased in the direction of the lower and middle marsh. The Friesland salt marsh coast was divided in four areas considering the accretion patterns. Accretion and erosion surfaces and height changes in these areas are shown in Table 6.2.

Table 6.2 - Accretion, erosion surfaces and height changes in the Friesland salt marshes between 1965 and 1995

<table>
<thead>
<tr>
<th>Area</th>
<th>Erosion surface (in %)</th>
<th>Erosion rate (m/30y)</th>
<th>Accretion surface (%)</th>
<th>Accretion rate (m/30y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0.70</td>
</tr>
<tr>
<td>F2</td>
<td>1</td>
<td>0.03</td>
<td>99</td>
<td>0.27</td>
</tr>
<tr>
<td>F3</td>
<td>4</td>
<td>0.07</td>
<td>96</td>
<td>0.34</td>
</tr>
<tr>
<td>F4</td>
<td>11</td>
<td>0.06</td>
<td>89</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Between 1965 and 1995, the accretion surface (Table 6.2 and Figure 6.9) decreased in an eastern direction. However, in the east (area F4), the accretion surface still covered 89% of the salt marsh. The accretion and erosion rates are low with values between 0.05m and 0.27m over a period of 30 years. In the western part of the Friesland (area F1) salt marshes have accreted with 0.70 m between 1965 and 1995. Salt marsh development in the central and most eastern part of Friesland (area F2 and F4) is comparable with accretion rates of 0.27 and 0.20 m and erosion rates of 0.03 and 0.06 m between 1965 and 1995. But the area in which erosion occurred is larger in the east compared to the central (11% versus 1%). In between the central and eastern part of the Friesland salt marshes (area F3) there is an area with a higher accretion rate of 0.34 m, bordered by areas that have eroded at a rate of 0.07 m between 1965 and 1995.

The height development of the Groningen salt marshes is shown in Figure 6.10. Height differences could only be calculated between 1965 and 1990. Due to a lack of measurements after 1993, the last period of five years was left out of the analysis. More and larger areas of net erosion appear in the Groningen salt marshes between 1965 and 1990, compared to the Friesland salt marshes.

Furthermore, the accretion increased towards the lower and middle marsh in areas G1, G2 and G4, but decreased towards the lower and middle marsh in area G3. The Groningen salt marsh coast was divided in four areas considering the accretion patterns. Accretion and erosion surfaces and height changes for these areas are shown in Table 6.3.

There was a large variation in accretion and erosion surface percentages along the Groningen salt marsh coast from 1965 to 1990. In the most western and most eastern area (area G1 and G4) respectively 55% and 70% of the area has eroded at a rate of 0.12 m. In the accretion area of area G1 and G4, the accretion rates were low with values of 0.17 and 0.14 m, compared to area G2 and G3, which have accretion values of 0.27 and 0.23 m. The accretion surfaces in area G2 and G3 were very large with values of 99.5% and 92%. The erosion rates were similar for area G2 and G3 with values of 0.05 and 0.06 m. The main difference between area G2 and G3 is the cross-shore accretion pattern. In area G2 accretion
increased towards the lower and middle marsh, whereas in area G3 accretion decreased towards the lower and middle marsh. This difference will be explained in the next paragraph.

Morphological changes in the Wadden Sea
In Figure 6.11 and 6.12 morphological changes of two tidal basins between 1986 and 1995 are shown. The area considered does not include the salt marshes along the mainland coast. The Friesland salt marshes are part of the tidal basin shown in Figure 6.11 and the Groningen salt marshes are part of the tidal basin shown in Figure 6.12. Budget calculations show that the area in which erosion occurred and the area in which accretion occurred between 1986 and 1995 both covered approximately 50% of the basin area. For both basins volumetric changes between 1986 and 1995 in erosion and sedimentation were equal: 11*10^6 m^3 for the Friesland basin and 36*10^6 m^3 for the Groningen basin. The Groningen basin is more than twice as large as the Friesland basin, but the volumetric calculations showed that relatively more sediment has been moving around in the Groningen system compared to Friesland.

The largest morphological changes took place in the channels of the tidal inlets between the barrier islands (Figure 6.11 and 6.12). Closer to the coast the morphological changes were small and channel migration was slower than in the tidal inlets (Figure 6.11 and 6.12). Therefore the migration of channels cannot explain the differences in accretion and erosion patterns along the mainland salt marsh coasts between 1965 and 1995.

Water level and wave energy
Because the sediment budget and the location of the tidal channels (within the basin) have not significantly changed over the last decade, the present morphology of the Wadden Sea (Figure 6.13) could be related to the different accretion and erosion patterns occurring between 1965 and 1995 along the salt marsh coasts.

The influence of the seaward morphology on accretion patterns in the salt marshes was studied through differences in water level and wave heights along the coast. A wave model (SWAN) was used by Wolf et al. (2000) to calculate water levels and wave height in the salt marshes during a storm from north-north-western direction with wind speeds of 14 m/s. The wind speed of 14 m/s was the closest model possibility to the top 10% wind speed of 11.3 m/s, which was used in Chapter 6.3.1. Storms like this appear to be important in salt marsh development along the Wadden Sea mainland coast (see 6.3.1;
Chapter 5; Janssen-Stelder, 2000b). A fixed water level of 3 m + NAP was used at the start of the modelling because then the salt marshes are completely submerged. A compound depth configuration, of data collected between 1980 and 1996, was used in the model.

The model results are shown in Figure 6.14, 6.15 and 6.16. Figure 6.14 indicates that during the storm, wave propagation from the North Sea into the Wadden Sea is limited. Waves break on the ebb tidal deltas and wave heights reduce to an order of 50% when propagating through the main tidal channels in the tidal inlets. On the tidal flats behind the barrier islands, waves do not achieve heights higher than about 1 m, diminishing to approximately 0 m at some locations in the salt marshes along the coast. Figure 6.15 and 6.16 show modelled water levels, significant wave heights and wave periods during the storm at the sea dike in the study area along the salt marsh coasts of Friesland and Groningen. Average values of the modelled water depth ($h$), wave height ($H_{1/3}$) and wave period ($T_{1/3}$) are given in Table 6.4.

Table 6.4 - Modelled water depth ($h$), wave height ($H_{1/3}$) and wave period ($T_{1/3}$) at the dike of the Friesland and Groningen salt marsh coast.

<table>
<thead>
<tr>
<th></th>
<th>$h_{\text{average}}$ (in m)</th>
<th>$H_{1/3 \text{average}}$ (in m)</th>
<th>$T_{1/3 \text{average}}$ (in s)</th>
<th>$H_{1/3}/h_{\text{average}}$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friesland</td>
<td>1.52</td>
<td>0.43</td>
<td>2.7</td>
<td>0.28</td>
</tr>
<tr>
<td>Groningen</td>
<td>1.74</td>
<td>0.60</td>
<td>4.2</td>
<td>0.34</td>
</tr>
</tbody>
</table>

At the dike along the Friesland coast (Figure 6.15) greater significant wave heights and significant wave periods occur in the most western and most eastern part of the area during the storm. In the western part of the area especially higher wave periods occur. At the dike along the Groningen coast (Figure 6.16) greater water depths, significant wave heights and significant wave periods occur around coordinate 225000 and especially in the most eastern part of the area.

At the dike along the Groningen coast the average water depth is 0.22 m higher than at the dike along the Friesland coast. Water depth is related to significant wave height (as shown in Chapter 5.3) and therefore the average significant wave height is higher for the Groningen part of the coast (0.60 m versus 0.43 m), but also the relative wave height ($H_{1/3}/h$) is higher along the Groningen coast (0.34 versus 0.28). The average significant wave period is 4.2 s for Groningen and 2.7 s for Friesland. Longer waves reach the Groningen coast, meaning that more wave energy from the North Sea can propagate to the Groningen coast as compared to Friesland.
Figure 6.13 - Present morphology seaward in the Friesland (A) and Groningen (B) part of the Wadden Sea.

Morphological development of the salt marshes
This paragraph treats the way in which alongshore variation in water depth and wave parameters is a function of the morphology of the Wadden Sea, and how this affects the accretion patterns in the salt marshes. The assumption is made that the modelled storm is a representative one for salt marsh development along the mainland coast of the Wadden
Sea. This assumption is based on the results of Chapter 5 and Chapter 6.3.1.

The spatial variation in water levels and wave parameters is related to the morphology of the Wadden Sea and helps to explain the spatial variation in height development of the salt marshes along the mainland coast between 1965 and present. Relations between height development and Wadden Sea morphology were already treated in Chapter 4.3.2. The salt marsh areas with different accretion patterns between 1965 and present, distinguished in Figures 6.9 and 6.10, are indicated in the figures showing the Wadden Sea morphology (Figure 6.11 and 6.12) and in the diagrams showing the alongshore patterns in water levels and wave parameters during the modelled storm (Figure 6.15 and 6.16).

In Table 6.5 average water levels and wave parameters of the modelled storm are shown for the four different accretion areas along the salt marsh coast of Friesland.

In area F1 the average relative wave height (H_{1/3}/h) of 0.36 and the average significant wave period of 3.4 s are high compared to the other three areas. Area F1 is located behind a tidal inlet (Figure 6.11). During stormy conditions higher and longer waves can propagate in the direction of the coast (Figure 6.14). These waves have a larger transport capacity than the waves approaching the coast in areas F2, F3 and F4. Due to the fact that area F1 is located in the vicinity of a tidal divide (Figure 6.11), large amounts of sediment are
available for transport. At a tidal divide, currents from opposite direction meet and sediment settles during calm conditions. During stormy conditions this sediment can be resuspended and transported towards the coast. The combination of high and long waves during storms and a source of sediment may have resulted in accretion in area F1 in the period of 1965-1995 at high rates of 0.7 m (Figure 6.9 and Table 6.2).

<table>
<thead>
<tr>
<th>Area</th>
<th>h average (in m)</th>
<th>H₁/₃ average (in m)</th>
<th>T₁/₃ average (in s)</th>
<th>H₁/₃h average (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area F1</td>
<td>1.42</td>
<td>0.51</td>
<td>3.4</td>
<td>0.36</td>
</tr>
<tr>
<td>Area F2</td>
<td>1.28</td>
<td>0.35</td>
<td>2.2</td>
<td>0.27</td>
</tr>
<tr>
<td>Area F3</td>
<td>1.13</td>
<td>0.33</td>
<td>2.5</td>
<td>0.30</td>
</tr>
<tr>
<td>Area F4</td>
<td>1.81</td>
<td>0.48</td>
<td>2.8</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Table 6.5 - Modelled water depth (h), wave height (H₁/₃) and wave period (T₁/₃) at the dike of the Friesland salt marshes

Figure 6.15 - Water levels, significant wave heights and significant wave periods along the Friesland part of the salt marsh coast.
Areas F2, F3 and F4 have similar average relative wave heights and the average significant wave periods (Table 6.5). Short wind waves characterise the areas during stormy conditions. However, there are some fluctuations in the modelled water levels and wave heights along the shore (Figure 6.15). High values in significant wave height (0.5 m) and period (3 s) occur at the sea dike along the salt marsh coast where tidal channels are present seaward of the salt marshes (Figure 6.11 and 6.15).

In Table 6.6 average water levels and wave parameters of the modelled storm are shown for the four different accretion areas along the salt marsh coast of Groningen.

The average water depth decreases from area G1 towards area G3, but average significant wave heights are similar in areas G1, G2 and G3 (Figure 6.16). In area G4 the average water depth and average significant wave height are significantly larger. Despite these differences, the modelled relative wave heights are fairly similar along the entire coast (Table 6.6). There are two clear peaks in the significant wave period along the coast, in area G2 and G4 (Figure 6.16). Through two main channels of the tidal inlets longer waves can propagate towards the coast in these areas (Figure 6.13).
Directly seaward of area G1 a tidal channel is eroding towards the coast (Figure 6.12). Due to a lack of sediment supply, 50% of this area has been eroding in the period from 1965 to 1995. Area G2 is located behind a large tidal channel with an orientation perpendicular to the coast (Figure 6.13). Therefore longer waves can propagate towards the coast (Table 6.6). Large mudflats on the tidal divide are located directly seaward of the salt marshes of area G2. These mudflats are a source of sediment that is supplied to the coast by currents and long waves propagating through the large channel system during storms. This may have resulted in accretion in 100% of area G2 at a rate of 0.27 m in the period of 1965-1990. The development in this area is rather similar to area F1 along the Friesland salt marsh coast.

A large tidal channel with an orientation parallel to the coast is present directly seaward of area G3 (Figure 6.13), and accretion occurred in 92% of the area. Most of the accretion occurs in the front of the salt marshes and decreases towards the sea dike (Figure 6.10). This accretion zone can be interpreted as a kind of channel bank deposit. Furthermore, the water levels west and east of area G3 are higher than within the area (Table 6.6) leading to a sediment supply towards the area during storms.

In area G4 significant wave height and period increase towards the east (Figure 6.16). The outer bend of a large and deep channel of the Ems estuary lies in front of the salt marshes of area G4 (Figure 6.13). This channel is eroding the mudflats in front of the salt marshes and therefore leaving no sediment source for the salt marshes. High hydrodynamic energy and no sediment source resulted in erosion of 70% of the salt marshes in area G4 at a rate of 0.12 m in the period of 1965-1990.

In general, during storms, higher (0.50 m) and longer (3-5 s) waves can approach the salt marshes when the salt marshes are situated behind tidal inlets or in the vicinity of large tidal channels. Whether this results in a larger sediment supply towards the salt marshes depends on the presence of a sediment source in the vicinity of the salt marshes. A sediment source can be located at a tidal divide or on extensive mudflats seaward of the salt marshes. Furthermore, the morphology causes variations in water level during storms and sediment is transported towards a salt marsh area with lower water levels.

### Table 6.6 - Modelled water depth (h), wave height (H1/3) and wave period (T1/3) at the dike of the Groningen salt marshes

<table>
<thead>
<tr>
<th></th>
<th>h average (in m)</th>
<th>H1/3 average (in m)</th>
<th>T1/3 average (in s)</th>
<th>H1/3/h average (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area G1</td>
<td>1.70</td>
<td>0.54</td>
<td>3.1</td>
<td>0.31</td>
</tr>
<tr>
<td>Area G2</td>
<td>1.64</td>
<td>0.56</td>
<td>4.1</td>
<td>0.34</td>
</tr>
<tr>
<td>Area G3</td>
<td>1.45</td>
<td>0.52</td>
<td>3.7</td>
<td>0.36</td>
</tr>
<tr>
<td>Area G4</td>
<td>2.24</td>
<td>0.77</td>
<td>5.2</td>
<td>0.34</td>
</tr>
</tbody>
</table>

6.4 Discussion

Rijkswaterstaat have already studied the morphological development of the salt marshes of...
the Dutch mainland coast since the completion of the sedimentation fields in 1960. However, the studies were restricted to the salt marsh development along separate transects. In this study, spatial interpolation was used to examine the development of the mainland salt marsh area. In this way temporal and spatial salt marsh surface development, volume changes and seaward extension have been quantified for the coasts of Friesland and Groningen.

The effect of variations in water level on salt marsh development was already recognised by Dijkema et al. (1990). They ascribed the retreat in salt marsh development between 1975 and 1985 to an increase in mean high water level from 1971 until 1983. The present study reveals that the combination of an increase in the amount of days with high wind speed per year and increasing high water levels up to 1983 have had a temporary deteriorating effect on salt marsh development.

At a small time scale, one year with high storm surge levels followed by calm years has the same effect on salt marsh development in Friesland and Groningen (Figure 6.8). At the start a year with high storm surge levels induce erosion. During and at the end of the storm year accretion takes place. During a year with many storm surges much fine sediment is transported towards the shores and is available for accretion. Erosion occurs in the year after the storm year because in a storm year many seeds and seedlings are washed away (Houwing et al., 1995). Therefore, in the next year the pioneer zone is less well developed and protects the salt marsh to a lesser extend. This results in erosion of the salt marsh. Two years after the storm year sedimentation in the salt marsh has recovered. The long-term trend of accretion as shown in Figure 6.2 is not permanently disturbed by stormy years.

The modelled storm (Chapter 6.3.2) is used as indicative for differences in salt marsh development along the mainland coast. Depending on the Wadden Sea morphology, sediment can be transported into the salt marshes or not. Therefore, in some cases storms can locally lead to onshore deposition of sediment. This seems in contradiction with the offshore fluxes measured during storms as discussed in Chapter 5, but in that chapter only the upper mudflat and pioneer zone were considered. In this chapter the entire salt marsh, pioneer zone and upper mudflat are part of the studied area. During a storm, erosion of the pioneer zone/mudflat and deposition on the vegetated salt marsh can occur simultaneously. This can have a net result of deposition over the entire area.

Results from this chapter showed that during sea level rise and an increase in storm frequency and duration, the salt marshes of Groningen have been susceptible to erosion. The Friesland salt marshes have adjusted better to such changes in the past. The salt marshes have a stable accretion balance at the moment and are therefore robust. The difference in long-term accretion balance between the coast of Friesland and Groningen may be related to differences in embankment history. In Groningen more extensive embankments were executed than in Friesland (Dijkema, 1987b). Therefore the salt marshes that were formed after the constructions of the brushwood groins were located at lower levels than the Friesland salt marshes. The first part of the salt marsh growth curves (Figure 6.2) is linear for both areas. Assuming that this linear fit is valid for the past, the starting point of the development of the vegetated salt marsh is both Friesland and Groningen lies around 1945. This seems reasonable since almost all of the present salt marshes have developed as a result of the brushwood groins (after 1935). The Groningen
Salt marshes are part of a tidal basin that is still adjusting to the closure of the Lauwerszee. This could explain why the growth curve of Groningen (Figure 6.2) is sloping to a maximum, while the Friesland salt marsh area is still extending.

Another part of the explanation to why the long-term accretion balance differs between the coast of Friesland and Groningen may lie in the different type of tidal basin and the different exposure of the salt marshes. The Groningen salt marshes are part of a more dynamic tidal basin than the Friesland salt marshes because more sediment is being moved around in the Groningen tidal basin. Furthermore, the Groningen salt marsh coast is located behind a system of large tidal inlets with very small barrier islands and is therefore more exposed than the Friesland salt marsh coast, which is located almost entirely behind a large barrier island. Therefore, the hydrodynamic conditions during storms are rougher in the Groningen salt marshes and less accretion can occur.

Soil subsidence due to gas extraction in the Wadden Sea also influences the net accretion rates in the salt marshes. Presently, subsidence rates of 0.02 m are calculated for the eastern half of the Friesland salt marshes in the year 2000 (Oost and Dijkema, 1993). In the period of 1965-1995 accretion rates in this area varied between 0.30 m and 0.50 m. An influence of the subsidence of 0.02 m will therefore not be noticeable here. For the eastern part of the Groningen salt marshes subsidence rates between 0.04 m and 0.08 m are predicted for the year 2000 (Oost and Dijkema, 1993). This will also not be noticeable compared to the accretion rates between 1965 and present.

6.5 Conclusions
The salt marsh coast of the Dutch Wadden Sea has been accreting since 1965. The accretion is almost linear for the Friesland part of the salt marshes. In the Groningen salt marshes the growth is asymptotic, with near stagnation since 1985.

At a large time scale (decades), the Friesland salt marshes rapidly respond to changes in wind speed and high water levels. The Groningen salt marshes react slower to changes in wind speed and high water levels compared to the Friesland salt marshes.

At a small time scale, the effect of one year with many storm days in combination with high water levels, followed by calm years, is similar for the Friesland and Groningen salt marshes. At the beginning of the storm year and in the year after the storm year erosion occurs and in the storm year accretion occurs. The salt marsh area recovers in some years after the storm year.

Differences in hydrodynamic energy during storms can explain spatial differences in accretion patterns within the Friesland and Groningen salt marsh areas. The presence of tidal channels or mudflats seaward of the salt marshes cause differences in hydrodynamic energy. Mudflats are sources of sediment, but tidal channels are needed to transport the sediment to the salt marshes. Similar relations between Wadden Sea morphology and accretion patterns in the salt marshes were also treated in Chapter 4. The salt marshes of the Wadden Sea are part of a larger system and will therefore be affected if the morphology of the Wadden Sea changes.