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MORPHOLOGICAL CHANGES OF THE EBB-TIDAL DELTA OF THE EASTERN SCHELDT DURING RECENT DECADES[1]

J.H. VAN DEN BERG[2]

ABSTRACT

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The ebb-tidal delta of the Eastern Scheldt consists of a complicated system of shifting channels and shoals. From 1959 onwards detailed soundings of the area have been carried out almost yearly and thus the most important morphological changes in the last 25 years have been established. An attempt has been made to trace the impact of 'Delta-project' constructions which have already been completed upon the trend of the morphological evolution. Attention is paid to implications of this investigation for the study of fossil examples of ebb-tidal deltas. A main conclusion is that a rather small increase in tidal discharge at the entrance of the Eastern Scheldt basin resulted in a remarkable and rapid expansion of the ebb-tidal delta.

INTRODUCTION

The ebb-tidal delta of the Eastern Scheldt is part of a series of coalescing tidal deltas adjacent to the North Sea shelf. They are formed in front of the coast by tidal currents passing through a number of tidal inlets and estuaries connected with the Rhine-Meuse-Scheldt fluvial system. The sediment of the inlets and tidal deltas largely consists of fine to medium sand (TERWINDT, 1973).

The vertical tide in the tidal delta area is essentially semidiurnal. The mean tidal range in the Eastern Scheldt outer delta varies between 3.4 m at the coalescence of the Eastern and Western Scheldt tidal deltas and 2.8 m at the inlet entrance. The median grain size varies between 150 and 350 μm. The coarsest sediments are generally found in the deepest parts of the channels. For the current and sand transport patterns in the coastal area of the SW Netherlands prior to the closure of the Haringvliet estuary (1970) and the Grevelingen (1971) see TERWINDT (1973).

The sand is transported by both waves and currents, resulting in a complicated circulation of sediments governed by the presence of ebb and flood channels. A general picture of the present current velocity pattern is given by VOOGT & ROOS (1980) and SIEGENTHALER (1982).

The 'Delta Project' is bringing about major changes in the tidal current pattern and sediment transport in the area. As shown in Figure 1 several major dams have already been built. With the construction of a storm surge barrier in the mouth of the Eastern Scheldt and two secondary dams within the estuary, the project is nearing completion. The storm surge barrier will be finished by the end of 1986 and will reduce the present 12 x 10^8 m^3 tidal prism by about 30% (ANONYMOUS, 1983).

In the proximal part of the tidal delta, tidal current velocities are expected to decrease drastically and a direct change in current pattern is expected up to a distance of 20 km off the barrier (VOOGT & ROOS, 1980). It is obvious that this will result in drastic changes in the morphodynamics of the area and may have repercussions on coastal evolution. A study of the present hydraulic and morphodynamic system is essential to evaluate possible changes. This paper deals with the morphological evolution of the tidal delta during the past 150 years. Attention is focused on changes in recent decades

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[2] Rijkswaterstaat, Delta Department, Hydraulic Division, P.O. Box 5005, 4300KA Zierikzee, The Netherlands.

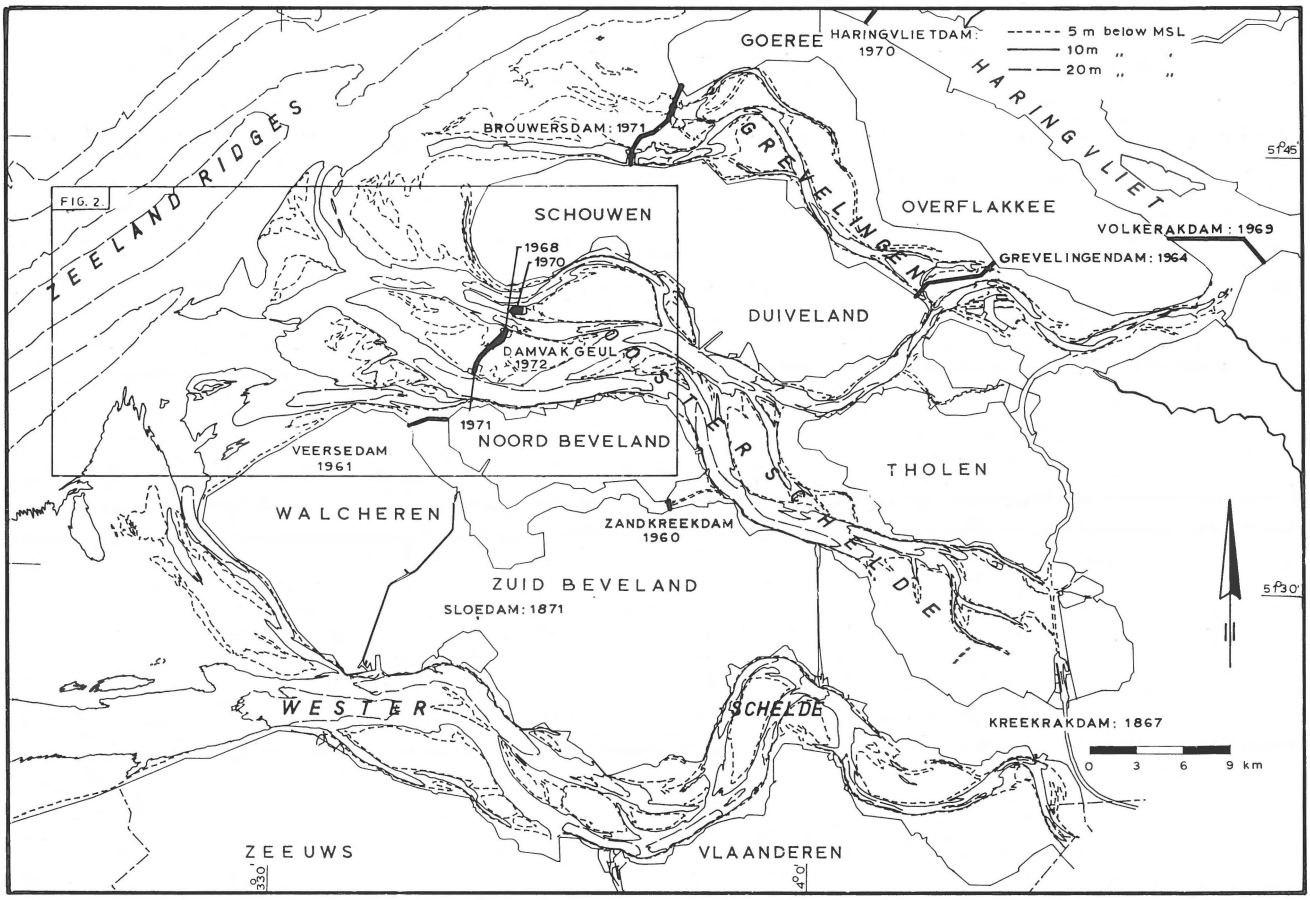


Fig. 1
Bathymetry of the South-Western Netherlands with dates of the main channel closures.

and their relationship to those parts of the 'Delta Works' already completed within the tidal basin and in the alignment of the Storm Surge Barrier.

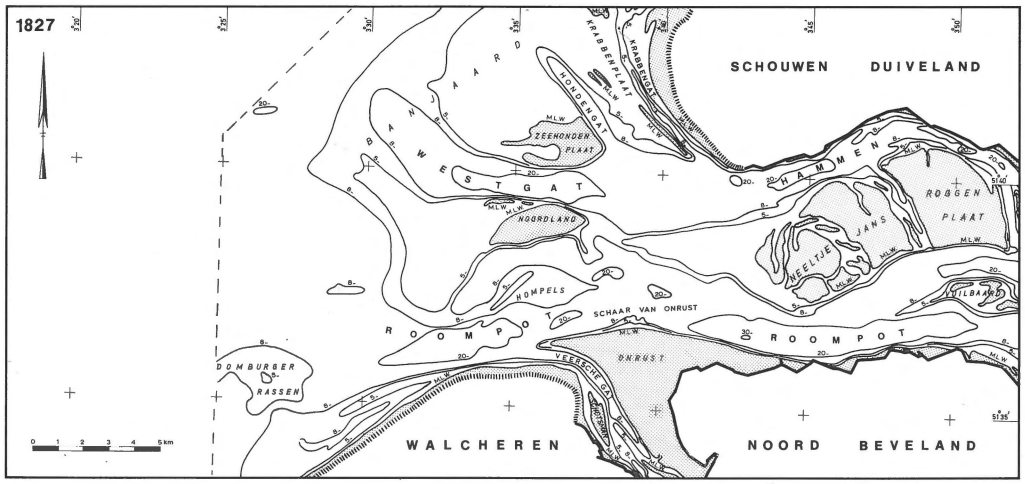
EVOLUTION OF THE TIDAL BASIN

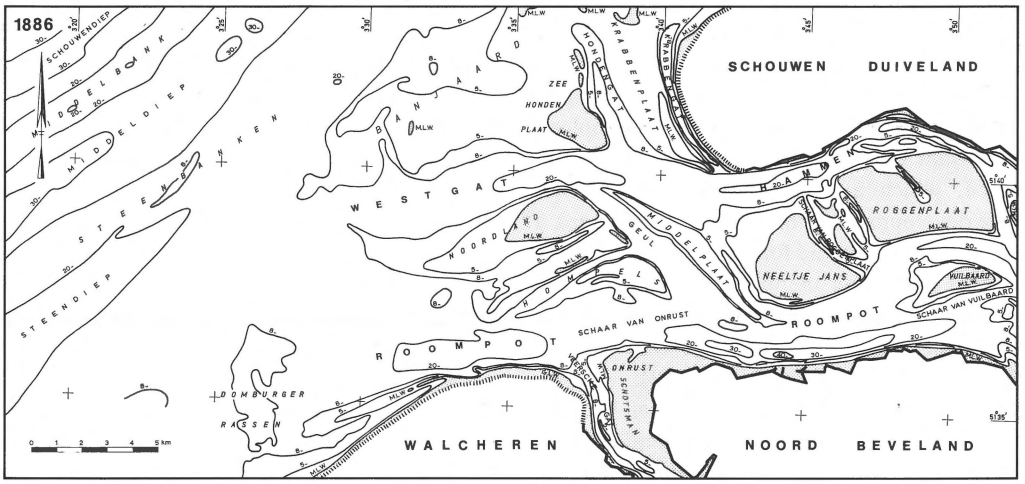
The origin of the system of inlets and estuaries in the SW part of the Netherlands lies in the last major transgression of the Holocene – the Dunkirk incursions from 2500 B.P. onwards.

Presumably after 500 B.C. but certainly before Roman times, a large estuary – the Eastern Scheldt – was formed as a main distributary of the River Scheldt (VAN RUMMELEN, 1978). Only after about 700 AD the more southerly Western Scheldt estuary started to form and gradually took over the fluvial discharge of the River Scheldt. This proces was finally completed artificially in 1867-1871 when two dams were built to seal the last connections between the Eastern Scheldt and the River Scheldt.

The early Eastern Scheldt had one major channel which was relatively narrow as compared to its present dimensions (WILDEROM, 1964). Storm incursions and floodings during mediaeval times widened the estuary at the expense of the neighbouring land (GOTTSCHALK, 1971). As a result the tidal prism must have increase by many hundreds of millions of cubic metres. The effect of this increase became apparent after 1400 AD when the main channel (the Hammen; Fig. 2) developed a large meander near the mouth of the inlet, causing a retreat of the coastline to the north to a maximum of 4 km. After 1600 AD the increase of tidal discharge resulted in the development of a second major channel, the Roompot (See Fig. 2 for location), leading to a coastal retreat of Noord Beveland and a further widening of the mouth of the estuary (VAN DEN BERG ET AL., 1980). Most of the eroded sediment must have been transported to the sea and likely has contributed to the growth of the tidal delta.

Morphological changes during the past 150 years are well-documented by a series of hydrographic charts. A selection of maps derived from these charts is presented in Figure 2. The figure shows that between the Roompot and Hammen channels a complex shoal area developed, cross-cut by smaller (5-15 m deep) blind-ending flood and ebb channels that were shaped by currents generated by small gradients in water-level between the two major channels at particular stages of the tidal cycle (VAN DEN BERG ET AL., 1980).





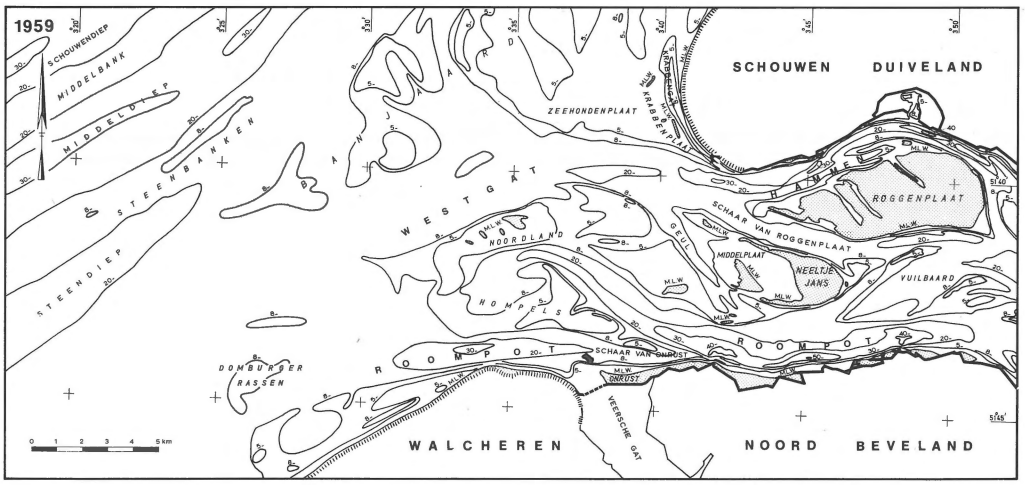


Fig. 2
The tidal delta of the Eastern Scheldt between 1827 and 1980 (continued on p. 366).

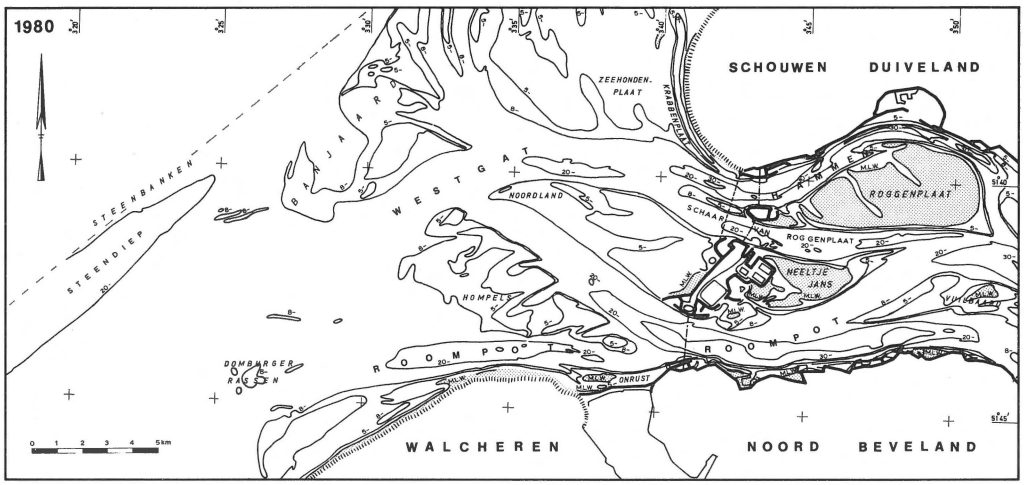


Fig. 2 continued.

During the 20th century a third major channel has developed in the entrance area of the Eastern Scheldt, the 'Schaar van Roggenplaat', running NW-SE between the Hammen en the Roompot. With its development from equilibrating stream into a major channel, the 'Schaar van Roggenplaat' became more important as a transit channel like the Roompot and the Hammen, which accounts for its anticlockwise rotation. With the development of this third major channel, a permanent connection between the former two channels was established. Most of the earlier mentioned small flood and ebb channels with a similar NW-SE orientation lost their hydraulic function and were rapidly silted up. One of those channels, the Geul, was dammed in 1972 (Fig. 2).

The origin of the 'Schaar van Roggenplaat' can be considered as a response to a further increase in the tidal prism, mainly caused by human interference in the tidal estuary; in the first half of the 20th century a considerable increase in the tidal discharge was caused by regulating works – dredging and canalization – in the northern tributary.

Since 1960 some of the closures of the Delta Project have influenced the tidal prism and other tide characteristics of the Eastern Scheldt. As a consequence of the closure of the Veerse Gat in 1961 the tidal prism of the estuary was reduced by about 5%. Before the construction of the Grevelingendam in 1962-1964 part of the ebb discharge from the Krammer-Volkerak area and, to a lesser extent, part of the flood tide, passed through the Grevelingen inlet. After this sea-arm had been dammed, these water masses were added to the tidal prism of the Eastern Scheldt. According to discharge measurements in the northern tributary, the tidal prism of the Eastern Scheldt increased by about the same quantity as it was reduced at the closure of the Veerse Gat some years earlier.

The closure of the Volkerak in 1969 caused an important change in the discharge curve and a dramatic increase in the tidal range on the northern tributary of the Eastern Scheldt, amounting to more than 50% in the northern-most part of this channel near the closure dam. According to calculations using the IMPLIC numerical one-dimensional network model of the Eastern Scheldt (DRONKERS, 1969), the maximum ebb discharge at the mouth of the Eastern Scheldt increased by 12%, whereas the maximum flood movement increased by 8%.

Apart from artificially induced changes of the tidal prism one natural factor is important: tidal gauge records indicate a natural increase of 4% in the tidal amplitude along the Dutch coast over the past century (DE RONDE, 1983). According to prolonged simultaneous measurements with automatic propellor current meters (Flachsee) this increase corresponds to a similar change of the tidal volume of the Eastern Scheldt.

Using data from various tidal inlets in the SW part of the Netherlands, an empirical linear relationship was established between the cross-sectional area of the inlet mouth below MSL (A_c) and the maximum tidal discharge ($\hat{Q}$) (VAN DE KREEKE & HARING, 1979):

$$A_c = 1.17\ \hat{Q}\ (m^2)$$

On the basis of this equation in conjunction with data from sounding charts and the results of the above-mentioned IMPLIC calculations, the increase in the tidal prism of the Eastern Scheldt since 1872 can be estimated at 25%, 9% of which has to be attributed to the damming of the Volkerak. As a consequence of this increase in tidal discharge, erosion has been dominant in most parts of the tidal basin.

Net sedimentation and erosion in the Eastern Scheldt and its tidal delta during the past century have been studied by HARING (1978). He analysed the change in cross-sectional area of a large number of parallel profiles through the Eastern Scheldt at intervals of 500 m. The changes in a profile were considered to represent a zone of 250 m to either side of the profile and the method is therefore not very accurate. Also, the accuracy of the older sounding charts is certainly not high. This holds especially for the tidal delta area. Therefore, HARING's data should be considered only as indicators.

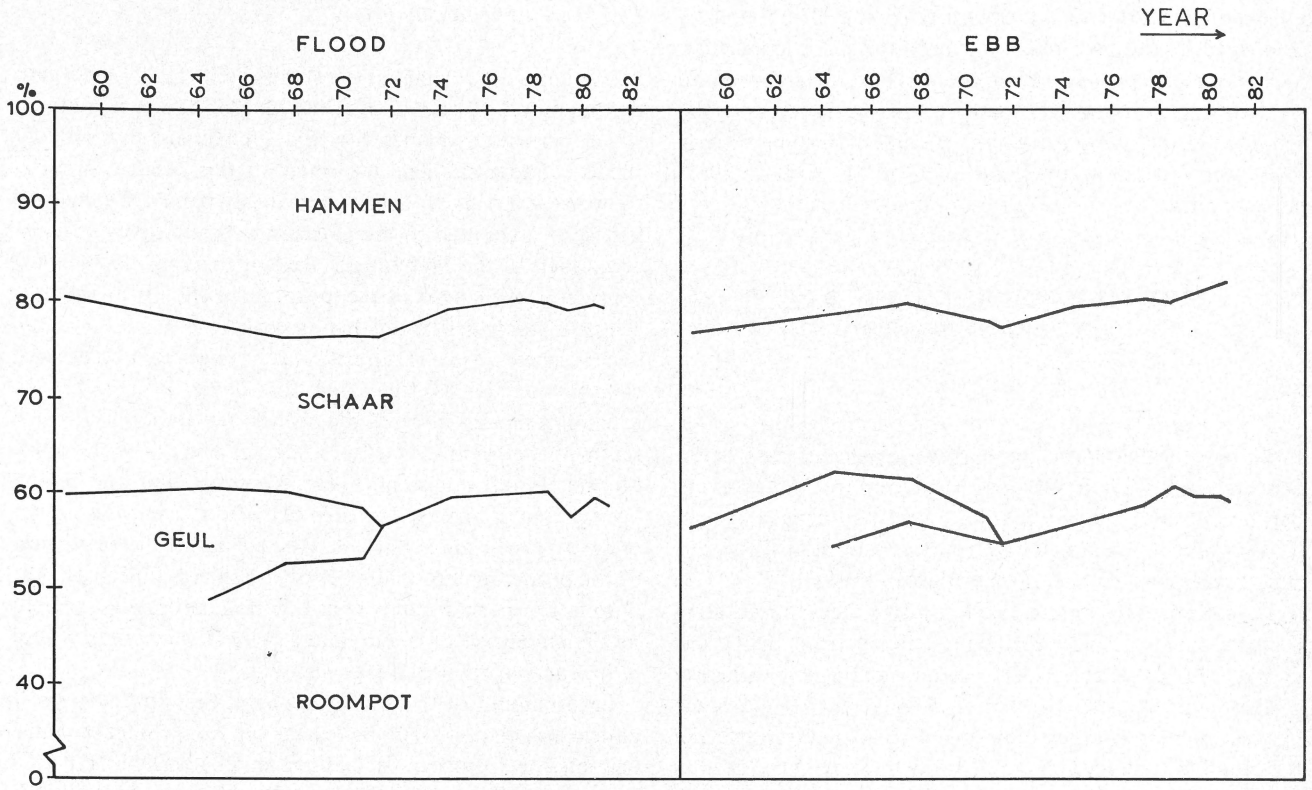


Fig. 3
Distribution of ebb and flood volumes among the channels in the mouth of the Eastern Scheldt since 1959. (Sum of ebb or flood volume = 100%).

The data suggest that the Eastern Scheldt lost some 2.8×10^8 m^3 of sediment during the period 1872-1959, resulting in a deepening of the area below MSL of on average 0.9 m (including the northern tributary). The amount of sediment transported to the sea between 1959 and 1974 can be estimated to be about 0.6×10^8 m^3. Another 0.78×10^8 m^3 was lost as a result of dredging. In that period , 1959 to 1974, the basin was deepened by about 0.4 m.

The building of the Storm Surge Barrier in the mouth of the Eastern Scheldt started with the construction of three artifical islands (1968 to 1970) and a dam across the Geul channel connecting two of these islands (Fig. 1). As mentioned before, the Geul channel was already declining as a tidal watercourse and its damming only accelerated the process of channel abandonment. According to a series of discharge measurements carried out by the Delta Department of the Rijkswaterstaat in the mouth area in recent decades, the ebb and flood volumes of the Geul after its closure were distributed between the Schaar van Roggenplaat and Roompot channels. These measurements further indicate some loss in tidal discharge in the Hammen channel after 1972, in favour of the Roompot (Fig. 3), which induced morphological changes in the Eastern Scheldt tidal channel system, to be discussed below.

MORPHOLOGY AND SEDIMENT BUDGET OF THE OUTER DELTA IN THE PERIOD 1827-1962

Morphological changes in this period are shown in Fig. 2. The Outer Delta contained a system of rapidly shifting channels involving the transfer of huge quantities of sand. The influence of the increasing tidal discharges through the inlet is reflected in a gradual deepening of the major channels in the proximal part of the tidal delta and – less apparent – the seaward extension of the underwater delta. The coeval disappearance of the intertidal shoals suggests a similar relationship with the change in tidal prism.

With respect to the sand budget HARING's data, partly summarised in MORRA ET AL. (1961), suggest a net erosion of the proximal and southwestern part of the outer delta between 1872 and 1962 of about 0.3×10^8 m^3 and 0.9×10^8 m^3 respectively. For the same period the amount of sediment involved in the seaward extension of the tidal delta can be estimated at 1.0×10^8 m^3. Together with the large amounts of sediment coming from the tidal basin, the total sediment export of the Eastern Scheldt system can be estimated at about 3.0×10^8 m^3. According to data about the sediment balance in the surrounding tidal areas, these sediments were partly transported northward along the coast and deposited in the Grevelingen and Haringvliet tidal systems, partly they were trapped on the innermost Zeeland ridges off the

underwater delta front (TERWINDT, 1973). The latter is confirmed by the occurence of a recent mollusc association including *Petricola pholadiformis* – a bivalve introduced into the North Sea around AD 1900 – in the upper layers of the sediment (LABAN & SCHÜTTENHELM, 1981). In some corings this layer reaches a thickness of 2 m (C. LABAN, 1982, pers.comm.).

MORPHOLOGICAL CHANGES IN THE PERIOD 1960-1980

Data

From 1860 till 1950 sounding charts were made of the Eastern Scheldt system by the Hydrographic Service almost every decade. From 1959 onwards the area has been surveyed almost annually by the Delta Department of the Rijkswaterstaat (Ministry of Transport and Public Works).

The latter surveys are carried out with Decca positioning (accuracy about 15 m) according to a fixed system of 100-200 m spaced sounding tracks. The accuracy of the determination of the sounded water-depth is estimated at 0.14 m. Since inaccuracies are mainly attributable to accidental errors in the reduction to Ordnance Datum, the average error in the area surveyed in a day – about 40 km^2 – will be less than 0.1 m. Deviations become progressively less as larger areas are considered. Calculations on the sand balance were performed on the basis of interpolated depth values using 200 x 200 m and 400 x 400 m grid squares (Fig. 4).

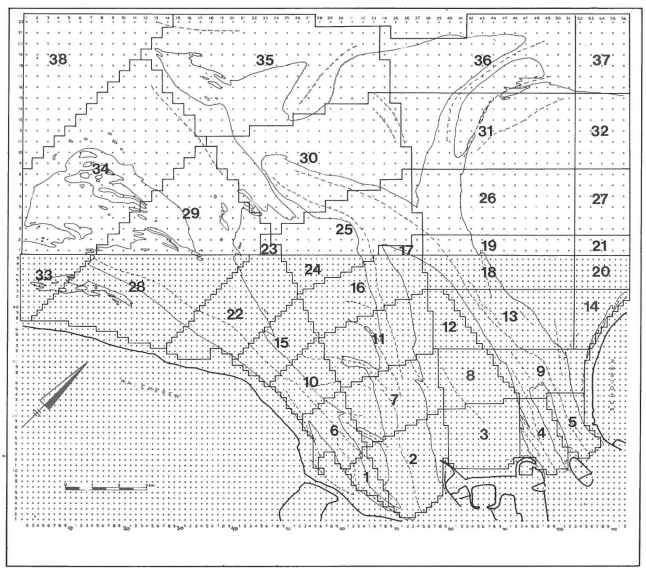


Fig. 4
Calibration grid and partition of the tidal delta.

The flood and ebb channels

Fig. 5 shows the changes in the channel pattern in the form of the migration of the 10 m below Mean Sea Level contour, which arbitrarily divides the major channels and subtidal shoals in the area. The movement of this depth contour is shown at intervals of 5 years. Obviously part of the changes has to be attributed to the inaccuracy of the survey. In flat areas such as the Domburger Rassen this may account for considerable changes in the position of the 10 m isobath, suggesting changes larger than in reality.

Nevertheless several trends are remarkable. The ebb channels of the Westgat and the Oude Roompot have expanded rapidly towards the sea. In the period 1970-1975 this happened at an accelerated rate, leading to a coalescence of two ebb channels the Oude Roompot and one of the Westgat ebb channels. The tidal delta front displays a similar seaward expansion, which is spectacular in the northwest where protuding terminal lobes of ebb shields form part of it. During the period under consideration, progradation here locally amounted to 700 m, and a layer of more than 9 m of sediment was deposited (see also Fig. 7).

In the mouth of the Eastern Scheldt the aforementioned anticlockwise rotation of the Schaar van Roggenplaat channel axis and the process of Geul channel abandonment and siltation may be noted. All these trends can be explained as reactions to the 20th century increase in the tidal prism of the estuary. This is clearly demonstrated by the increase in rate of expansion of the major ebb channels in the period 1970-1975, just after the sudden increase in tidal discharge connected with the Volkerak closure.

At the level of the 10 m depth contour the sill between the Oude Roompot and the Westgat channel was breached in 1974. At about the same time a similar breach occurred more inshore, between the Roompot channel and an ebb channel connected to the 'Schaar van Roggenplaat' (Fig. 2). As a consequence of these breaches the Roompot's share of the total ebb and flood discharges in the mouth of the Eastern Scheldt increased from 56 to 59% (Fig. 3).

A further illustration of ebb channel expansion and coalescence of ebb channels is given in Figure 6. The isallobath maps in this figure are based on data of interpolated depths in the 200 x 200 m and 400 x 400 m schematization of the area. The figure underlines the dominating influence of the ebb tide in the morphodynamics of this area: a large part of the sediment eroded by the ebb current near the blind end of the Westgat ebb channel is deposited downcurrent in a horseshoe-shaped accumulation on the flat ebb shields of the channel. Although less evident, the same holds for the other expanding ebb channels. It further emerges that two erosional processes played a role in breaching the sill between the Oude Roompot and Westgat channels:

– Firstly the seaward expansion of the Oude Roompot channel, which is predominantly achieved by channel bend

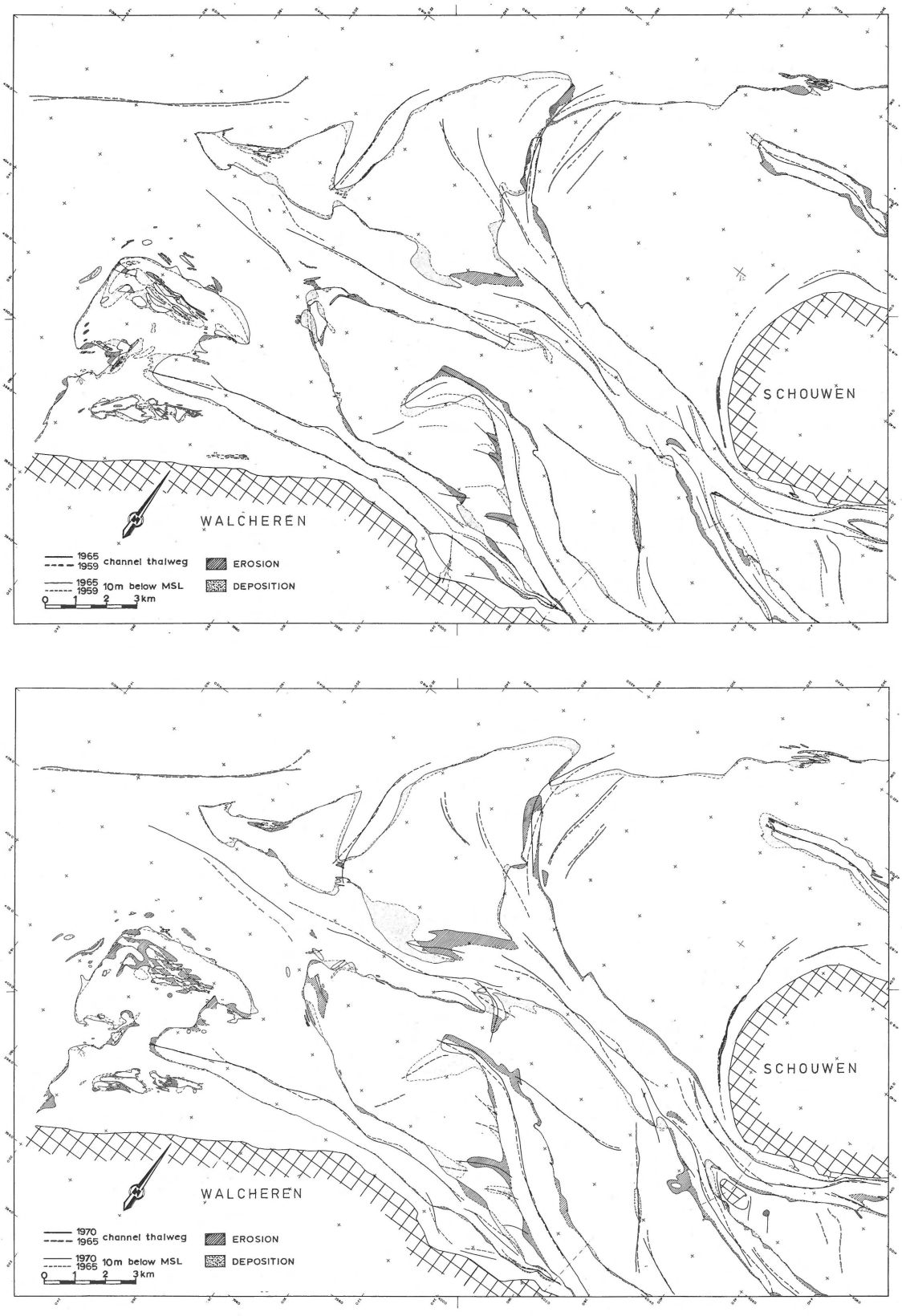


Fig. 5
Changes in the 10 m isobath between 1960 and 1980 (continued on p. 380).

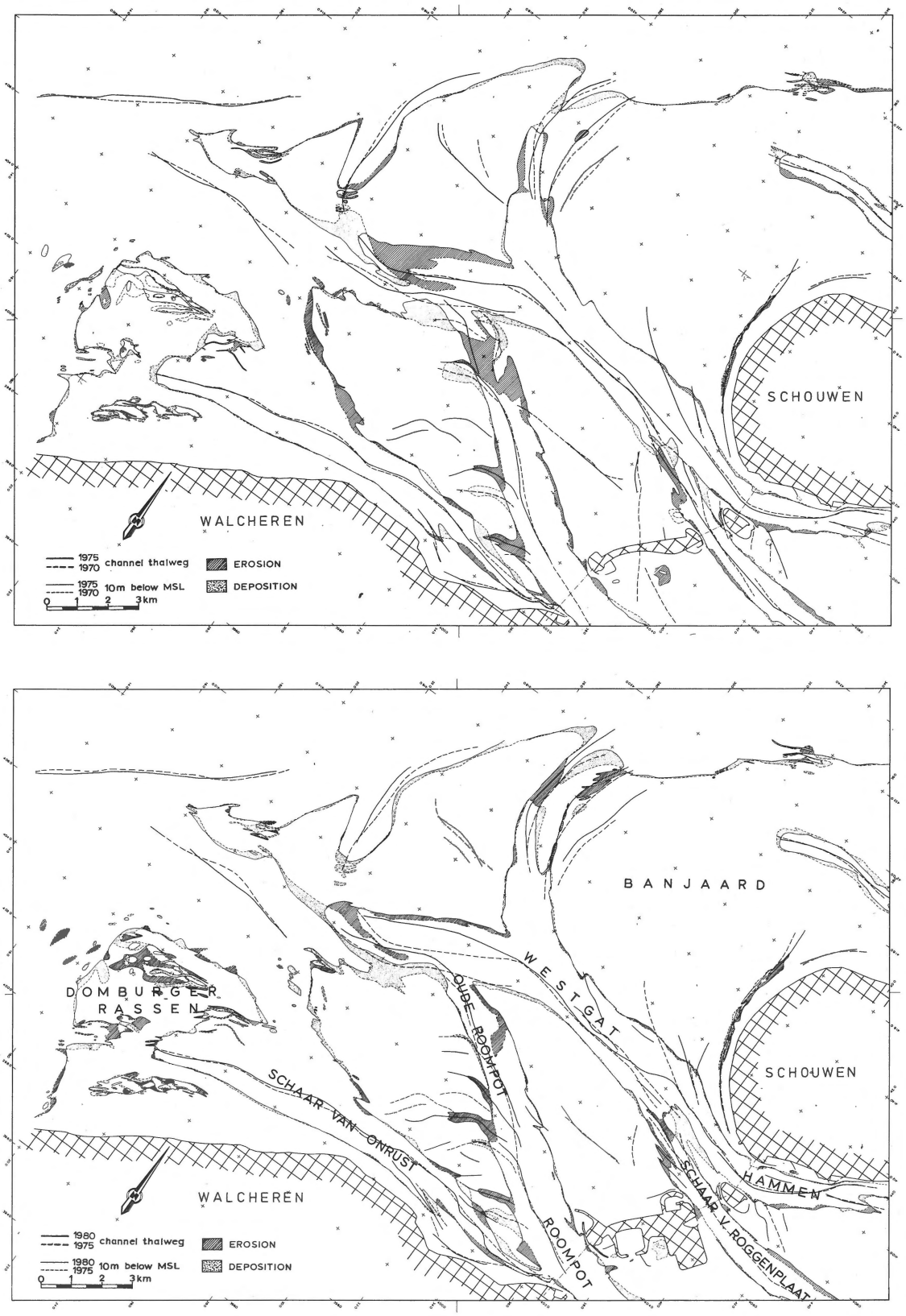


Fig. 5 continued

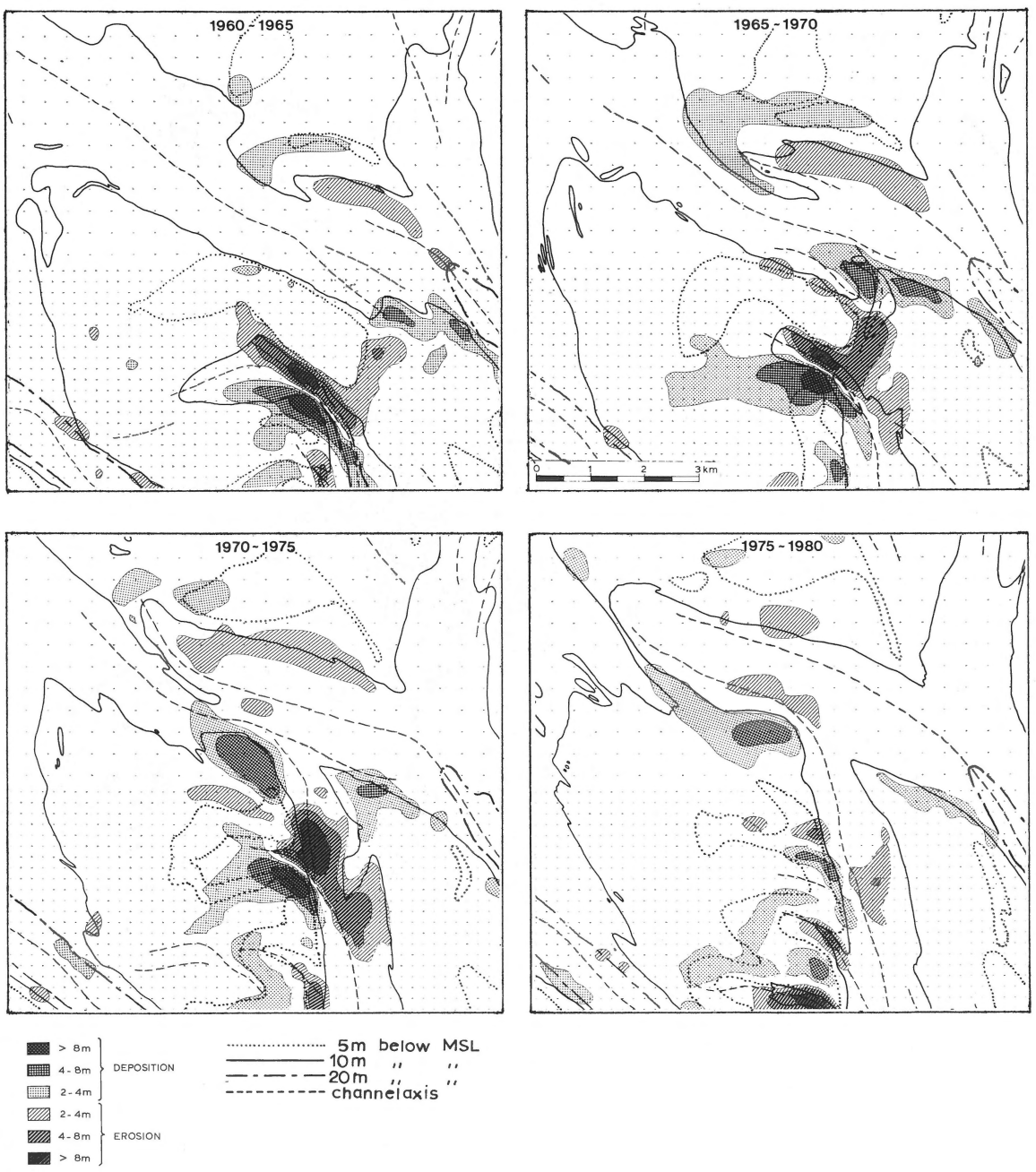


Fig. 6
Expanding ebb channels in the Eastern Scheldt tidal delta. For location see Fig. 7.

erosion in the westernmost part of the channel. The fast erosion by the ebb current of the outside of the bend is compensated by deposition in the inner bend. It may be noted that similar processes are taking place in secondary ebb channels branching off the SW bank of the Oude Roompot channel.

– Secondly the sill between the Oude Roompot and Westgat channels is eroded by currents that cross the bar. This is apparently caused mainly by the ebb current, since large amounts of sediment are deposited simultaneously just north of the sill.

After construction of the artificial islands and the damming of the Geul the total cross-sectional area below MSL of the Eastern Scheldt in the alignment of the Storm Surge Barrier was diminished by 17% (from 88.000 m^2 in 1968 to 73.000 m^2 in 1972). Therefore current velocities in the remaining channels have increased, resulting in erosion and deepening of an area extending several kms off the barrier alignment. This process was certainly enhanced by the increase in the tidal discharges after the damming of the Volkerak channel in 1969.

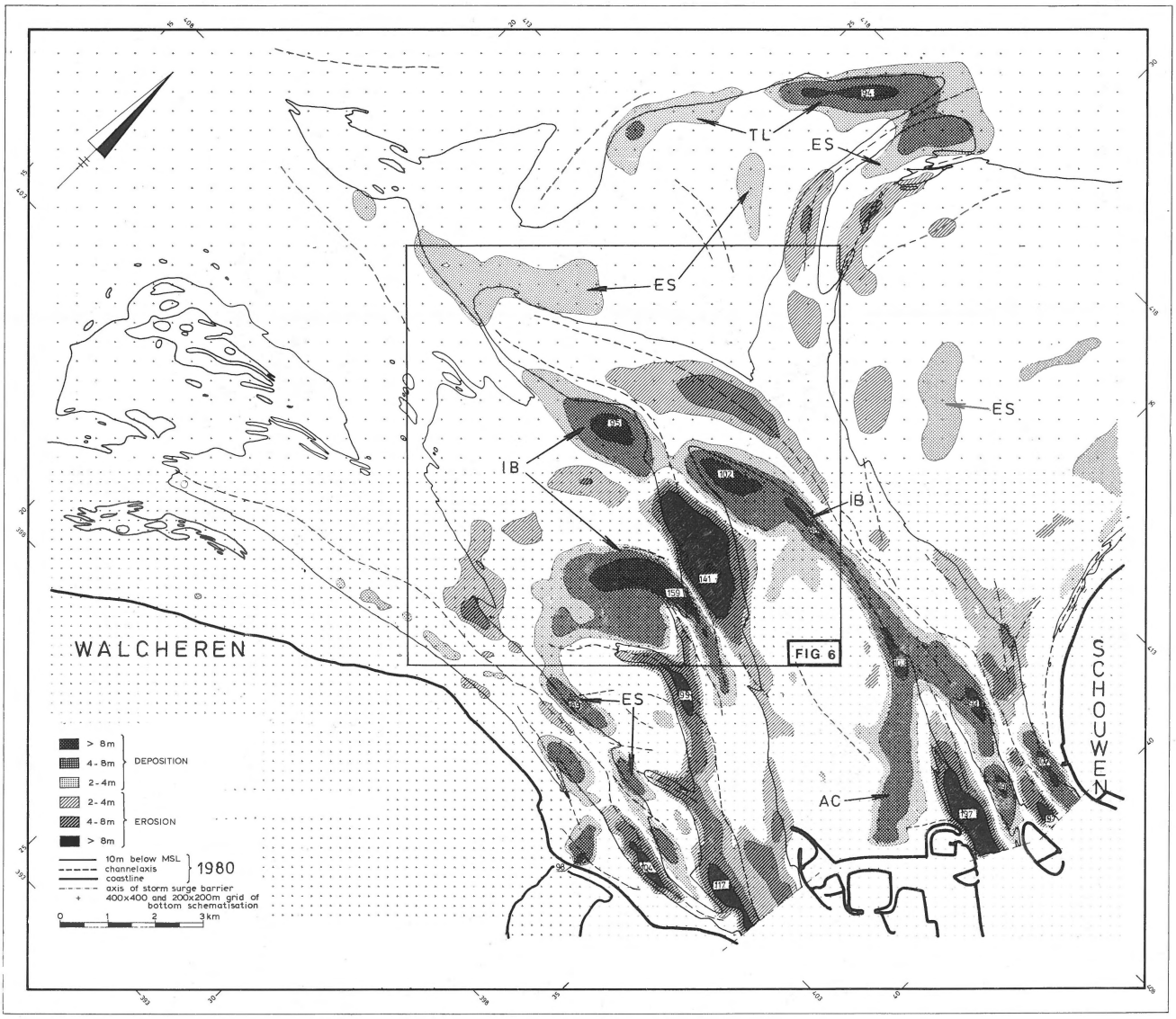


Fig. 7
Net deposition and erosion in the Eastern Scheldt tidal delta in the period 1960 - 1980. Nature of deposits: IB = Inner Bend of ebb channel; ES = Ebb Shield; TL = Terminal Lobe of ebb shield at the deltafront; AC = Abandoned Channel.

In accordance with the change in the distribution of the tidal discharge in the mouth after the damming of the Geul (Fig. 2) erosion in the Hammen channel was less than in the remaining channels. The extent of the erosion is illustrated by an isallobath map covering the period 1960-1980 (Fig. 7).

Erosion was concentrated along the southern margin of the channels. This remarkable fact is connected to long-term processes of channel migration quoted before: rotation of the Schaar van Roggenplaat channel and southward bending of the Roompot channel (Fig. 2). Although considerable erosion occured, the maximum depth of the channels did not change very much. Between 1968 and 1980 the maximum depth of the Roompot channel increased by 1 m to 34 m and the Schaar van Roggenplaat channel deepened from 19.5 to 21.5 m. The maximum depth of the Hammen channel even diminished by 1 m and became 28.5 m.

In spite of the southward migration of the left bank of the Oude Roompot channel, some erosion still occurred along the right (NW) bank of this channel, owing to a considerable widening process. Obviously this is related to the increase in tidal discharges through this channel caused by the Volkerak and Geul closures and to the coalescence of the Oude Roompot and Westgat channels.

The sand budget

Using the interpolated depth values per grid-square, the net erosion and sedimentation of the ebb tidal delta and parts of it over periods of 5 years have been calculated for the period 1960 to 1980. To discriminate between sedimentation processes in the different channels and between proximal and more distal parts of the tidal delta the area was divided

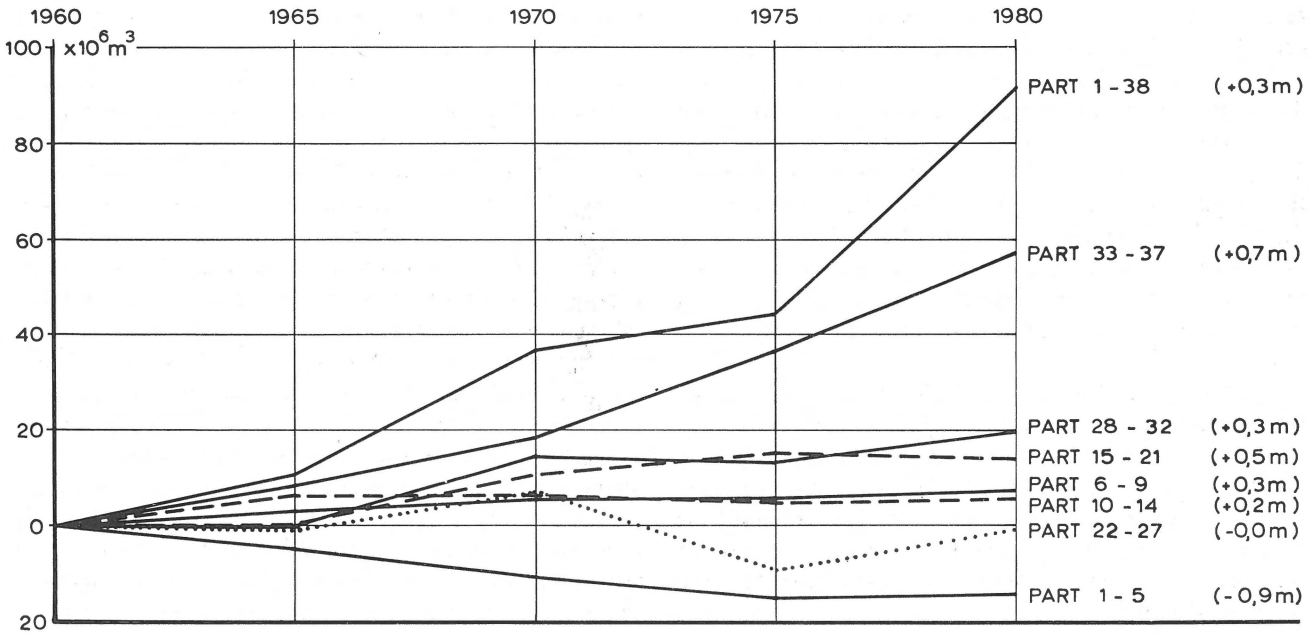


Fig. 8
Sediment budget of the tidal delta and parts of it in relation to proximity of the inlet entrance (1960 - 1980).

according to flow areas of the major channels and proximity of the inlet (Fig. 4). Some of the results are shown in Figs. 8 and 9.

One of the most remarkable results of the calculations is the large volume of sand deposited in the tidal delta in a period of only 20 years (0.9×10^8 m^3). Although accurate calculations of the erosion in the estuary have not yet been carried out it is certain that this is the main source area of the sediment. A source of minor importance, estimated at about 0.02×10^8 m^3, is found in the net loss of sand from beaches and dunes, especially along the Schouwen coastline, which locally retreated by 120 m in this period. The absence of a significant morphological change in the SW part of the tidal delta does not indicate a substantial sediment transfer from the Western Scheldt region. Therefore, other sediment sources – if any – must by considered negligible. Instead some loss of sand might be expected that accumulated in the Zeeland Ridges offshore and along the coast farther the north, as was the case in former periods. It is not obvious why the calculated total net deposition in the period 1975-1980 should have been more than in the preceding period of five years. The difference in the rate of deposition between the two periods seems too large

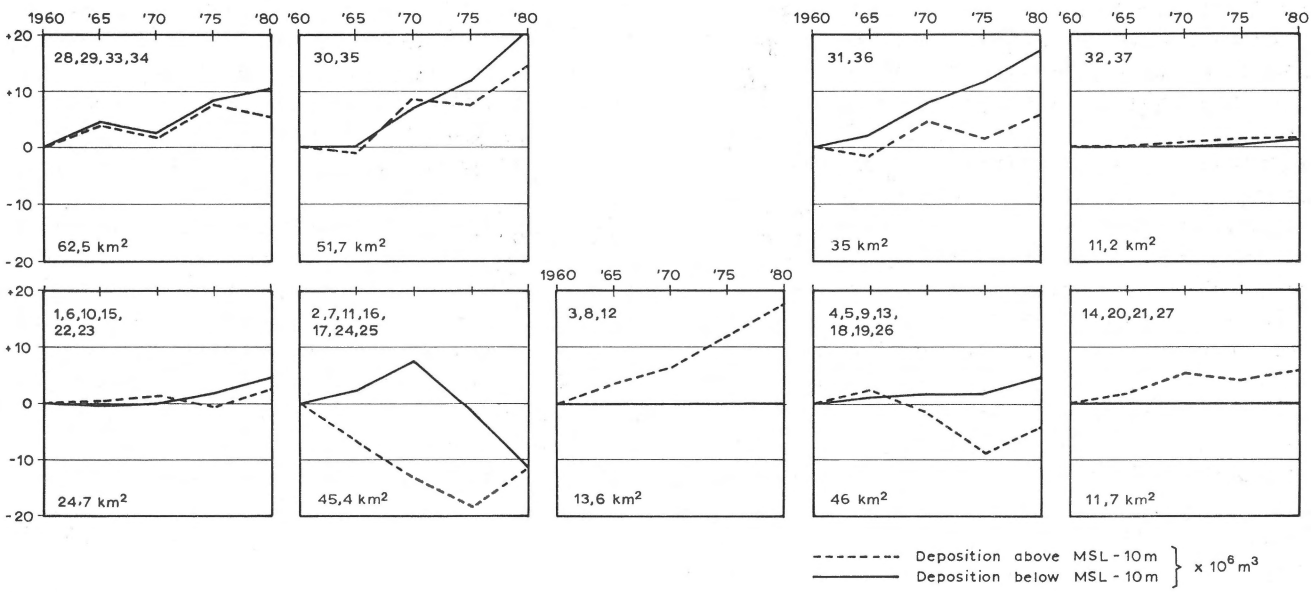


Fig. 9
Sediment budget of different flow areas in the tidal delta (1960 - 1980). Numbers refer to zones as indicated in figure 4.

to be ascribed to errors in the calculated sediment volumes caused by inaccuracies of the soundings. At least part of it must be explained, however, by a natural increase in the tidal discharge after the damming of the Volkerak channel, that was connected with a 18.61 year cyclic change in tidal range. This period represents the variation of the mean longitude of the ascending node of the lunar orbit. The variation affects the tidal range. Along the coast of the SW Netherlands it causes a cyclic variation in the mean tidal range of about 3%. As mentioned before, this leads to a variation in the tidal discharges of the Eastern Scheldt of about the same proportion.

By chance, the closure of the Volkerak took place at the tidal minimum of the cycle. Consequently, after the sudden increase of 8% of the tidal discharge of the Eastern Scheldt, caused by the damming of the Volkerak channel, a further increase of 3% occurred till about 1978. This enhanced the erosion in the tidal basin which could at least partly explain the relatively high rate of deposition in the tidal delta in the periode 1975-1980.

IMPLICATIONS FOR THE STUDY OF FOSSIL EXAMPLES OF EBB-TIDAL DELTAS

Although this investigation was focused on morphological changes some results bear interesting implications for the study of fossil ebb-tidal deltas which can not be disregarded. They will now be discussed briefly.

One of the most interesting aspects is the remarkable expansion of the tidal delta and the large sediment supply to it coming from the tidal basin in response to a rather small increase in tidal discharge through the inlet. In such a prograding ebb-tidal delta the expanding ebb channels are the most dynamic elements. Main depositional areas are the inner bends of these dynamic ebb channels, the major ebb shields and the terminal lobes of these shields at places where they form part of the underwater delta front (Fig. 7).

Echo soundings reveal that most of the ebb shield and inner channel bend environments is covered by a pattern of ebb-directed megaripples, indicating that deposits will consist mainly of ebb-directed cross-stratified sediments. A subrecent example of an inner bend deposit exposed in a construction pit of the storm surge barrier in the mouth of the Eastern Scheldt was described by VAN DEN BERG (1982). The terminal lobes of ebb shields at the delta front gradually encroach upon the innermost ridge of the system of sandwave-covered elongated sand ridges, known as the Zeeland Ridges, which run more or less parallel to the present coast (Fig. 1 ; for a discussion on the origin and stratigraphy of the Zeeland Ridges the reader is referred to LABAN & SCHÜTTENHELM, 1981). Prograding parts of the delta front show a concave upward seaward-facing ramp between 7 and 13 m below Mean Sea Level, with a maximum gradient of 4 to 12 degrees. Information on bedforms on this slope is rather scanty. A side scan sonar survey revealed a relatively flat surface that passes abruptly into a megaripple field at the base of the slope. Above the 7 m depth contour a transition is found to a rather flat subtidal terrace. Strong wave action during periods of onshore gales inhibits these outermost shoal areas to shallow above 4 m below Mean Sea Level.

Data from shallow cores taken by the Geological Survey of the Netherlands suggest that sediments of the distal part of the ebb-tidal delta hardly contain mud laminae. This is in sharp contrast with deposits of the same age described from inshore subtidal environments in this area (TERWINDT, 1971; 1981; VAN DEN BERG, 1981, 1982; VISSER, 1980). This difference can partly be ascribed to a more intense wave agitation of bottom sediments in the offshore area. A more fundamental reason lies in the absence of short stand-still stages of the current, allowing mud to settle out of suspension. In the relatively narrow and elongate inlets and estuaries currents are laterally confined. Therefore at the transition from flood to ebb and vice versa the current direction changes drastically by about 180 degrees, implying a short slackwater period during which indeed fine-grained sediment can settle. Off the inlet entrance currents gradually become less channelized. Longshore components of the tide become more important and current vectors tend to describe a more elliptical to circular pattern (SIEGENTHALER, 1982). At the 'turn of the tide' current vectors gradually rotate and velocities remain strong enough to inhibit the settling and deposition of mud.

CONCLUSIONS

Owing to both natural and artificial influences the tidal volume of the Eastern Scheldt during the past century has shown an increase of about 25%. As a result, large amounts of sand have been eroded in the Eastern Scheldt. Also, in the proximal part of the ebb-tidal delta some large intertidal shoals have completely disappeared and major ebb channels have deepened and expanded in a seaward direction. Part of the eroded material has been incorporated in the distal part of the tidal delta, giving rise to a gradual seaward extension of the large ebb shields and part of the underwater delta front.

This paper shows that after 1969 the processes accelerated and illustrates how this was related to hydraulic changes induced by the damming of certain channels; as a consequence of the damming of the Volkerak in 1969 the tidal prism of the Eastern Scheldt increased by about 8%. The damming of the Geul in the mouth of the sea-arm caused a further increase in tidal discharges through the Roompot and the Schaar van Roggenplaat channels.

It might have been reasonable to expect that the accelerated net sedimentation in the tidal delta and associated morphological trends in delta front progradation and ebb channel expansion would have slowed down some years after the sudden increase in the tidal prism that was caused by the

damming of the Volkerak. No confirmation for this hypothesis could be found, however, in the results of calculations on the sand budget and the progress of the morphological changes. This could possibly be explained by a temporary further 3% increase in the tidal prism – after the initial 8% increase due to the damming of the Volkerak – related to the 18.61 year cyclic change in the tidal range. More certainty about this possibility will be obtained before long, as the calculations of the sand budget since 1960 are extended to the estuary and the coastal zone to the north.

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