Journal of Coastal Research	14	3	1134–1151	Royal Palm Beach, Florida	Summer 1998

Geomorphological Changes of the Oosterschelde Tidal System During and After the Implementation of the Delta Project

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ABSTRACT

LOUTERS, T.; VAN DEN BERG, J.H., and MULDER, J.P.M., 1998. Geomorphological Changes of the Oosterschelde Tidal System During and After the Implementation of the Delta Project. *Journal of Coastal Research*, 14(3), 1134–1151. Royal Palm Beach (Florida), ISSN 0749-0208.

The Dutch Delta project, initiated in 1959 for the protection of the south-western Netherlands, reached its conclusion in 1987 with the completion of the Oosterschelde project: an open storm surge barrier and the Oesterdam and Philipsdam in the landward parts of the Oosterschelde basin. The Delta project has increasingly influenced the tidal characteristics of the various basins in the area. The Oosterschelde basin was showing a tendency towards erosion until ca. 1980, when the Oosterschelde project was launched. Completion of this project in 1987 caused enormous changes in hydraulic conditions and initiated a large-scale transformation in the geomorphology of the Oosterschelde tidal basin and ebb tidal delta. Since 1987, the tidal prism (ebb or flood volume) has decreased by 30% and the average tidal range by 12%. Tidal current velocities have generally declined by 20–40% in the western and central parts of the Oosterschelde, and by as much as 80–100% near to the closure dams in the landward end of the basin. Consequently, sediment export from the basin towards its ebb tidal delta has ceased. In response to these changes, the sediments in the deeper parts of the tidal channels are now tending to be composed increasingly of silt and mud, while the tidal shoals and salt-marshes are showing distinct erosion. To establish a new dynamic equilibrium between hydraulic conditions and geomorphology will require an import into the basin of 400–600 million m^3 sediment. The adaptation process will take centuries, if not longer.

ADDITIONAL INDEX WORDS: *Coastal engineering, human impact, tidal inlet system, estuaries, geomorphology.*

INTRODUCTION

The present geomorphology of the Oosterschelde tidal system in the south-western Netherlands (Figure 1) is the result both of the natural evolution of an estuary in a wide alluvial plain and of increasing human interference over recent centuries. The human impact on the geomorphological development of the system as a whole, including the inshore basin and the ebb tidal delta of the Oosterschelde, reached its climax in the implementation of the Delta project (1959–1987). This project, designed to protect the south-western Netherlands against flooding, involved the implementation of a series of large coastal engineering works in the area (Figure 1). The last of these were an open storm surge barrier in the inlet and compartmentalization dams in the landward parts of the Oosterschelde basin, completed in 1986 and 1987 respectively. Together these constructions are part of the Oosterschelde project (KNOESTER *et al.*, 1984; SAELJS, 1982). The barrier consists of three gate sections crossing the main tidal channels, from south to north Roompot, Schaar and Hammen. These are to be closed only in case of severe storms or environmental catastrophes. Under normal conditions the gates will remain open in order to preserve the tide-dominated character of the Oosterschelde ecosystem. The engineering works in the Oosterschelde have abruptly reduced the in and outgoing tidal discharge of the basin by approx. 30%, dramatically affecting the geomorphological development of the tidal basin and its ebb tidal delta.

A major multidisciplinary research project has been conducted to evaluate recent changes and predict developments in the geomorphology and ecology of the Oosterschelde basin as a result of the Oosterschelde project (SMAAL *et al.*, 1991). This paper focuses on the large-scale geomorphological development of the Oosterschelde tidal system. It outlines the well-documented changes in the system's geomorphology over recent decades and the large-scale response of the system to the implementation of the Delta project, especially highlighting the effects of the construction of the Oosterschelde storm surge barrier. It then goes on to discuss the dominant processes underlying these changes.

The paper distinguishes three periods of geomorphological change:

(1) a period of several decades prior to the start of the

95083 received 28 June 1995; accepted in revision 5 October 1997.

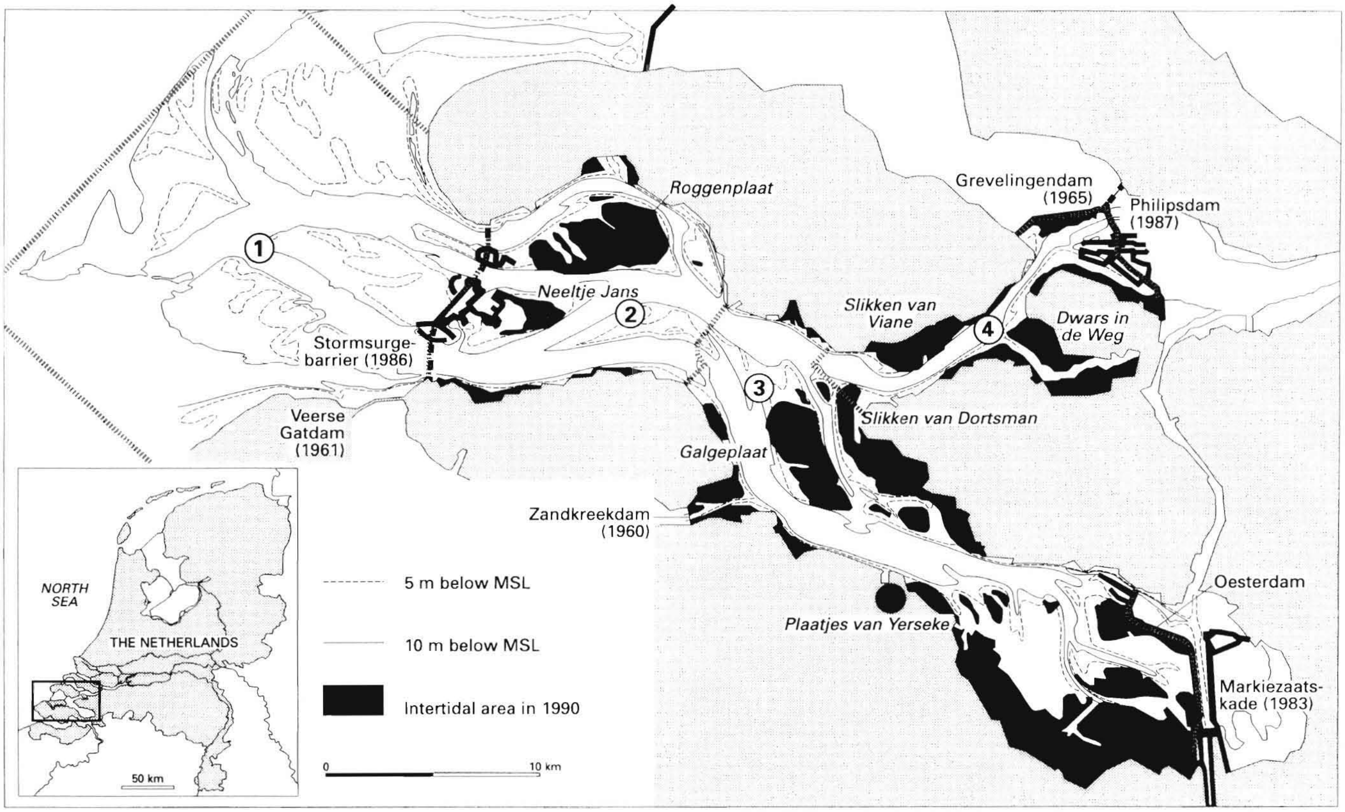

Figure 1. Location map of study area. Depth contours represent the situation in 1990. In that year the total area of the shoals was up to: 18,471 ha and the total intertidal area (zone between MLW and MHW) was about 10,831 ha. The total area of the salt-marshes was estimated to be 643 ha and that of the ebb tidal delta about 200 km². For sediment volume computations the area is partitioned in (1) ebb-tidal delta, (2) western part, (3) southeastern branch, (4) northeastern branch.

Oosterschelde project in 1983. During this period a number of engineering works in the Delta increased the tidal discharge and amplitude of the tide in the Oosterschelde basin.

(2) the period of construction of the Oosterschelde storm surge barrier and compartmentalization dams (1983–1987). During this period much effort was devoted to documenting the actual processes of geomorphological development in the system.

(3) the initial period of a few years following completion of the engineering works in the Oosterschelde (1987–1994), which provided valuable information on intermediate changes due to the construction of the storm surge barrier.

PRESENT CHARACTERISTICS OF THE OOSTERSCHELDE TIDAL SYSTEM

Hydraulic Setting

The wind regime along the SW coast of the Netherlands shows seasonal variations. The prevailing winds are from a westerly direction, with an average velocity varying from about 8 m/s near the mouth of the Oosterschelde to approx. 6.5 m/s in its eastern part (Figure 2b).

Wave records over the last decade indicate that, in the prevailing SW-NW winds, the average significant wave height decreases from about 0.4 m near the mouth to 0.1 m in the landward part of the Oosterschelde (Figure 2c). The majority of the short waves are induced locally by wind. The dominant wave energy flux is from the SW (Figure 2d).

The mean tidal range varies from approx. 2.5 m near the mouth to approx. 3.4 m in the landward part of the basin. The maximum current velocities vary from approx. 1–1.5 m/s in the tidal channels to approx. 0.2–0.4 m/s in the shallow areas on the flats and sandy shoals. The mean tidal prism of the basin is about 880 million m³ (Table 1).

Geomorphology of the Oosterschelde Tidal System

The Oosterschelde tidal system comprises a tidal basin and its ebb tidal delta. The tidal basin occupies the area eastward of the storm surge barrier and is bounded to the east by the Oesterdam and the Philipsdam (see Figure 1). In 1987, the total area of the tidal basin below AOD—Amsterdam Ordnance Datum—was approximately 304 km² (Table 1). The total water volume (below AOD) was about 26,100 million m³. The geomorphology of the basin is characterized by a complex of meandering tidal channels intersecting tidal shoals, mud-

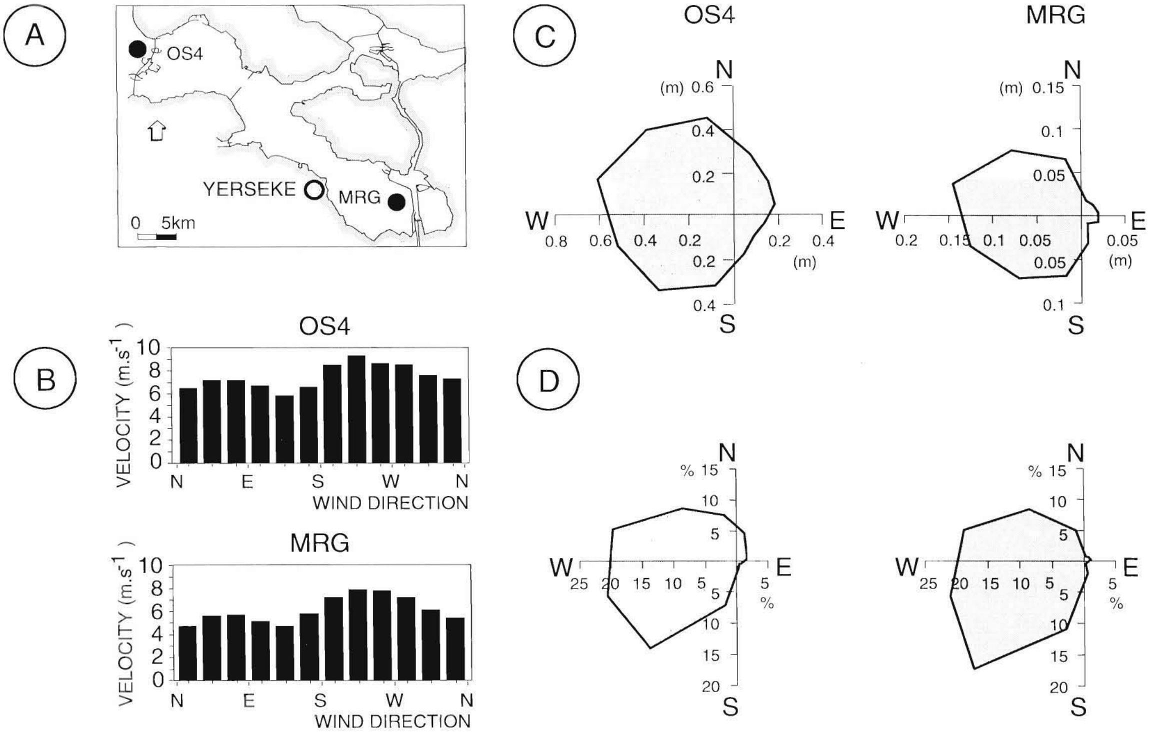

Figure 2. Wave and wind characteristics of the Oosterschelde tidal basin observed over the last decade (1977–1990): (a) location of wave stations OS4 and MRG; (b) average wind velocity; (c) average significant wave height (m); (d) proportional wave energy distribution for different wind directions.

flats and salt-marshes. The ebb-dominated tidal channels are generally deeper than the flood-dominated channels. The average channel depth decreases from west to east, varying from approx. −30 m AOD to −10 m AOD. Individual tidal shoals increase in height on average from west to east, reaching a maximum of approx. +1 m AOD. Median grain size in the basin varies from about 210 μm in the tidal channels to less than 150 mm in the shoals and salt-marshes.

The ebb tidal delta of the Oosterschelde is approximately delineated by the −10 m AOD depth contour. To the northeast, it connects with the ebb tidal delta of the former Grevelingen inlet, which was closed by a dam in 1971, while to the south it merges into the outer delta of the Westerschelde. The geomorphology of the ebb tidal delta is characterized by shoals and tidal channels with a generally east-west orientation. In the seaward part, the maximum depths of the channels vary between −15 and −23 m AOD. The average maximum height of the tidal shoals in the ebb tidal delta decreases as they get closer to the sea, and varies between −1 and −2 m AOD.

RESEARCH METHODS

The large-scale geomorphological development of any tidal inlet system tends towards a dynamic equilibrium between hydraulic conditions and the corresponding geomorphology

Table 1. *Selected hydraulic and area characteristics in the period before (1983), during (1983–1987) and after (1987) implementation of the Oosterschelde project.*

	Before Implementation of the Oosterschelde Project 1983	During Implementation of the Oosterschelde Project 1983–1987	After Implementation of the Oosterschelde Project 1987	Change in Hydrodynamic and Morphometric Characteristics due to Oosterschelde Project (%)
Mean tidal range (m) at Yerseke	3.70	2.50	3.24	−12%
Maximum current velocity (m/s)	1.5	1.0	1.0	−30%
Mean tidal prism ($m^3 * 10^6$)	1,230	—	880	−28%
Total area ($m^2 * 10^6$)	452	—	351	−22%
Area below AOD ($m^2 * 10^6$)	362	—	304	−16%
Intertidal area ($m^2 * 10^6$)	170	—	118	−31%
Salt-marsh area ($m^2 * 10^6$)	17.2	—	6.4	−63%

(BRUUN *et.al.*, 1978). Several aspects of this dynamic equilibrium can be described in terms of empirical relations. These relations provide indications of the development of a new equilibrium in a system following a major change in hydraulic conditions, and thus provide clues to future developments. Geomorphological changes on an intermediate time-scale (10–30 years) under non-equilibrium conditions may be studied from documented records of adaptation after earlier abrupt changes in the same system or similar systems.

Quantitative and qualitative indications of the large-scale geomorphological behavior of the Oosterschelde tidal system have been derived from a combined analysis of bathymetric and morphodynamic measurements (KOHSIEK *et al.*, 1988; LOUTERS *et al.*, 1991; VAN DEN BERG, 1986) and of the results of both empirical and 2D-numerical models (DE VRIEND *et al.*, 1989).

Bathymetric Data

The analysis is based on bathymetric data. Annual echo soundings have been carried out in the study area ever since the early 60s. These are estimated to be accurate to within approx. 0.1–0.2 m (VAN DEN BERG, 1986). Since the higher parts of the intertidal area, including salt-marshes, cannot be sounded from vessels, levelling data have been collected for these areas. These are thought to be accurate to within approx. 0.05 m.

The depth data have been used to study cross-sectional developments and changes in sediment volume at 5-yearly intervals throughout the period 1960–1990. Estimates of the latter have been based on calculations of interpolated depth values using 50 × 50 m and 200 × 200 m grid squares derived from the sounding maps. In order to study the spatial variability of changes in sediment volume, the Oosterschelde tidal system has been subdivided into four areas: the ebb tidal delta and three areas within the tidal basin (Figure 1).

Data on the Processes of Geomorphological Development

The basin's tidal and wave characteristics have been studied on the basis of data collected over the last decade at two separate stations, viz. OS4 and MRG (see Figure 2a). Discharge measurements taken along a number of monitoring transects across the basin over the 1959–1990 period have provided data on the spatial distribution of discharges in the Oosterschelde system.

Estimates of sediment exchange between the tidal basin and ebb tidal delta are based on sediment transport measurements taken in the vicinity of the storm surge barrier in 1983 and 1987/1988. Acoustic measuring devices were used to record sediment transport simultaneously from a number of vessels along a transect. Since the completion of the Oosterschelde project, continuous sediment transport measurements (especially concerning fine-grained sediment <53 μm) have been carried out at a permanent station located within the storm surge barrier itself (TEN BRINKE *et al.*, 1994).

The morphodynamic parameters (current velocity, sediment concentration and wave height) of the intertidal area were recorded in detail over the 1983–1988 period at two stations on the sandy Galgeplaat shoal (see Figure 1), situated in the central part of the Oosterschelde basin (KOHSIEK *et al.*, 1988).

EVOLUTION OF THE OOSTERSCHELDE SYSTEM

Geological data show that the Oosterschelde inlet already occupied its present position by Roman times (VAN RUMMELEN, 1978). At that time, the Oosterschelde was the main outlet from the River Scheldt. Figure 3 shows the evolution of the Oosterschelde basin since 200 A.D. In early medieval times, the mouth of the Oosterschelde is thought to have been about one kilometre wide (WILDEROM, 1964), or about 10–15% of its present width. During the 12th and 13th centuries, earthen dikes were constructed around most of the salt-marshes bordering the tidal channels in the SW Netherlands. As a result, large areas of salt-marsh were excluded from the natural process of sediment accumulation and the areas enclosed by the earthen dikes actually lost height both as a result of compaction following artificially improved drainage and because of the stripping of surface peat layers for use as fuel. Consequently, later breaches of the dikes turned parts of these areas into tidal waters. This, together with poor maintenance and repair of dikes due to a general decline in the economic prosperity of the region, resulted by the end of the Middle Ages in a loss of polder land and an increase in tidal areas.

A tidal creek in the western part of the present Westerschelde expanded over the centuries and is thought to have connected with the River Scheldt by the end of the 12th century (BRAND, 1985). The Oosterschelde tidal basin also expanded. This is illustrated by coastal erosion at the entrance to the northern channel, along the side of the island of Schouwen. During a dramatic storm surge in 1530, large areas of the SW Netherlands were permanently lost to the sea. As a result, the tidal discharges of the Oosterschelde must have increased by at least 50% (VAN DEN BERG, 1986). This caused a further widening and deepening of the western part of the Oosterschelde, while at the same time the north-eastern part, the Keeten–Volkerak channel, was gradually being captured from the Grevelingen system (a process which continued into the present century). Calculations by MORRA *et al.* (1961), based on hydrographic maps, indicate a net erosion in the Oosterschelde basin of about 244 million m^3 over the 1872–1933 period and suggest continued erosion of 108 million m^3 over the subsequent period to 1952.

GEOMORPHOLOGICAL DEVELOPMENTS DURING AND AFTER IMPLEMENTATION OF THE DELTA PROJECT

The centuries-old process of erosion and deepening of the Oosterschelde basin continued throughout the decades preceding the completion of the engineering works in the Oosterschelde, although the rate of erosion diminished. During the same period, the higher parts of the tidal shoals showed a distinct vertical accretion and the offshore-directed net sediment flux contributed to a seaward expansion of the ebb tidal delta. Since the completion of the barrier in 1986, however, tidal shoals in the basin have shown distinct vertical erosion,

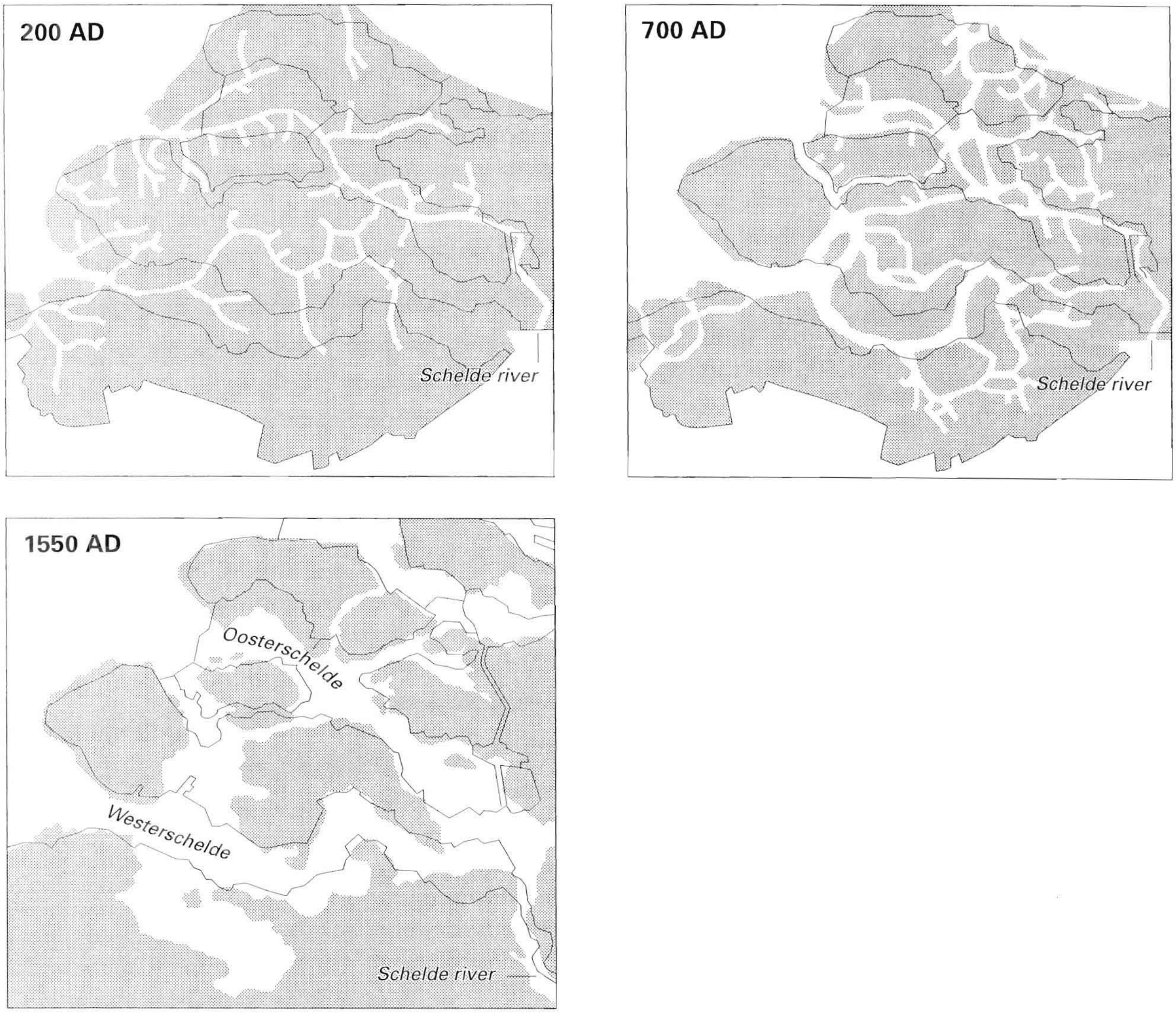

Figure 3. The evolution of the Oosterschelde tidal basin since 200 AD, 700 AD (after Vos & van Heeringen, 1993) and 1550 AD.

while the rate of sediment supply from the Oosterschelde basin to its ebb tidal delta has slowed dramatically and the direction of the net sediment flux has reversed. The front of the ebb tidal delta now shows an erosive trend.

These general features of recent geomorphological development are discussed in more detail below.

Changes in Sediment Volume

The changes in sediment volume in the Oosterschelde basin and its ebb tidal delta show contrary trends before and after 1987: before 1987 the basin's sediment budget was negative while that of the ebb tidal delta was positive (Figure 4).

Over the 1960–1989 period, the tidal basin lost a total of approx. 120 million m^3 of sediment (Figure 4a). The total effects of dredging on the net natural sediment budget during this period are thought to amount to approx. 80 million m^3. The remainder of the lost sediment (approx. 40 million m^3) was exported in a seaward direction. Dredging activities, strongly influencing the natural sediment budget of the basin, were mainly restricted to tidal channels deeper than −7.5 m AOD. The erosion rate in the basin declined significantly over the 1960–1989 period: the supply of sediment from the Oosterschelde to its ebb tidal delta was reduced. This statement is supported by sediment transport measurements in the Oosterschelde inlet before and after the completion of the barrier (Figure 5). Recent sand transport measurements in the main tidal channels on both sides of the storm surge barrier suggest that sand exchange is now negligible. Observations of the transport of fine sediments within the alignment of the barrier indicate an import of possibly approx. 1.0 million m^3 per year (TEN BRINKE, 1994).

Prior to the start of the construction works in the Ooster-

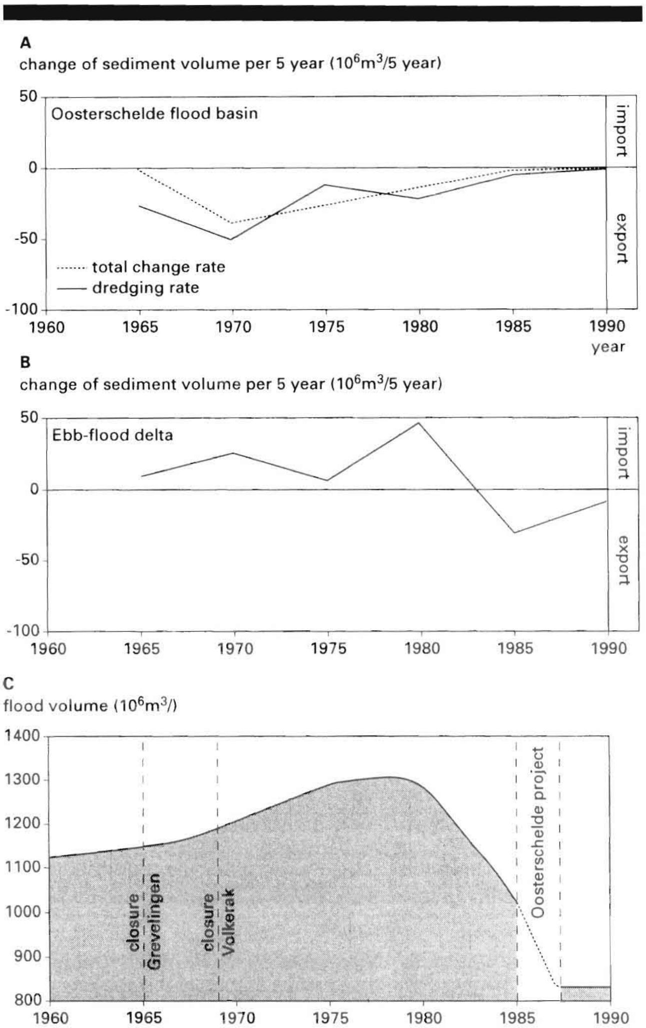

Figure 4. Sediment exchange of the tidal basin (a) and ebb tidal delta (b) in the period 1960–1990, and the evolution of the flood tidal volume in the vicinity of the Oosterschelde (c) since 1960.

schelde, the trend in the rate of change in the sediment volume in the ebb tidal delta (Figure 4b) indicates a net sediment surplus. Over the 1960–1989 period, the ebb tidal delta shows a net total deposition of approx. 34 million cubic metres. The major source of this observed sediment surplus was presumably erosion of the Oosterschelde tidal basin. The negative trend in the sediment budgets of the ebb tidal delta during the implementation of the Oosterschelde project (1983–1987) suggests a slight reduction in the size of the ebb tidal delta.

Characteristic Changes in Geomorphological Units within the Tidal Basin and Ebb Tidal Delta

Tidal basin

Long-term trends in the development of tidal channels in the Oosterschelde basin are illustrated by changes in cross-sectional area near the storm surge barrier (Figure 6). In the period from 1827 to about 1960, the cross-sectional area tended to increase slightly. After 1960, there was a considerable deepening and widening of channels in several parts of the basin. This is related to hydraulic changes caused by the Grevelingen Dam (1964), Volkerak Dam (1969) and extensive dredging activities in the second half of the 60s and early 70s (Table 2).

Although erosion was clearly the general trend in the Oosterschelde tidal channels up until the early 1980s, there were spatial variations. This is illustrated by the opposing trends in channel development in the northern and southeastern branches of the Oosterschelde (Figure 7). There were also local phenomena in the form of the scour pits, which started developing in 1983/1984 in channels on both sides of the barrier, due to turbulence created by vortex formation in the flow behind the sills and pillars of the barrier gates. In 1991, the scour pits in the Roompot channel landward of the barrier had reached depths of −53 m AOD, while those seaward of the barrier had reached −49 m AOD. No equilibrium has yet been established.

The year 1986, *i.e.* the last phase of the construction period, probably marked a turning point in channel development. Since that time, analyses of sediment texture in the tidal channels have shown a distinct increase in the silt and mud content (53 < μm), indicating more favorable sedimentation conditions (Figure 8; TEN BRINKE *et al.,* 1994). In view of their limited accuracy, the echo soundings allow as yet no firm conclusions regarding any significant channel sedimentation since 1986.

Intertidal areas in the basin showed a tendency towards vertical accretion during the period of general basin erosion. This is illustrated by records for the 1872–1975 period (Figure 9). The vertical accretion trend continued until the end of the barrier construction phase in 1986, after which the general trend towards shoal sedimentation reversed and distinct erosion began to occur (Figure 10). Between 1986 and 1990, average vertical erosion rates of approx. 10 to 20 cm were recorded. Erosion appeared to be dominant at every level in the intertidal zone (Figure 11). The highest erosion figures were recorded for the higher parts of the shoals above MSL (=AOD), where over 20% of the original sediment volume has been eroded since 1983. In an absolute sense, the largest amounts of sediment have been lost from depth zones between MLW and MSL. The surface area per depth zone shows contrary developments above and below approx. −0.5 m AOD (Figure 11), with a decrease in surface area above this level and an increase below it. This development illustrates a general downward trend in slope gradients.

During the 19th century, there was a distinct increase in the area of salt-marshes in the Oosterschelde, mainly as a result of reclamation (Figure 12). Since around 1900, however, there has been less reclamation and the total area of salt-marshes has increased slightly. Little information is available on the varying rates of salt-marsh development over the last century, but over the last decade or two (if not before) the positive trend seems to have been reversed. In 1980, 90% of the salt-marsh edges appeared to be erosive cliffs. Detailed observations since 1982 indicate that, between that date and 1989, the total area of salt-marshes decreased by 16 ha (approximately 2.5%) as a result of cliff erosion. The

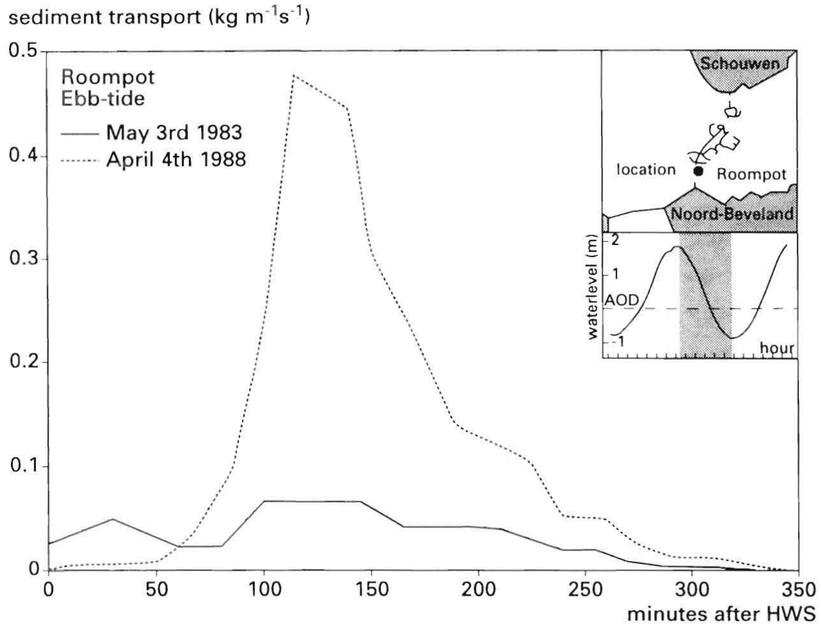

Figure 5. Sediment transport during ebb tide before (1983) and after (1988) implementation of the Oosterschelde project.

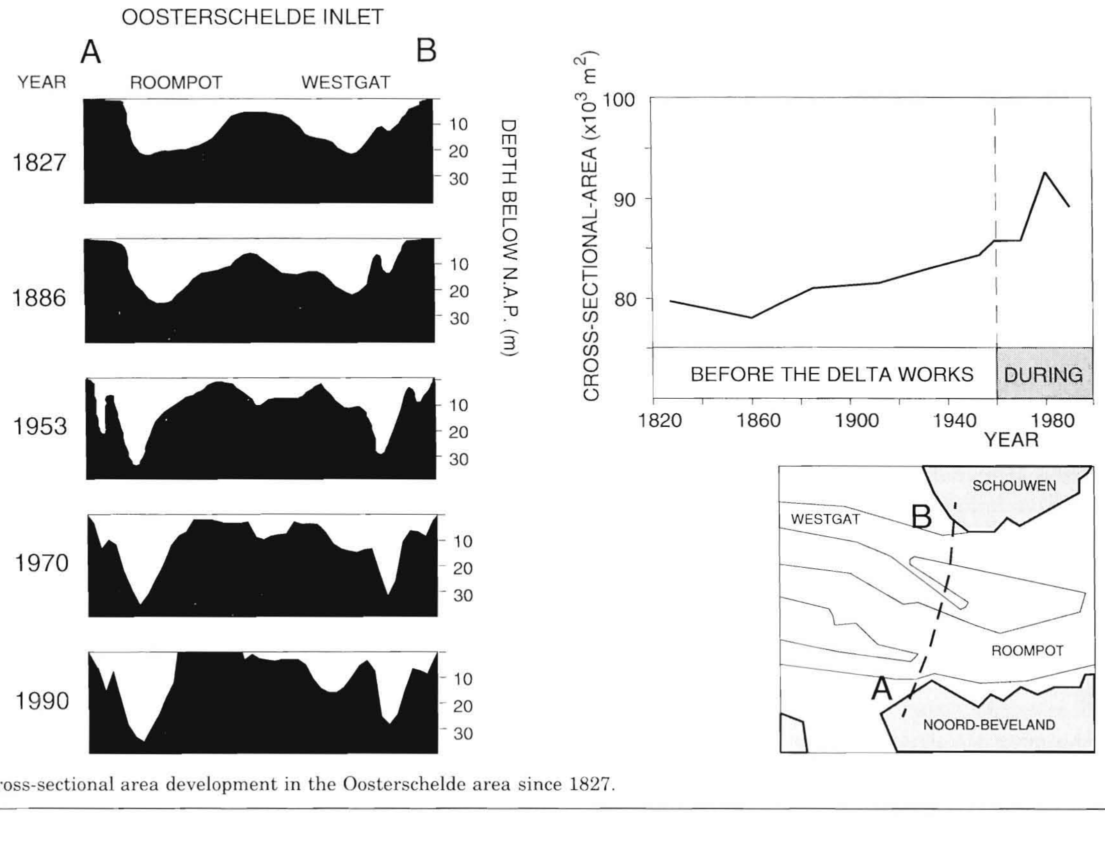

Figure 6. Cross-sectional area development in the Oosterschelde area since 1827.

Table 2. *Change in the maximum channel depth (m) of three main tidal channels since the 17th century [sh = very shallow] (based partly on Van den Berg, 1986).*

	Year					
Channel	1630	1670	1800	1960	1983	1989
Hammen	17	17	27	33	35	35
Roompot	10	17	30	49	50	51
Zijpe	sh	sh	24	38	44	47

rate of cliff retreat has approximately doubled since completion of the engineering works in the Oosterschelde in 1987 (DE JONG *et al.*, 1994). During the final phase of the project in 1986/87, the soil characteristics of the salt-marshes changed considerably. Increased aeration of the soil resulted in a drastic increase in the degree of ripening. This led locally to a decline of 0.01 to 0.10 m in the surface levels (DE JONG *et al.*, 1994).

Apart from this, a significant reduction in the pH level of the soil was observed during this period (VRANKEN *et al.*, 1990) and there was large-scale mortality of salt-marsh vegetation in 1987, during the first summer after completion of the works. Since 1987, the vegetation has largely recovered, although there has been a shift in the characteristic vegetation zones paralleling the reduced mean high tide level (DE JONG *et al.*, 1994).

Ebb Tidal Delta

The sedimentation surplus of the ebb tidal delta over the 1960–1980 period, resulted in a seaward expansion of the delta front. VAN DEN BERG (1986) identifies a general erosion and expansion of ebb channels in the delta during this period. Since the completion of the Oosterschelde project in 1987, the trend has reversed. Between 1987 and 1994, in the main channels on average a 1 m thick layer of sediment was deposited, while locally in the deepest parts a layer of more than 5 m was piled up. Most parts of the sandy shoals in the landward parts of the ebb delta eroded by several decimetres.

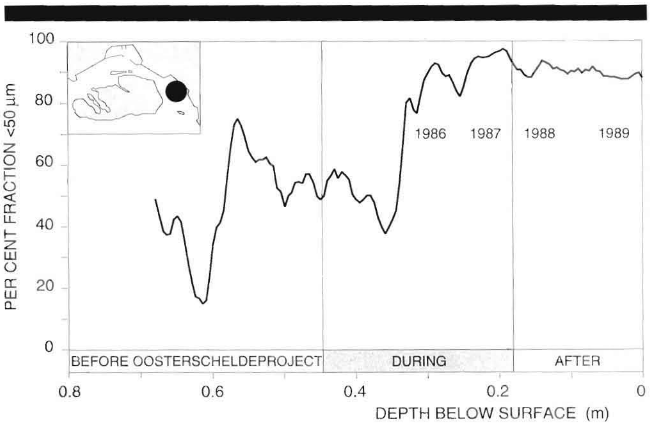

Figure 8. Change in silt and mud contents in the Hammen tidal channel since 1984, illustrating the tendency of the tidal channels to silt up after completion of the Oosterschelde project (after Ten Brinke *et al.*, 1994).

ANALYSIS OF DOMINANT PROCESSES OF GEOMORPHOLOGICAL DEVELOPMENT

Hydraulic Boundary Conditions

Geomorphological processes are dominated by hydraulic boundary conditions. The changes in hydraulic conditions induced by the implementation of the Delta project are having a major impact on geomorphological developments. Other factors are tidal variations and a general rise in sea level.

Analysis of the tidal range in the Oosterschelde basin over the last 100 years indicates a cyclical variation of about 4% in the tidal range, due to the 18.6 year cyclical variation in the lunar orbit. It is noticeable that the cyclical variations in

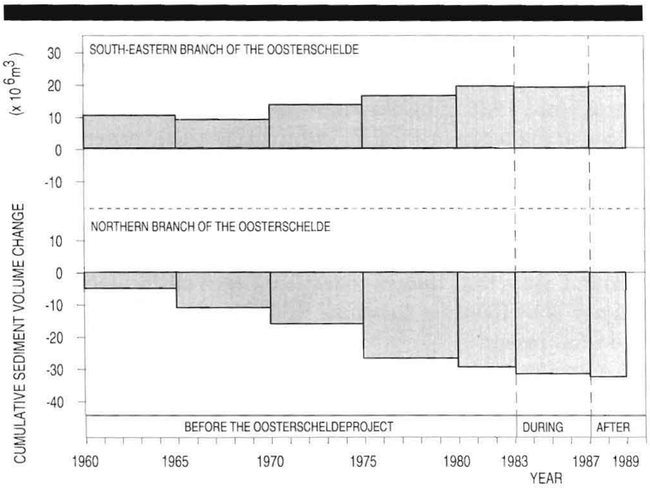

Figure 7. Cumulative changes in sediment volume in the northern and southern branches of the Oosterschelde over the 1960–1989 period, illustrating the variability in response to the implementation of the Delta works.

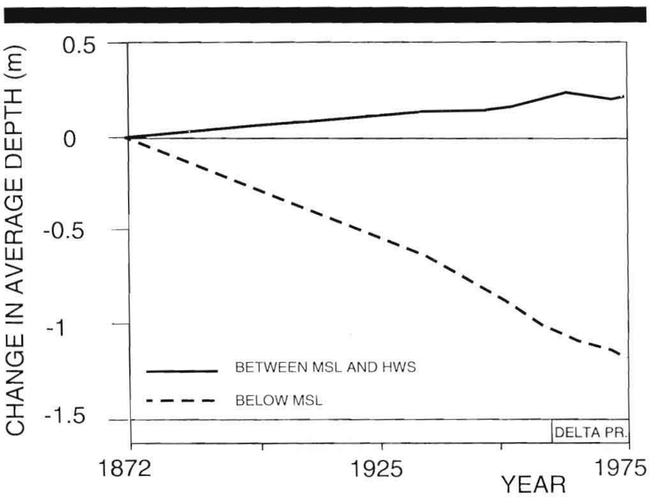

Figure 9. Net sedimentation of intertidal shoals (zone between mean sea level and mean high water slack in the Oosterschelde basin (after Mulder, 1989).

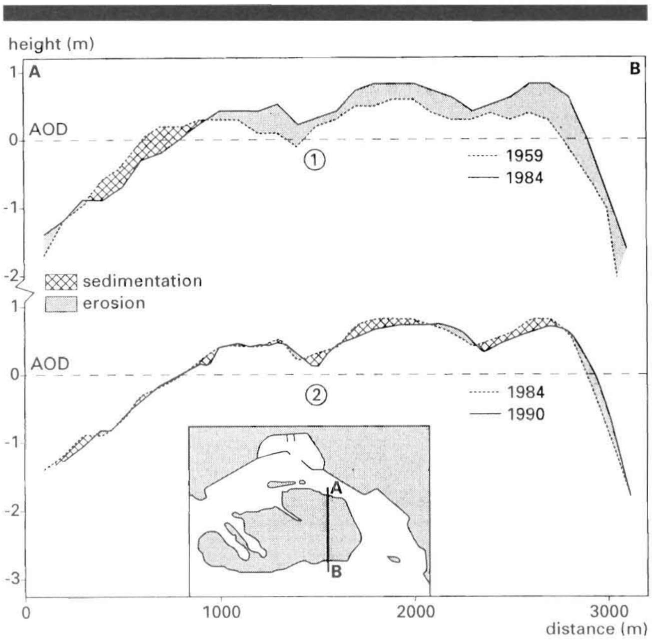

Figure 10. Change in a cross-section of the Roggenplaat shoal between 1959 and 1989, illustrating the vertical accretion of shoals before the Oosterschelde project (a) and their levelling-down response following it (b).

tidal range and tidal volume both peaked in around 1980 (Figure 13). According to analyses of tidal records from Hook of Holland and Vlissingen (situated respectively north and south of the study area), there was a relative rise in sea level of approx. 0.25 m over the period between 1900 and 1980, while the tidal amplitude increased by 3% to 4% (DE RONDE, 1983). Over the period of major engineering works (1959–1987), the geomorphological effect of sea level rise was relatively minor, and was secondary to the effect of the 18.6 year cyclical tidal variation (Figure 13) and of the engineering works themselves.

The most dramatic impact, especially in the northern branch and the western part of the Oosterschelde basin, resulted from the closures of the Grevelingen Dam (1964) and the Volkerak Dam (1969). The first caused an increase in tidal area, and the second an amplification of the tidal wave in the northern branch of the basin. Mainly as a result of these changes, the mean total discharge (flood and ebb volume) during a half tidal cycle increased over the 1959–1984 period by approx. 7% near to the mouth, and by as much as around 60% in the northern branch of the Oosterschelde. Over the same period, the mean tidal range increased by amounts varying from approx. 2% near to the mouth to about 22% in the northern branch (Figure 14).

Prior to implementation of the Oosterschelde project, the geomorphological development of most of the Oosterschelde system was dominated by a continuing increase in tidal energy. Since the commencement of construction activities, the opposite has been the case. The wet cross-sectional area (A_c) of the inlet has gradually been reduced from 80,000 m^2 in 1984 to approx. 17,900 m^2 in 1987. During the final stages of project implementation (1985–1987), it was necessary for the sake of construction activities deliberately to reduce the mean tidal range to an extremely low level by closing a number of gates in the storm surge barrier (see also Table 1). In the central part of the basin, near Yerseke, this reduced the mean tidal range from around 3.70 m to approx. 2.50 m (a 40% reduction!). Since the completion of the works in 1987, a new equilibrium has been established in the area's hydraulic conditions, characterized by a mean tidal range of approx. 3.24 m (a 12% reduction) and a tidal prism of approx. 880 million m^3 (70% of the original). Since completion, current velocities have declined by 20–40% in the tidal channels and by over 40% around the tidal shoals and salt-marshes.

The decline in tidal range over the last decade has dramatically reduced the frequency of flooding in different height zones in the intertidal area. For the higher salt-marsh zones, for example, flooding frequency has declined by 100% in 1986 and 70% since 1987.

Tidal Basin and Tidal Channels

The tidal prism (P) of a tidal inlet and the cross-sectional area below mean sea level of its entrance (A_c) show a linear relationship:

$$P = a * A_c + b \ (\mathrm{m^3/tide}) \quad (1)$$

in which a and b are coefficients.

VAN DE KREEKE and HARING (1979) have shown that this type of relationship holds for the equilibrium conditions of inlets in the SW Netherlands, while other researchers (DE JONG and GERRITSEN, 1984; GERRITSEN, 1990; VAN DEN BERG, 1986) have shown that it also applies to channels within tidal basins (Figure 15). Coefficient values for Oosterschelde channels are a = 12200 m and b = 2 * 10^6 m^3 (VAN DEN BERG, 1986).

Equation 1 implies that, in order to achieve a new equilibrium, any change in tidal prism must be followed by a proportional adaptation in channel cross-sectional area (Ac). This is in line with the observed basin erosion and general expansion in the cross-sectional areas of tidal channels in the Oosterschelde over recent decades, at a time when the tidal prism was still increasing. The dramatic decrease in tidal prism since 1986 must therefore result in a general sedimentation of the basin and shrinking cross-sectional areas in tidal channels. This is illustrated by a more friendly sedimentation climate in the tidal channels since 1986, and the reversal of the direction of net sediment transport between the basin and its ebb tidal delta. The equilibrium relationship (Figure 15) also indicates that the cross-sectional area of the storm surge barrier is by itself far too small to create an equilibrium with the tidal prism.

Ebb Tidal Delta

Empirical relationships between hydraulic and geomorphological parameters have also been derived for ebb tidal deltas. OERTEL (1988) and WALTON and ADAMS (1976) have shown a direct correlation between the sediment volume of an ebb tidal delta (V_d) and its tidal volume (V_t), which can be written as:

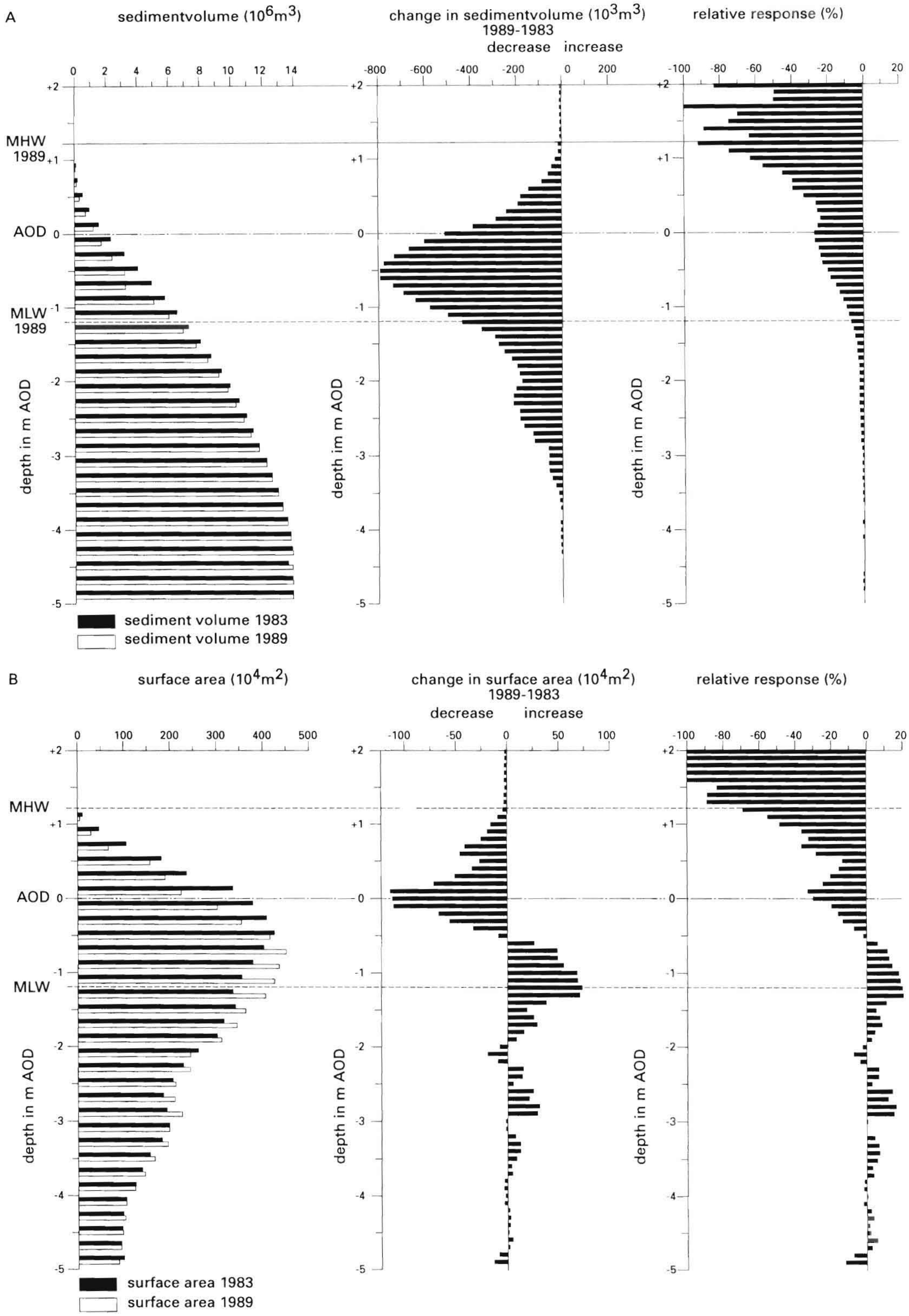

Figure 11. (a) Changes in sediment volume in the intertidal zone of the Oosterschelde basin per 0.1 m depth interval (based on Mulder & Louters, 1994); (b) Changes in surface area per 0.1 m depth interval.

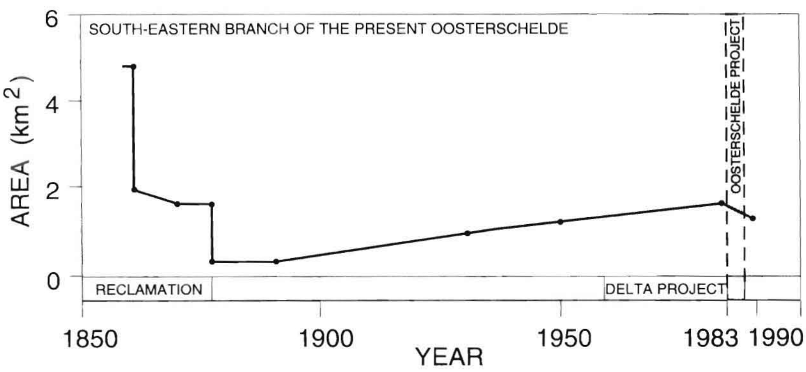

Figure 12. Long-term trends (1850–1990) in the area of salt-marshes in the south-eastern branch of the Oosterschelde basin. The figure does not include the total loss of marsh area resulting from the construction of the compartmentalization dams in 1986/87 (approx. 440 ha).

$$V_d = a * V_t^{\beta} \ (m^3) \quad (2)$$

where, β = approx. 1.23 (WALTON and ADAMS, 1976)
α = positive coefficient

This empirical model implies that, in order to reach a new equilibrium, any reduction in tidal volume will cause a reduction in the sediment volume of the ebb tidal delta, while any increase in tidal volume will lead to an increasing sediment volume in the delta.

The observed trend in sediment volume in the Oosterschelde ebb tidal delta over recent decades shows a similar response to the increase in the basin's tidal volume over this period. No reduction in sediment volume since 1986 has yet been determined quantitatively, but the qualitative observation of delta front erosion since 1986 indicates that the actual processes are proceeding in accordance with equation 2. On the other hand, a reduction in tidal volume will continue to cause sedimentation in the tidal channels of the outer delta until a new equilibrium has been reached between channel cross-section and tidal discharge.

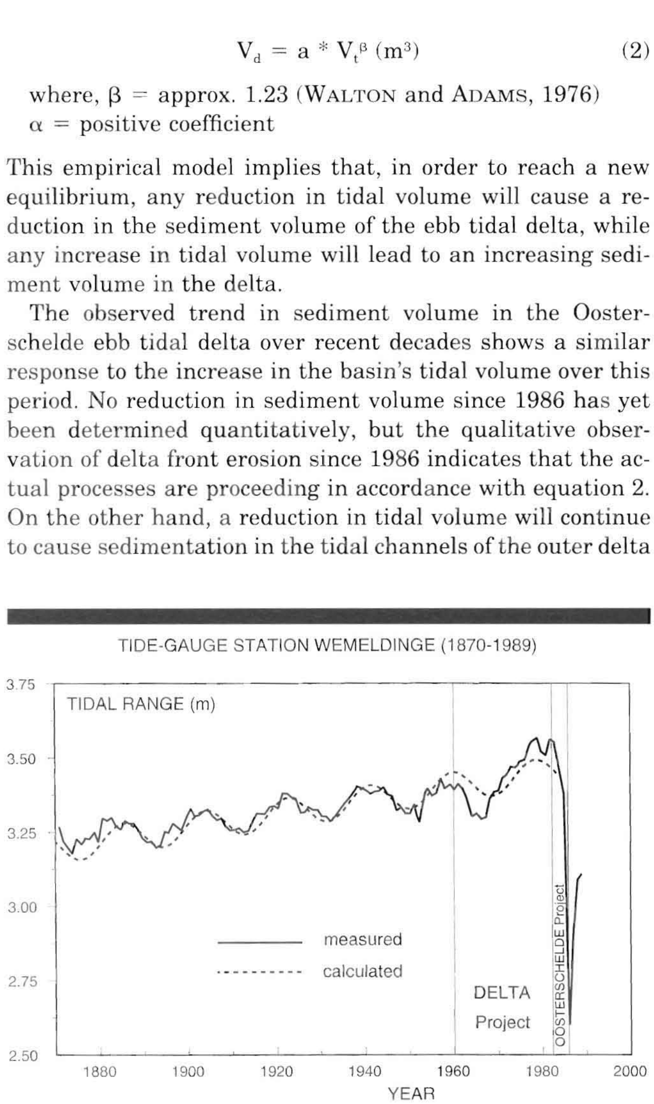

Figure 13. Variation in the tidal range at the Wemeldinge water level station over the last century, illustrating the influence of the 18.6 year cyclical variation in the lunar orbit: Tidal range = 0.229274 * year + sin ((year + 2)/18.6 * 2 * π) − 109.289.

Tidal Shoals

Many investigators accept the hypothesis that the initial formation of shoals is dominated by tidal currents (OFFICER, 1981; ROBINSON, 1960). Once shoals grow above the subtidal level, however, waves become increasingly important for their geomorphological development. Whether there is a net sedimentation or a net erosion of sandy shoals depends on the direction of the residual sediment transport gradient.

For this reason, numerical model experiments have been used to study both the residual sediment transport and the geomorphological activity of a particular sandy shoal under different conditions (see Figure 1). The shoal used for this is the Galgeplaat, which is situated in the central part of the Oosterschelde (DE VRIEND *et al.*, 1989). The findings have generally been confirmed by detailed observations of the parameters of geomorphological development and changes in bathymetry (KOHSIEK *et al.*, 1988).

Prior to the construction of the Oosterschelde storm surge barrier, moderate wind conditions apparently generated a rather low level of geomorphological activity; only small amounts of sediment were transported from the channels and spread out over the shoal (Figure 16a). Calm weather generally resulted in an overall trend towards slight vertical accretion. Under storm conditions, on the other hand, substantial amounts of sediment were stirred up by wave action and picked up by the current. Storms usually caused a distinct overall erosion of the upper part of the shoal. There were significant geomorphological changes, especially near the edges exposed to the wind, a zone where wave energy dissipation is high. Long-term morphological changes indicate that, prior to the engineering works, the morphology of the Galgeplaat was near to a dynamic equilibrium, with only a slight tendency towards sedimentation.

Since completion of the works, however, both the tidal current velocity and the tidal range at the shoal have been dramatically reduced, leading to a significant reduction in sediment transport (Figure 16b). Under calm weather conditions,

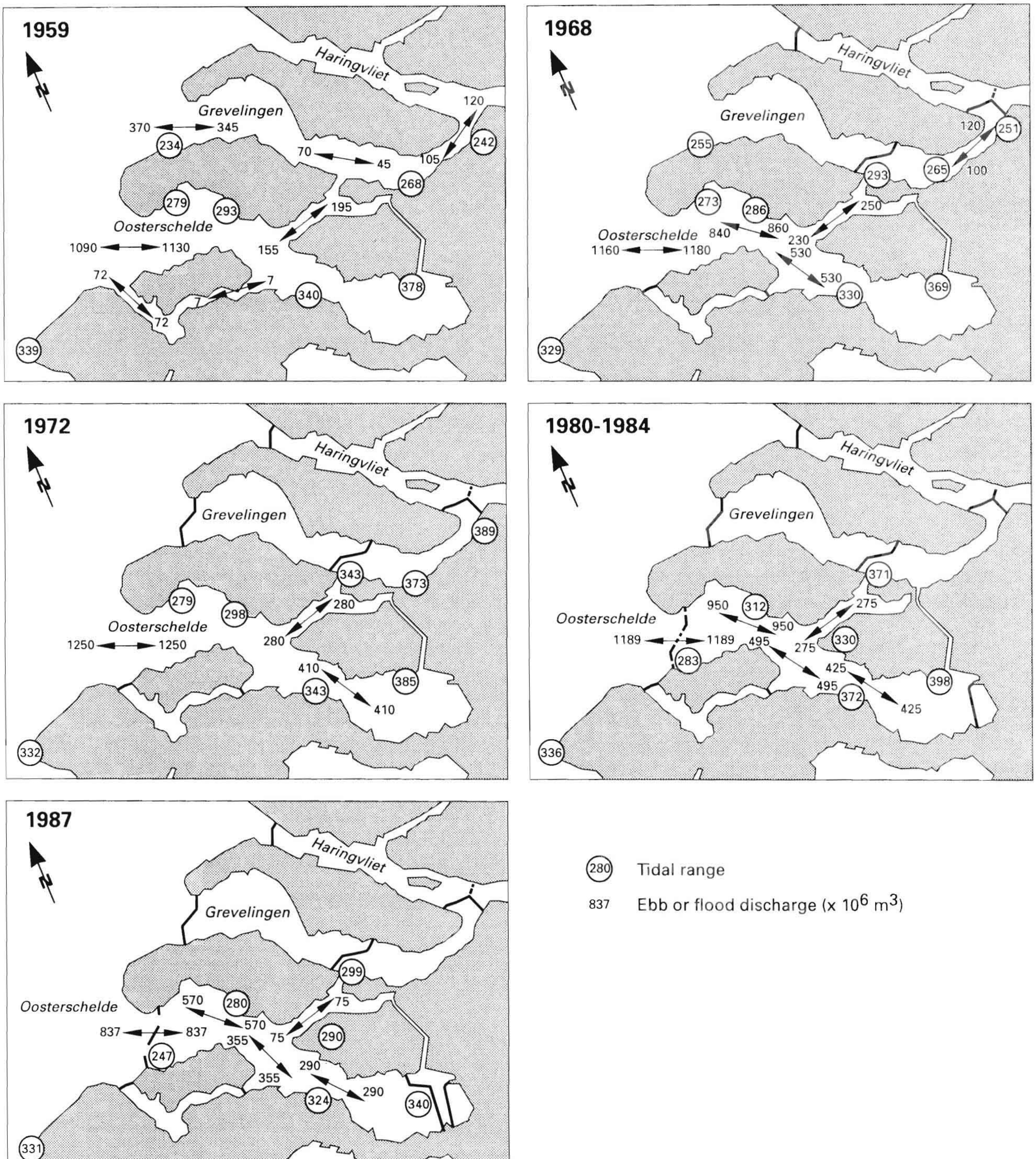

Figure 14. Large-scale changes in tidal discharge and tidal ranges in the Oosterschelde basin over the 1959–1989 period (based partly on Van den Berg, 1986).

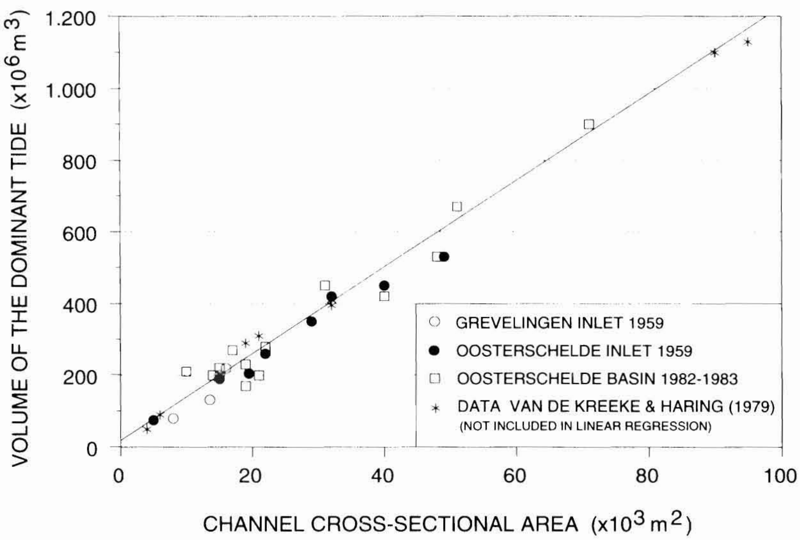

Figure 15. Tidal discharge versus cross-sectional area (below AOD) in the Oosterschelde basin, illustrating the linear relationship (after Van den Berg, 1986).

only low sediment concentrations are observable in either the upper or the lower half of the water column, resulting in little accretion of the shoal. Model computations (De Vriend *et al.*, 1989) have shown that, because of the reduction in tidal range, more wave energy is dissipated near to the edges of the shoal and this results in greater vertical erosion in those areas. Due to the reduced current velocities, there has been an exponential diminution in transport capacities, with the result that the eroded sediments are transported only over small distances. These conditions result in a net vertical erosion of the shoal (Figure 17) and a net accretion at the channel 'shoulder', mostly below −5 m AOD. Between 1987 and 1994 the intertidal area of the Galgeplaat lowered by 0.2–0.4 m in most places. Most of the eroded sediment was deposited along the banks of the eastern channel, locally more than 2.5 m, indicating the important role of westerly storms in this process. It seems reasonable to assume that part of the sediments deposited on the channel shoulders will ultimately be transported into the deeper parts of the tidal channels as a result of wave action and gravity, thus contributing to the observed overall reduction in depth gradients. So far the analysis of the sounding record of the period 1989–1994 indicates a net deposition in the channels shoulder areas of the Oosterschelde, between −2 and −10 m AOD, of 1.3 million m^3, while below the latter level the sedimentation amounted 5.5 million m^3.

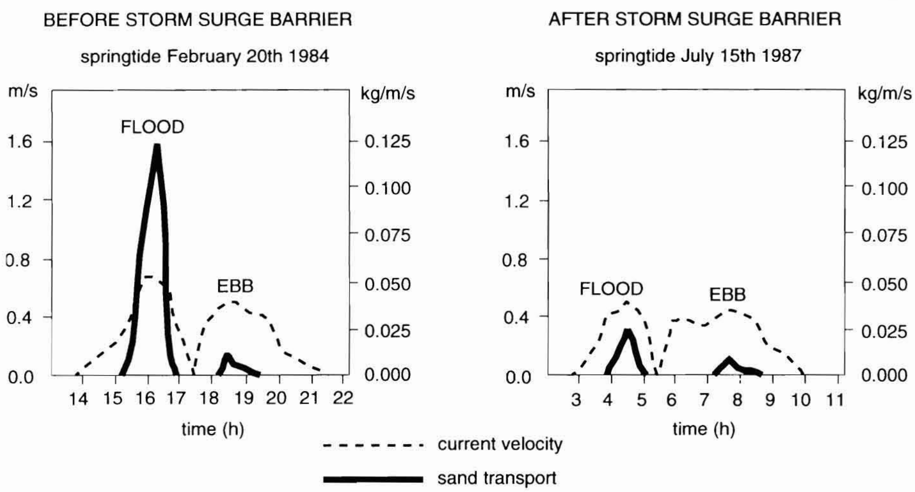

Figure 16. Sediment transport measurements during calm weather conditions on the Galgeplaat tidal shoal in 1984(a) and 1987(b), illustrating the dramatic reduction in sediment transport resulting from implementation of the Oosterschelde project.

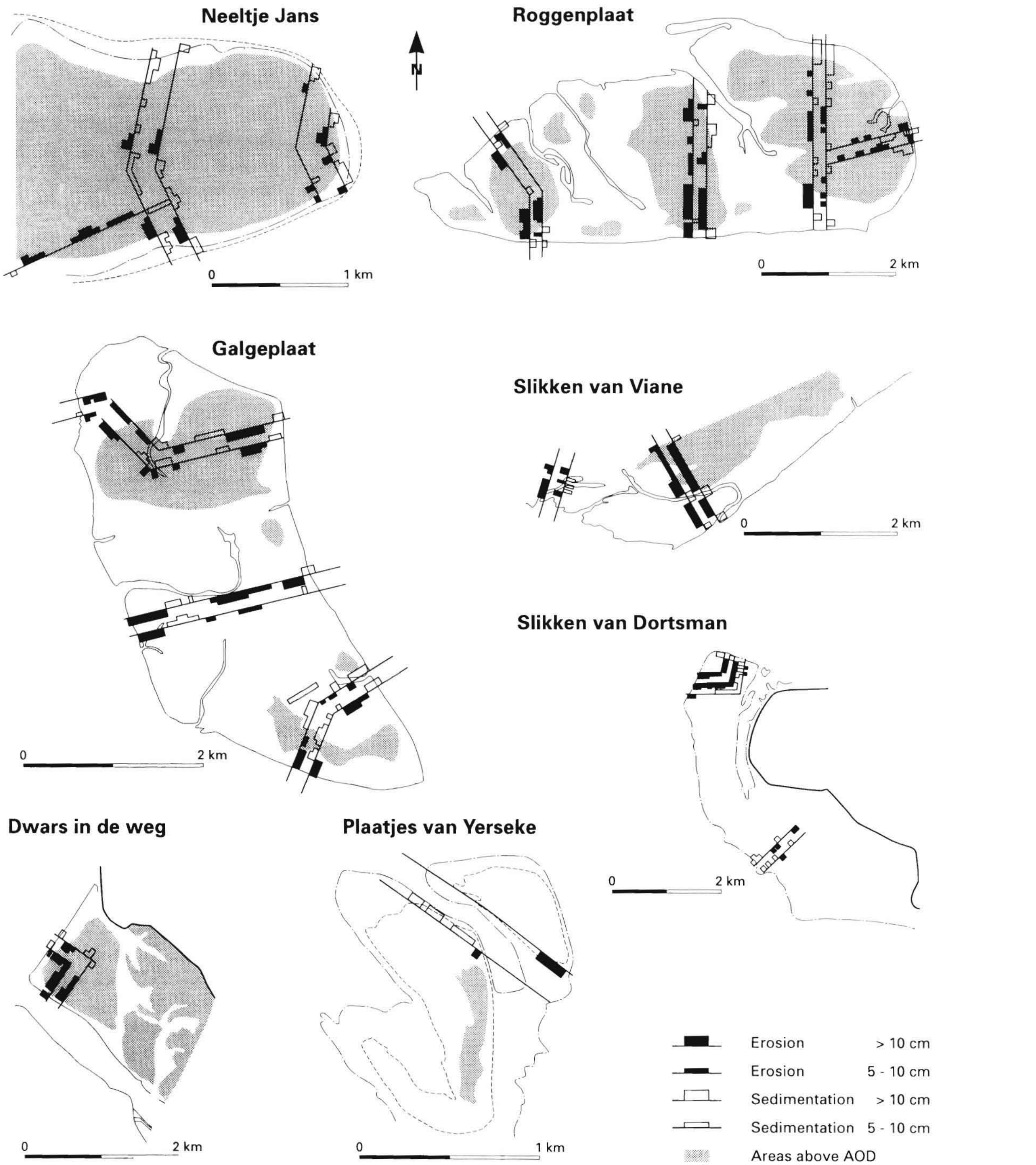

Figure 17. Spatial variability in erosion and sedimentation of tidal shoals in the Oosterschelde basin over the 1987–1990 period showing a net vertical erosion trend in the higher parts of the shoals following completion of the Oosterschelde project.

With respect to the height of the shoals above the subtidal level, EYSINK (1993) and DIECKMANN (1985) have demonstrated that the maximum height of sandy shoals in the Dutch and German Wadden Sea is related to the mean tidal range, which is in fact a reflection of local tidal energy. Both the general sedimentation trend of the higher parts of the sandy shoals in the period prior to completion and the observed erosion trend of the shoals after completion (Figure 18) correspond to the observed changes in the mean tidal range: a continuing increase in mean tidal range before the

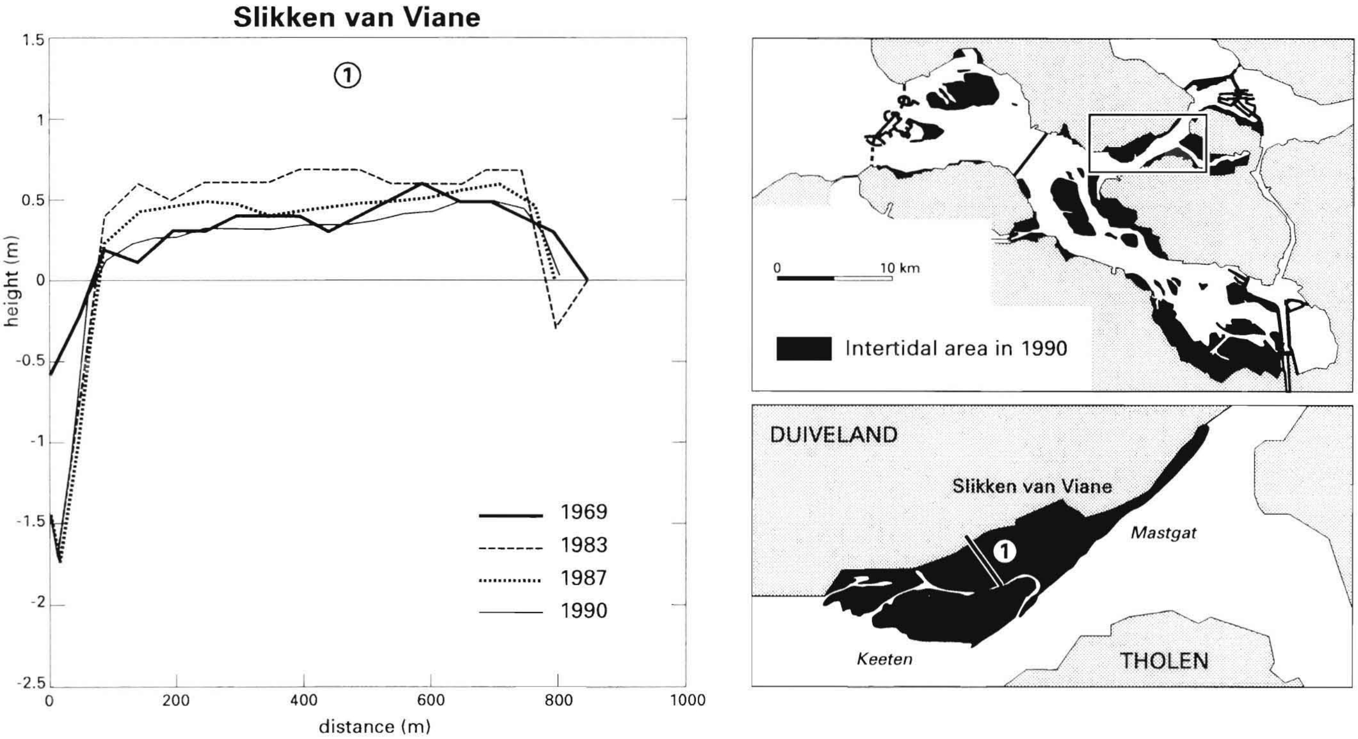

Figure 18. The development in the 'slikken van Viane' tidal shoals illustrates the general sedimentation trend in the higher parts of the shoals in the period prior to completion of the Oosterschelde project and the observed erosion trend in the shoals after completion of the project (based on Mulder & Louters, 1994).

engineering works, followed by an abrupt reduction thereafter.

Salt-Marshes

A gently sloping shore line with little wave energy and sufficient sediment supply are basic conditions for salt-marsh formation in an estuary (DIJKEMA, 1987), while the salinity of the water and the flooding frequency and duration, dependent on tidal range and surface elevation, determine the salt-marsh's character. Tidal range and surface elevation must provide periods of soil drainage and aeration sufficiently long to allow plant growth to occur (ARMSTRONG *et al.*, 1985), and these therefore determine the typical zoning of salt-marsh vegetation. Characteristic zones in the Oosterschelde salt-marshes range from mud pioneer to high marsh zones. Annual variations in mean high tide level lead to changes in species composition in the different zones, paralleling the changes in flooding frequency (BEEFTINK, 1979, 1987; OLFF *et al.*, 1988).

The observed changes in vegetation zones and the specific changes in soil characteristics in the Oosterschelde salt-marshes over the period between 1986 and 1990 may be related to the changes in flooding frequencies between 1985 and 1987 (Figure 19). The significant mortality of marsh vegetation in 1987 was probably due to the combined effects of drought, soil acidification and a severe winter, during a period in which there was an extra reduction in tidal range.

Changes in tidal range also have a significant effect on salt-marsh erosion (FÜHRBÖTER, 1986). Tidal range reduction leads to a greater dissipation of wave energy in the seaward part of the salt-marsh, and consequently to an acceleration of erosion. This causes a steeper slope at the transition between marsh and mud-flat. The relative increase in wave energy may discourage colonization by marsh plants (VAN EERDT, 1985) and the accretion of sediment particles. The increased erosion of salt-marsh cliffs since the completion of the Oosterschelde project in 1987 is in accordance with the observed changes in hydraulic conditions. Another factor, however, is a reduction in cliff strength, resulting from increased soil ripening and temporary dieback of vegetation (DE JONG *et al.*, 1994).

Expected Long-Term Changes

The change in hydraulic conditions following completion of the Oosterschelde project has brought a reduction in the tidal energy available for sediment transport and modification of the channel morphology. The time required for the system to achieve a new equilibrium will generally depend on whether the change implies a reduction or an increase in tidal energy. The relaxation period following an increase in energy will be much shorter than that following a reduction of similar magnitude. In the Oosterschelde, the channel cross-sections appear in most areas to have completed their adaptation to the increase in tidal discharges resulting from the closure of the

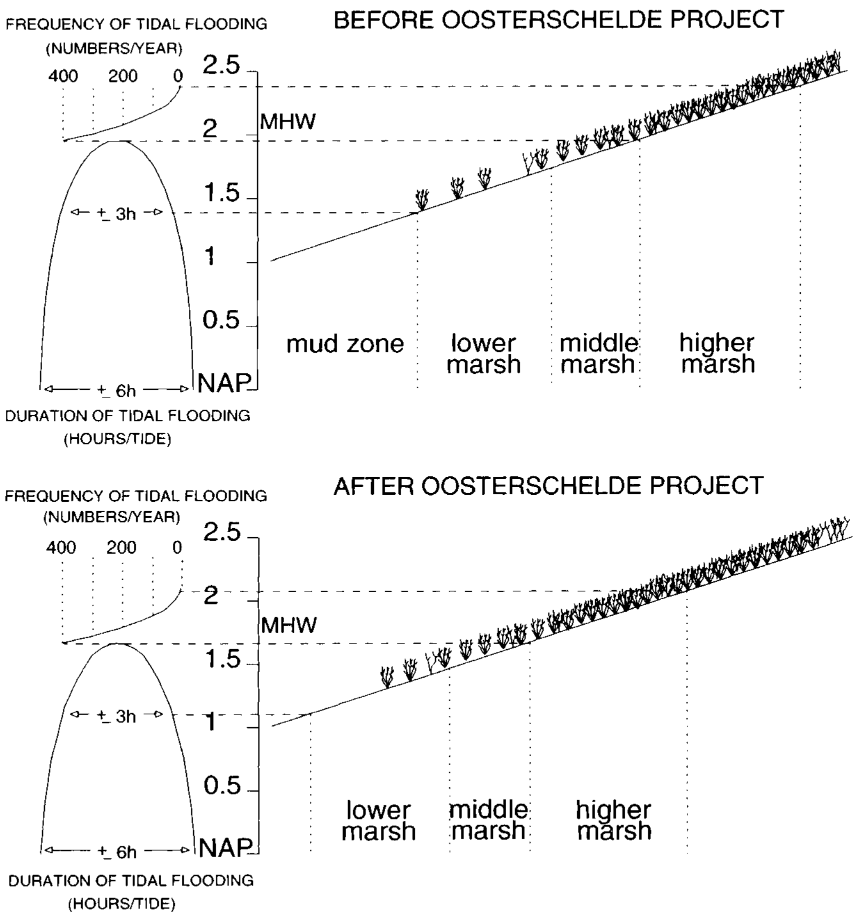

Figure 19. Diagram of the general geomorphological and biological response of a salt-marsh area to changes in hydraulic conditions (based partly on Dijkema *et al.*, 1990).

Grevelingen and Volkerak Dams (in 1965 and 1969 respectively) by 1983, *i.e.* in less than two decades (VAN DEN BERG, 1986). The period required for the system to achieve a new dynamic equilibrium following the reduction in tidal discharges induced by the storm surge barrier will probably exceed this by one or two orders of magnitude. The Oosterschelde project has reduced the tidal prism of the basin to its mid-19th century level. Since that time (*i.e.* in one century), approx. 400 million m^3 of sediment have been eroded from the western part of the Oosterschelde. Using equation 1, it has been estimated that a similar amount of sediment will be needed to restore the equilibrium. It follows that the time needed to achieve this will be two to four centuries.

However, this estimate is subject to a number of uncertainties. An increased sea level rise would produce a need for extra sediment import to the basin, and thus a longer relaxation time (EYSINK, 1993). The sediment import itself depends both on the development of the scour pits on both sides of the barrier and on the geomorphological adaptation of the tidal channels in the ebb tidal delta.

The scour pits might effectively rule out any chance of a net sand import into the basin. It was originally expected that the erosive effect of the turbulence might continue over several decades and produce very large scour pits up to −80m AOD deep and approx. 1500 m in length. In pits of this size, the tidal flow velocity would decrease dramatically and most sand carried in suspension by ebb or flood currents would be deposited in the pits before reaching the barrier. In this case, the scour pits would act as effective sand traps. However, recent sand transport measurements up and downstream of the pits show comparable figures at both locations. Obviously the scour pits are still too small to be effective as sand traps and no equilibrium has yet been established. Moreover, the scouring process is slowing down and it is now not expected that the pits will become much deeper. For this reason, the sand-trapping mechanism is now expected to remain of minor importance.

The transport capacities of the tidal channels near the storm surge barrier (see Figure 5) are at present too small to allow any substantial sand or mud transport in the direction of the basin. The major part of the sediment transport is silt.

Like the channels within the basin, the ebb delta channels show a major need for sediment. Until a new equilibrium has been established in the ebb tidal delta, there is unlikely to be any significant sand import into the basin.

CONCLUDING REMARKS

The geomorphological development of the Oosterschelde tidal system has been dominated by human interference for many centuries. In former times, this resulted—intentionally or otherwise—in successive increases in the tidal discharge of the basin. The geomorphological system responded accordingly by a general erosion of the basin and expansion of the ebb tidal delta. The basin erosion was characterized by deepening and widening of the tidal channels and vertical accretion of sandy shoals.

Implementation of the Oosterschelde project brought an abrupt reversal in long-term trends. Since 1985/86, the tidal discharge of the Oosterschelde has been reduced by 30% and the system has changed into a sedimentation basin and degrading ebb tidal delta. A remarkable characteristic of the sedimentation basin is the general trend towards the erosion of the intertidal area, caused by a reduction of tidal amplitude leading to a relative increase in the erosive effects of wave energy dissipation near the edges of the shoals.

ACKNOWLEDGEMENTS

This study was authorized by the Ministry of Transport and Public Works, Directorate General for Public Works and Water Management (Rijkswaterstaat). The investigations were carried out within the framework of the EOS multidisciplinary research project, the aim of which was to evaluate developments in the Oosterschelde. The EOS project was supervised by the National Institute for Coastal and Marine Management/RIKZ and the Zeeland Department of Rijkswaterstaat. The research institutes participating in the study presented here were the Institute for Marine and Atmospheric Research (Utrecht) and the Centre for Estuarine and Coastal Ecology (Yerseke).

We are grateful to Dr. ir. J van der Kreeke and Dr. ir. F. Gerritsen for critical remarks greatly improving the manuscript. We also acknowledge the help of Drs. W. Jonkers in analysing bathymetric and process data, and the helpful discussions we had with him while preparing this paper. Data on long-term salt-marsh development were provided by Drs. P.M. Schoot and Drs. M.M. van Eerdt.

LITERATURE CITED

ARMSTRONG, W.; WRIGHT, E.J.; LYTHE, S., and GAYNARD, J.T., 1985. Plant zonation and the effects of the spring-neap tidal cycle on soil aeration in a Humber salt-marsh. *Journal of Ecology,* 73, 323–339.

BEEFTINK, W.G., 1979. The structure of salt-marsh communities in relation to environmental disturbances. *In*: JEFFERIES, R.L. and DAVY, A.J., *Ecological processes in coastal environments.* Oxford: Blackwell, pp. 77–93.

BEEFTINK, W.G., 1987. Vegetation responses to changes in tidal inundation of salt-marshes. *In*: J. VAN ANDEL *et al., Disturbance in Grasslands.* Dordrecht: Junk, pp. 97–117.

BRAND, K.J.J., 1985. Zeeuws Vlaanderen, een gebied met een lange en rijke bedijkingsgeschiedenis (in Dutch). *Waterschapsbelangen,* 16, 382–393.

BRUUN, P.; MEHTA, A.J., and JOHNSON, I.G., 1978. *Stability of Tidal Inlets.* Developments in Geotechnical Engineering, 23. Amsterdam: Elsevier, 506p.

DE JONG, D.J.; DE JONG, Z., and MULDER, J.P.M., 1994. Changes in area, geomorphology and sediment nature of salt-marshes in the Oosterschelde estuary (SW Netherlands) due to tidal changes. *Hydrobiologia* 282/283, 303–316.

DE JONG, H. and GERRITSEN, F., 1984. Stability parameters of the Western Scheldt Estuary. *Proc. 19th Int. Conf. Coastal Eng.,* (Houston), Vol. IV, 3078–3094.

DE RONDE, J.G., 1983. Changes of relative mean sea level and of mean tidal amplitude along the Dutch coast. *In*: RITSEMA, A.R. and GÜRPINAR, A., (eds): *Seismicity and Seismic Risk in the Offshore North Sea Area.* pp. 131–142.

DE VRIEND, H.J.; LOUTERS, T.; BERBEN, F., and STEIJN, R.C., 1989. Hybrid prediction of a sandy shoal evolution in a mesotidal estuary. *In*: FALCONER, R.A.; GOODWIN, P., and MATTHEW, R.G.S., (eds), *Hydraulic and Environmental Modelling of Coastal, Estuarine and River Waters.* Int. Conf. Bradford, England. Vol. 14, pp. 145–156.

DIECKMANN, R., 1985. Geomorphologie, Stabilitäts- und Langzetverhalten von Watteinzuggebieten der Deutschen Bucht, Mitt. Franzius-Institut, Univ. Hannover, *Heft 60,* 1985, 133–161.

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

DIJKEMA, K.S.; BOUWSEMA, P., and Van den Berg, J., 1990. Possibilities for the Wadden Sea Marshes to Survive Future Sea-level Rise. *In*: OVESEN, C.H., (eds), *Proceedings of the Second Trilateral Working Conference on Salt-marsh Management in the Wadden Sea Region,* pp. 125–145.

EYSINK, W.D., 1993. Impact of sea-level rise on the morphology of the Wadden Sea within the scope of its ecological function; General considerations on hydraulic conditions, sediment transports, sand balance, bed composition and impact of sea-level rise on flats. *DELFT HYDRAULIC, ISOS*2 project, Phase 4, Report H1300,* pp. 1–35.

FÜHRBÖTER, A., 1986. Veränderungen des Säkularanstieges an der deutschen Nordseeküste. *Wasser und Boden,* 9, 452–460.

GERRITSEN, F., 1990. Morphological stability of inlets and channels of the Western Wadden Sea. *Rijkswaterstaat report,* GWAO-90.019.

KNOESTER, M.; VISSER, J.; BANNINK, B.A.; COLIJN, C.J., and BROEDERS, W.P.A., 1984. The Eastern Scheldt project. *Water, Science, and Technology,* 16, 51–77.

KOHSIEK, L.H.M.; BUIST, H.J.; BLOKS, P.; MISDORP, R.; VAN DEN BERG, J.H., and VISSER, J., 1988. Sedimentary processes on a sandy shoal in a mesotidal estuary (Eastern Scheldt). *In*: DE BOER, P.L. *et al.,* (eds), *Tide-Influenced Sedimentary Environments and Facies.* Dordrecht: Reidel, pp. 201–214.

MORRA, R.H.J.; OUDSHOORN, H.M.; SVASEK, J.N., and DE VOS, F.J., 1961. The movement of sand in the tidal region of the south-western part of the Netherlands. *Report Delta Committee,* Vol. V, 328–380.

MULDER, J.P.M., 1989. The changing tidal landscape in the delta area of the South-West Netherlands. *In: Hydroecological Relations in the Delta Waters of the South-West Netherlands.* TNO Committee on Hydrological Research, Proceedings and Information, No. 41, 71–88.

MULDER, J.P.M. and LOUTERS, T., 1994. Changes in basin geomorphology after implementation of the Eastern Scheldt estuary project. *Hydrobiologia,* 282/283, 29–39.

LOUTERS, T.; MULDER, J.P.M.; POSTMA, R., and HALLIE, F.P., 1991. Changes in coastal morphological processes due to the closure of tidal inlets in the SW Netherlands. *Journal of Coastal Research,* 7(3), 635–652.

OERTEL, G.F., 1988. Processes of sediment exchange between tidal inlets, ebb tidal deltas and barrier islands. *In*: AUBREY, D.G. and WEISHAR, L., (eds), Lecture Notes on Coastal and Estuarine Studies, *Hydrodynamics and Sediment Dynamics,* 29, 297–383.

OFFICER, C.B., 1981. Physical dynamics of estuarine suspended sediments. *Marine Geology,* 40, 1–14.

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.
ROBINSON, H.H.W., 1960. Ebb-flood channel systems in sandy bays and estuaries. *Geography*, 45, 183–199.
SAEIJS, H.L.F., 1982. Changing estuaries: A review and new strategy for management and design in coastal engineering. *Rijkswaterstaat*, Communications no. 32/1982.
SMAAL, A.C.; KNOESTER, M.; NIENHUIS, P.H., and MEIRE, M.P., 1991. Changes in the Eastern Scheldt ecosystem induced by the Delta works. *In*: ELLIOTT, N. and DUCOTROY, J.P., (eds), *Estuaries and Coasts, Spatial and Temporal Comparisons*. Olsen and Olsen, pp. 375–384.
TEN BRINKE, W.B.M., 1994. The impact of biological factors on the deposition of fine-grained sediment in the Eastern Scheldt (The Netherlands). Thesis, Univ. of Utrecht: 7–252.
TEN BRINKE, W.B.M.; DRONKERS, J., and MULDER, J.P.M., 1994. Fine sediments in the Eastern Scheldt tidal basin before and after partial closure. *Hydrobiologia*, 282/283, 41–56.
VAN DE KREEKE, J. and HARING, J.A.C., 1979. Equilibrium flow areas in the Rhine-Meuse delta. *Proc. 16th Int. Conf. Coast. Eng.*, 3, 97–111.
VAN DEN BERG, J.H., 1986. Aspects of sediment and morphodynamics of subtidal deposits of the Eastern Scheldt (The Netherlands). *Rijkswaterstaat*, Communications no. 43/1986.
VAN EERDT, M.M., 1985. The influence of vegetation on erosion and accretion in salt-marshes of the Eastern Scheldt, The Netherlands. *Vegetatio*, 62, 367–373.
VAN RUMMELEN, F.F.F.E., 1978. Toelichting bij de Geologische kaart van Nederland 1:50.000, NoordBeveland (in Dutch). *Rijks Geologische Dienst*, Haarlem, 138p.
VOS, P.C. and VAN HEERINGEN, R.M., 1993. The impact of environmental changes on the occupational history in the south-western coastal area of the Netherlands (province of Zeeland). *Rijks Geologische Dienst*, Report 1459.
VRANKEN, M.; OENEMA, O., and MULDER, J.P.M., 1990. Effects of tide range alterations on salt-marsh sediments in the Eastern Scheldt, SW-Netherlands. *Hydrobiologia*, 195, 13–20.
WALTON, T.L. and ADAMS, W.D., 1976. Capacity of inlet outer bars to store sand. *Proc. 15th Conf. Coast. Eng.*, (New York, ASCE), Vol. 2, pp. 1919–1937.
WILDEROM, M.H., 1964. *Tussen afsluitdijken en deltawerken II* (in Dutch). NoordZeeland, Littooy & Olthoff (Middelburg), 415p.