CHAPTER 143

SAND BUDGET OF THE DUTCH COAST

The Dutch Coast: Paper No. 4

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1. Introduction

About 255 kilometer (70%) of the Dutch coast is protected against flooding and storm surges by dunes. Another 43 kilometer is defended by dikes with a sandy nearshore. The sand is transported by physical processes in alongshore and onshore-offshore direction. As a result the coast shows continuous alternations. A detailed sand budget is very useful to gain insight into the dynamics of the coast and of different morphological zones. Within the framework of the Coastal Defence Study in the Netherlands recent advances in modelling of large scale coastal development were made (Louisse and Kuik, 1990; Stive, Roelvink and De Vriend, 1990). Verification and calibration of these models is possible by comparing the model results with the sand budget of the coast.
According to the Shore Protection Manual (1984) the sediment budget is defined as a sediment transport volume balance for a selected segment of the coast. The elements of the budget are processes that increase (sources) or decrease (sinks) the quantity of sand in a defined control volume. Usually a sand budget analysis is made to calculate an unknown erosion or deposition rate by estimating the different elements of the budget like for instance longshore transport, on- and offshore sand movement and the building or erosion of dunes. The method is clearly described by Bowen and Inman (1966) and Chapman (1981).
The balance itself is defined by Bowen and Inman (1966) and Komar (1983) as the component of the budget that gives the net gain or loss of sand in a control volume. This balance is obtained by monitoring the erosion or deposition rate over a number of years. This paper is concerned with the sand balance of the Dutch coast over the years 1965 - 1986. A method for calculating the balance based on yearly measured profiles is described. Besides the more general results for the Dutch coast a more detailed example of the Schouwen peninsula is given.

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2. Measurements

Along the Dutch coast in the second half of the 19th century a monitoring system was set up to observe the coastal development. Therefore along the whole Dutch North Sea coast poles were placed on the beach at a distance of 1000 m. The line connecting these poles is the reference line for coastal monitoring. The beach poles were placed between the mean high water line and the foot of the dune.
The position of the mean low water line, the mean high water line and location of the foot of the dune is measured yearly with respect to the reference line. In this way a detailed picture of the development of the coastline during the last 100 to 140 years is obtained.
Since 1964 the morphological monitoring is considerably enhanced. A system of about 2000 fixed measuring lines perpendicular to the coastline has been established. The distance between the lines is 200 - 250 meter, less where the coastline is curved.
The height and depth are determined in respect to Dutch Ordnance Datum (NAP) which is about mean sea level. To define the horizontal position in the profiles the original reference line is maintained. Because of the coastline changes since the poles were placed there is no relation between the location of the reference line and the present morphology.
Until 1975 the measurements of the dry part of the profiles were carried out by levelling from the mean low water line to the top of the first dune row. From 1975 onwards the heights are determined by aerialphotography and were extended to at least 200 meter inland from the top of the first dune row.
The measurements of the underwater part of the profiles are carried out by echo-sounding from the low water line to at least 800 m out of the reference line. In several parts of the coast, especially in the Wadden Area the profiles reach much further seaward, up to about 1500 meter.
The survey area includes the first dune row, the beach and the surfzone. Some tidal channels in front of the Delta en Wadden Islands are situated within the reach of the measurements. The tidal deltas and inlets are not included in the data set.
The profiles are measured annually in the non-storm period from April to September and are not equidistant in time. Apart from normal measurement inaccuracy the dataset still contains systematic and random errors due to wrong individual height or depth values or to faults in the distance to the reference line or reference height. To correct for these errors a visual validation is executed by plotting all the yearly profiles of a measuring line together and remove or correct the unreliable values. This procedure can lead to the elimination of yearly profiles or to total elimination of a measuring line from the data set.
In the years before 1975 the levelling was not executed far enough inland to reach a more or less closed boundary in the dunes. The photogrammetrical height measurements do come up to this requirement. For the coast of Holland it was possible to lengthen the earlier profiles by complementary investigations of detailed maps of the dune area (De Ruig, 1987). The dunes in the Wadden Area and the Delta Area are too dynamic to allow such a procedure.
In addition to the yearly measurements every 5 year 2500 m long profiles are measured with an interval of 1000 m along the coast. This has resulted in a dataset of 3 to 4 profiles for each measuring line, what is not yet sufficient for a reliable trend analysis.

3. Method

To make a useful sand balance the following main conditions are specified:
- the relation between the transport processes and the morphological changes must be well connected
- the balance must describe the natural development of the coast (as far as possible on the Dutch coast with dikes, revetments, groynes and harbour moles)
- the control volume only consists of those parts of the nearshore from which the sediment transport is directly related to the safety of the coast.

The first condition means that the changes in volumetric content between predefined upper and lower boundaries must be calculated. Every part of the profile within such a layer accounts for the content (figure 1).
Optionally the upper boundary coincides with the maximum height measured in a yearly profile. This option is used if one wishes to calculate the yearly loss or gain of sediment due to storm surges and eolian sand transport. The other option is to choose a relevant height, for instance mean low-water level.
The lower boundary is formed by the maximum depth within the reach of all measured depths of a specific profile or by an other suitable depth.
It is obvious that the position of the horizontal boundaries determines which of the morphological processes account for the calculated changes.
The already mentioned landward boundary is situated landward of the first dune row. It is preferable that inland of this point the elevation of the profile is more or less constant. In this case there is no net transport through the boundary. Otherwise the transport rate has to be estimated.
All the boundaries are determined for each profile and are time independent, except for the optional "free" upper boundary.
To calculate the volumetric content between two adjacent profiles it is assumed that a profile is representative for the area between the profile and the bisector (figure 1). Given a horizontal distance of less than 200 - 250 m this seems a realistic assumption. Only for small-scale safety problems this assumption must be checked. The first calculated area between two profiles coincides with the lower boundary. This area is multiplied by a given height of 0.1 meter and the procedure is repeated until the upper boundary is reached. The content of the control volume is calculated.
From 1952 onwards beach nourishment projects have been carried out at several locations. Because the sand balance must give insight in the "natural" development of the Dutch coast (second mentioned limiting condition) the calculated contents are corrected with the amount of supplied sand brought into the control volume (Roelse, 1990). There is no correction made for the possible loss of supplied material out of the control volume due to the redistribution of sediment.
Also activities to restore the dune profile after storm surges can influence the amount of sand in the control volume. Other examples of artificial displacement of sand are the building and conservation of elevated beach sections against the dunes to protect recreational facilities on the beach. It is assumed that the involved quantities are small compared with natural sand transport rates. Usually there is only a redistribution of sand within the control volume.
Given the corrected yearly sand content, the net gain or loss of sand in a given period

is calculated by a linear regression analysis.
To gain insight in the annual variations the mean, minimum and maximum value of the difference in sand volumes of the successive years are calculated. Short-term events, such as storm surges, are averaged out.

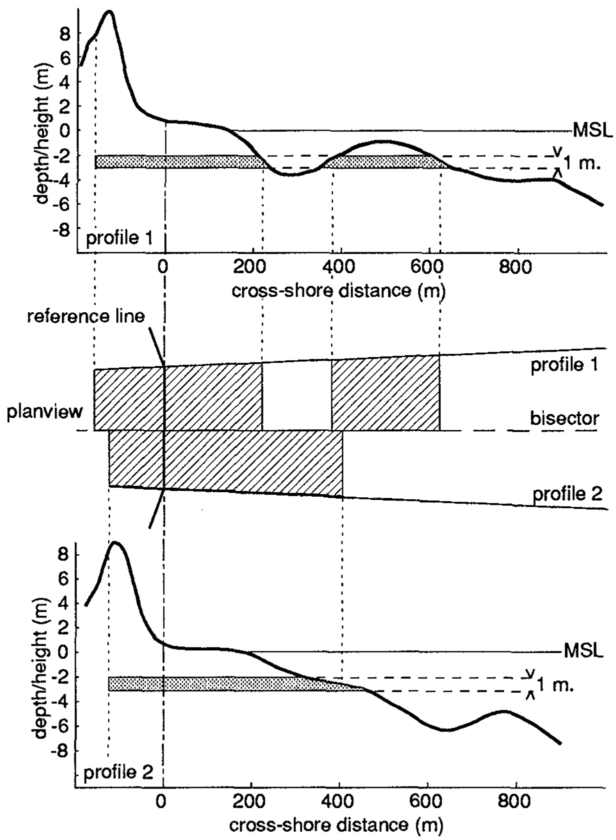

figure 1.Sketch to define the calculation procedure.

4. Results Dutch coast sections

As a first approach the changes in volumetric content of 13 coast sections are calculated. These sections are separated from each other by ebb tidal deltas (Wadden), harbour moles (coast of Holland) and estuaries and tidal basins (Delta). These interruptions are the cause of a more or less independent development of adjacent sections. All sections have specific control volumes from which the balance is calculated.
The length of a section is determined by the first and last measuring line.
The vertical dimension depends, besides on the length of the measured profiles, on the

local morphology. The lower boundary varies from 3 - 10 m along the central parts of the islands and the coast of Holland. The depth of the tidal channels within reach of the measurements varies from 10 - 30 meter. The upper boundary coincides with the maximum height of the profile. This means that sedimentation or erosion in the first dune row are accounted for.

The measurements on the coast of Holland are far enough inland to reach a more or less closed boundary (de Ruig, 1987) The transport rate across the landward boundary in the Wadden and Delta Area are not yet estimated.

It is certain that the lower boundary do not reach the closure depth for cross-shore sand transport at de Dutch coast. This is indicated by the 5 yearly measurements and other, more local, repeated profiling which extended to a greater depth. Roelvink (1990) calculated an onshore transport across the -10 meter line in the order of 10 m3/m/year. This is an important source term in the sand budget.

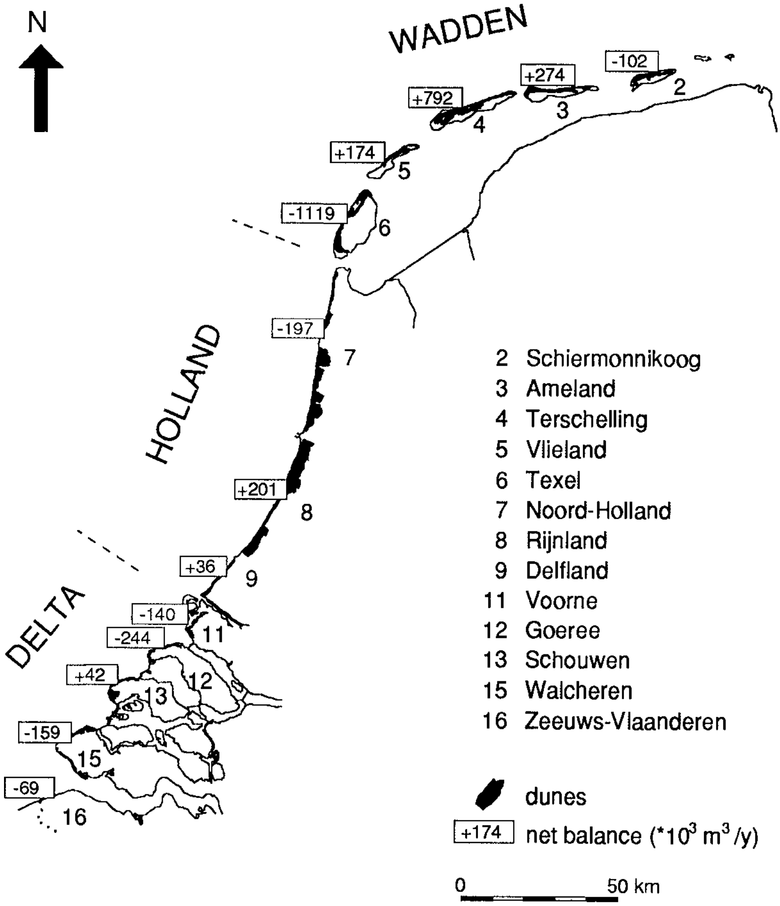

figure 2.Calculated sand balance of the Dutch coast.

Despite of the above mentioned uncertainties the sand balance is calculated (figure 2). The total sum of -511*103 m3/y indicates that over the specified period of 20 years and a length of about 302 km the Dutch coast is very slowly eroding (-2 m3/m/y). On the scale of separate coast sections, 8 - 53 km, the variability is much greater. Trends normalized to coast length of -41 up to +28 m3/m/y are calculated (table 1). The difference between the coastal sections are great in respect to the total sum.
The dynamic of a sandy coast is best illustrated by the yearly fluctuations. The mean value varies from 19 to 68 m3/m/y. The minimum and maximum yearly difference amount to respectively 0 and 369 m3/m/y. Due to this large time variability the reliability of the calculated trends depends strongly on the number of validated measured years.

table 1.Calculated sand balance of the Dutch coast.

	period	trend $m^3/m/y$	yearly fluctuations mean $m^3/m/y$	minimum $m^3/m/y$	maximum $m^3/m/y$
Schiermonnikoog	1966-1986	-7.	45.6	9.4	195.5
Ameland	1968-1984	11.	51.7	10.8	226.5
Terschelling	1969-1985	28.	45.9	3.8	146.3
Vlieland	1970-1984	8.	60.5	4.2	171.8
Texel	1965-1986	-41.	44.0	6.7	109.1
Noord-Holland	1965-1984	-4.	19.4	2.1	58.9
Rijnland	1965-1984	4.	33.3	6.2	79.3
Delfland	1965-1984	3.	62.4	0.4	142.2
Voorne	1966-1972	-17.	20.5	7.3	49.9
Goeree	1967-1981	-25.	67.8	1.2	369.4
Schouwen	1968-1983	3.	24.3	0.3	53.0
Walcheren	1969-1986	-6.	21.2	1.4	44.6
Zeeuws-Vlaanderen	1966-1984	-5.	40.2	8.2	150.2

5 Result Schouwen

5.1 Introduction

The peninsula of Schouwen is situated in the Delta Area between the tidal basins "Grevelingen" in the north and "Oosterschelde" in the south (figure 3). The tidal channel "Brouwershavense Gat" in front of the north coast of Schouwen is silting up now, due to the closure of the Grevelingen basin in 1972. A branch of this tidal channel, the "Schaar van Renesse" is situated very close to the coastline (figure 4). In the south the "Westgat" is one of the main tidal channels at the entry of the Oosterschelde. There is another tidal channel, "Krabbengat", around the west coast (figure 4). The tidal range is 2.5 meter.
The human interference with the about 17 km long North Sea coast of Schouwen is restricted to the construction of groynes on the northern part and pile rows on the western

part. Furthermore, there is the usual maintenance of the first dune row like planting of beach grass. The groynes were placed in the middle of the 19th century and were very effective in preventing coastline erosion by the Schaar van Renesse (Verhagen, 1989a). The coastal development in this coastal stretch is not complicated by beach or dune nourishment in the period (1968 - 1983).

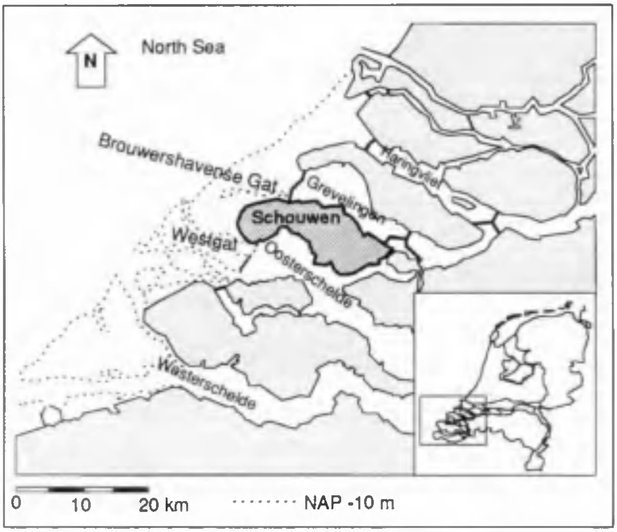

figure 3.The Delta Area with the peninsula of Schouwen.

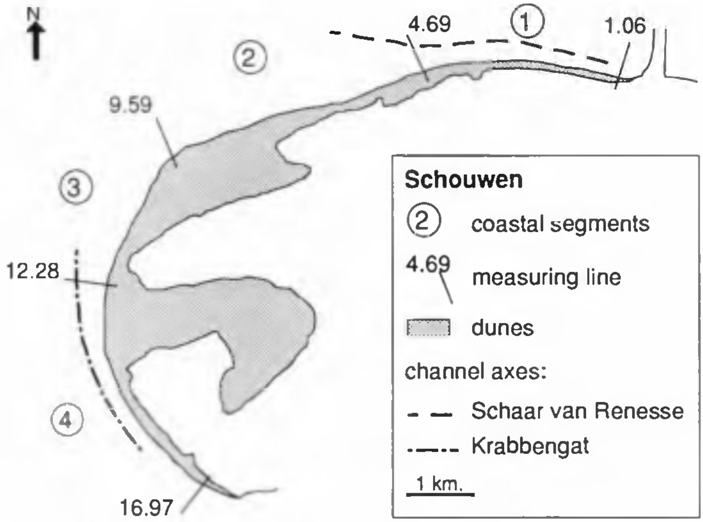

figure 4.Dune coast of Schouwen with channel axes within reach of measurements.

5.2 Profiles

The measuring lines along the part of the coast considered in this case study are numbered from beach pole 1.06 to beach pole 16.97 (figure 4). The numbering of the poles is related to a kilometer scale so the length of coast along the reference line is 15.9 km. In this area 91 measuring lines are situated.
The profile along the coast of Schouwen is not uniform but shows spatial and temporal variations. There is an obvious morphological difference between the northernmost and western coastal stretches, where tidal channels are situated close to the coastline, and the central part where the nearshore profile is more gentle. In the central part the beach is wide and in front of the first dune row some primary dunes have been formed.
There is also a temporal variation in profile morphology. In general the coastal development from 1965 - 1986 does not show a parallel retreat or a parallel progradation over the whole profile.
The coast of Schouwen shows different types of profile development. In a first approximation we divide the profile in an upper part, the dunes, and a lower part, the (upper) shoreface and make a visual estimation of the profile development in three classes; sedimentation, stability and erosion.
A matrix of this kind of two classes gives nine possibilities for profile development. When we group the profiles in the matrix we see that the coast of Schouwen shows all possibilities except a total stable profile (table 2).

table 2.Different classes of profile development, Schouwen.

dunes	(upper)shoreface		
	sedimentation	stable	erosion
sedimentation	4.1 km (25.2%)	0.4 km (2.5%)	1.8 km (11.0%)
stable	3.1 km (19.0%)	-	1.2 km (7.4%)
erosion	1.2 km (7.4%)	1.0 km (6.1%)	3,5 km (21.5%)

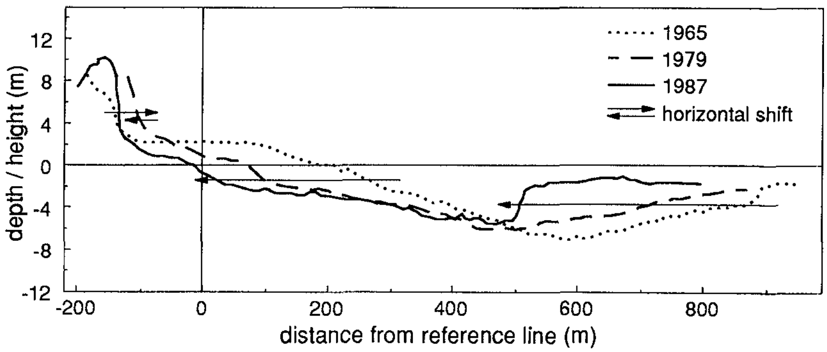

figure 5.Coastal profiles along measuring line 9.59 at Schouwen.

The profiles that show either total sedimentation or total erosion are well represented (25.2 and 21.5% of the coast length). In more than half of the coastal stretch (51.6%) there is a net sedimentation on the shoreface. About forty percent is eroding. In the dunes the classes are more equally represented; 38.7% of the dunes show sedimentation, 35.0% erosion, and 26.4% is stable in the period 1965 - 1986.
An example of profile development is given in figure 5, where some profiles are drawn for measuring line no. 9.59, situated at the very west of the peninsula. This example illustrates the steepening of a dune profile to a certain maximal gradient. The dunefront migrates seaward in the period 1965 - 1979. A landward migration of a small branch of the Krabbengat caused a shifting of the nearshore profile in a landward direction. Therefore the the seaward movement of the dune is interrupted and inverted to a landward movement from 1980 onwards because of undermining of the dunefront. Over the period 1965 - 1986 there still is a net sedimentation in the dunes, but when the process goes on the sediment volume in the dunes will soon come down to the value of 1965.On the basis of the different categories of profile development four coastal segments can be distinguished (table 3; figure 4).

table 3.Coastal segments Schouwen.

segment (measuring lines)	profile development
1 (1.06 - 4.69)	stable or eroding dunes and sedimentation in the nearshore
2 (4.69 - 9.59)	sedimentation in the dunes and mainly sedimentation in the nearshore
3 (9.59 - 12.28)	strongly varying profile development in both the dunes and the nearshore
4 (12.28 - 16.97)	mainly erosion in the dunes and nearshore

table 4. Migration mean low-water line (m/y) at Schouwen (+ progradation - recession)

segment	1900-1984 (*1880-1984)	1964-1984
1	+0.17 (*)	+1.70
2	+2.84	+7.76
3	-3.28	+2.79
4	-1.91	-2.29

5.3 Sand balance

The sand balance is calculated for the North Sea coast of Schouwen between measuring line 1.06 and 16.97 as well as for the four segments separately. The landward and seaward boundaries of the control volume are selected according the procedure described in section 3. So a control volume is defined for which the calculated trends are reliable. The area for which the sand balance is calculated is not uniform in distance to the coastline and in maximum height and depth of the profiles (figure 6). On the landward side always the first dune row is included, except in segment 4. In segment 4 the landward side of the control volume was chosen at the end of the profiles of the first years of the monitoring. These profiles were too short to cover the position of the dune top in later years. So the top of the first dune row moves out of the control volume in this area.
Because of the variation in height of the dunes the maximum height of the control volume varies along the coast. Because of the variation of the seaward boundary along the coast and the variation in local morphology the depth of the seaward boundary is also varying.Figure 7 shows the volumetric contents of the control volume for the period 1968 - 1983. Some years are not included in the calculation, because there were no reliable data for the whole coast of Schouwen. There is a considerable variation in the sand content from year to year, with a minimum of 4*103 m3 between 1979 and 1980, and a maximum of 841*103 m3 between 1970 and 1971. The fluctuations demonstrate that the coast is highly dynamic and sensitive to changes in e.g. meteorological conditions. Also the fact that the measurements were not carried out with exact twelve month intervals can be of influence.

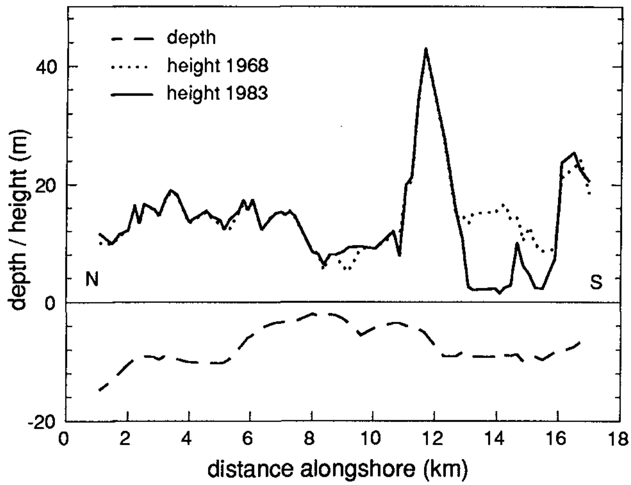

figure 6.Maximum height and depth of control volume of Schouwen.

In the control volume along the coast of Schouwen there is a net gain of 41.7*103 m3/year. When we look at the contribution of the various segments to the total amount,

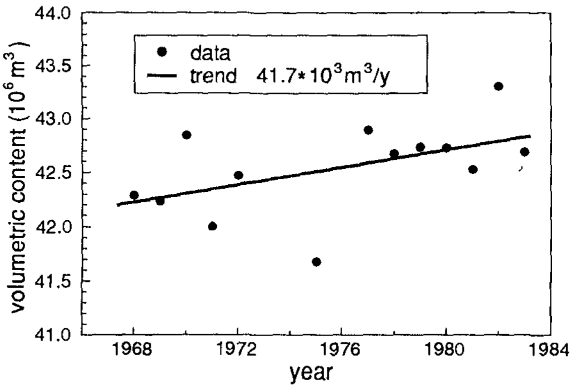

figure 7. Volume change coast of Schouwen; linear trend and yearly fluctuations.

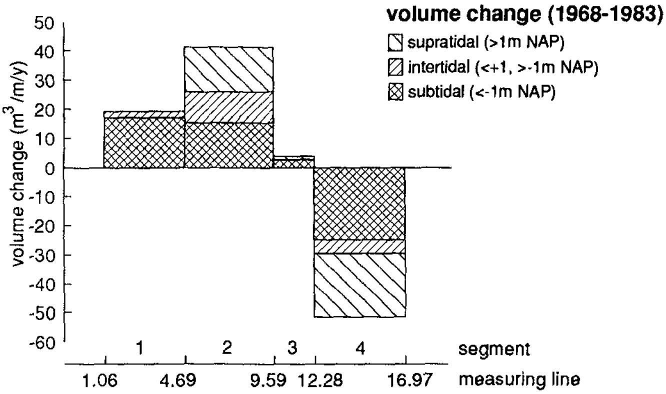

figure 8. Change in volumetric content, Schouwen. For locations see figure 4.

we see that the three northern segments (1,2 and 3) together gain sand to a total of 282*103 m3/year, and the southernmost segment (4) loose sand (240*103 m3/year). The volume changes normalized to coast length are given in table 5.
The overall impression of the results of the sand balance is not fundamentally different from the one based on shoreline records (table 4); accretion in segments 1, 2 and 3, and erosion in segment 4.

To get an insight in what processes are responsible for the volume changes we divide the control volume in three morphological zones :

- a supratidal zone, which is mainly influenced by storm surges and eolian processes
- a intertidal zone, which is influenced by eolian processes and wave action
- a subtidal zone, which is influenced by wave-, wind- and tide-related processes

The tidal range at Schouwen is 2.5 meter, with MLW at -1.18 m and MHW at +1.35 m NAP. The boundaries of the morphological zones are chosen at -1 m and +1 m NAP. In table 5 the normalized volume changes in the four segments are given, both the total

change and the change in the different morphological zones.
The normalized volume changes are also given in figure 8. This figure clearly shows the contribution of the different morphological zones to the total volume change.
Segment 1 is visually characterized (see section 5.2) by profiles who are stable or eroding in the dunes and gain volume in the nearshore. The sand balance shows the quantitative volume changes. The supratidal zone shows almost no net volume change. In the intertidal zone very little sedimentation took place. For the major part the net sedimentation in segment 1 is due to the sedimentation in the subtidal zone.

table 5. Volume change (m3/m/y) Schouwen.

segment	total	supratidal >+1 m NAP	intertidal -1 to +1 m NAP	subtidal <-1 m NAP
1	+19.2	-0.1	+2.2	+17.1
2	+41.2	+15.3	+10.5	+15.4
3	+4.1	+1.1	+0.2	+2.8
4	-51.4	-21.9	-4.7	-24.8
total	+2.6	-1.6	+2.5	+1.7

The subtidal zone within the control volume reaches depths of 13 meter and includes parts of the Schaar van Renesse. The sedimentation in the tidal channel caused by the decrease of the tidal currents after the closure of the Grevelingen is responsible for the major part of the net sedimentation in this coastal segment.
Segment 2 is characterized by profiles with sedimentation in the dunes and nearshore. The sand balance shows that the contribution of the three morphological zones to the total net sedimentation is quite the same. This means that all kinds of processes are involved with the volume change in this coastal stretch. The depth of the control volume is for the major part between 2 and 5 meter and hardly any influence of the silting up of the tidal channel can be expected here. However, the changed tidal patterns can have influenced the sediment transport pattern e.g. by a relative increase of wave influence.
Segment 3 is characterized by its non-uniform profile development in alongshore direction. The depth of the control volume varies from 3.5 to 5.5 meter (locally 9 m). There is no deep tidal channel included. But there is a shallow gully in the subtidal zone in this segment. In the north it migrates landward (see figure 5) and causes erosion in the intertidal and supratidal zone. This is attended by a coastline retreat in this part of the segment. For the segment as a whole the overall coastline development shows progradation, also the overall volume change is positive. The net volume change is positive in all morphological zones (figure 8). Two thirds of the sedimentation takes place in the subtidal zone.
The erosion and sedimentation pattern in this segment can be explained by the lateral migration of the gully, both in an alongshore and crosshore direction. The sandwave that can be seen in the displacement of the mean low water line represents the impact

of this process on the coastline (Verhagen, 1989b).
Segment 4 is characterized by profiles with erosion in the dunes and nearshore. The depth of the control volume is about 9 meter. The landward part of the Krabbengat tidal channel is included in the sand balance. The sand balance shows that the amounts of erosion in the supra- and intertidal zones are about the same. There is less erosion in the intertidal zone. The decrease in volume in the supratidal zone is due to a retreat of the dunefront, rather than a lowering of the dune. As mentioned before the first dune row moves out of the control volume. The decrease of volume in the subtidal zone is due to the landward migration of the Krabbengat tidal channel.
The coast of Schouwen shows a variation in the sand balance in an alongshore direction; negative volume change in the south changing to positive volume change in the north over the period 1968 to 1983.
In every segment the sand balance of the various morphological zones shows the same qualitative trend as the total sand balance for that segment. Their relative contribution to the total sand balance of the segment varies in alongshore direction (figure 8).
Oertel et al. (1989) suggested a classification for volume changes in terms of m3/m/month. According to this classification the coast of Schouwen with a gain of sediment of 2.6 m3/m/year is stable over the period 1968 - 1983.
The length of the coastal stretch (15.9 km) and the long period tend to average out the spatial and temporal variations in erosion and accretion. When we focus on the coastal segments we see that segment 3 is stable, segment 1 has a mild accretion rate, segment 2 has a moderate accretion rate and segment 4 has a strong erosion rate.
However, the classification mentioned is based on data from the microtidal Atlantic and Gulf coasts of the U.S.A. In these areas the sediment transport is concentrated between the upper backshore and the breaking waves at low water, with the foreshore as the major element affecting the volume change (Oertel et al., 1989).
The data from Schouwen shows that the relative small intertidal foreshore is of less influence on the sand balance, especially where tidal channels are close to the coast like in segments 1 and 4. Most of the volume changes occur in the supratidal and subtidal parts of the coast.
It can be concluded that not the normal wave-driven longshore transport is the main process affecting the sand balance of Schouwen, but the eolian- and storm surge related processes (including wave-driven longshore transport at high levels) in the supratidal zone, and the wave- wind- and tide-related processes in the subtidal zone.

6. Conclusions

The results clearly shows the advantage of the horizontal approach in calculating the sand balance for a better understanding of the coastal behaviour. The division of the coast of Schouwen in alongshore segments and cross-shore morphological zones shows how the sand balance is composed and gives insight in the processes that are responsible for the sand transport.

A question is of the dynamic of the Dutch coast is underestimated until now. This can be checked by coastal models with different length and time scales.

On the basis of nine categories of profile development, more or less uniform coastal segments can be distinguished. It is recommended to calculate a separate sand balance for each segment.

Because of the difference in zones where the major net transport take place, it is questionable if the classification as proposed by Oertel et al. (1989) can be used without change for the Dutch coast.

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