Chapter Seven

Hydraulic processes affecting the morphology and evolution of the Westerschelde estuary

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7.1 INTRODUCTION

The Westerschelde is part of a system of coastal plain estuaries and tidal basins in the southwestern Netherlands (Figure 7.1). It is a young estuary, that started to evolve only a thousand years ago (Vos and Van Heeringen 1993). At present the Westerschelde is a well mixed estuary, with well developed channels and shoals covering an area of about 300 km^3 (Figure 7.2). The mean amplitude of the semidiurnal tide increases from 3.8 m at the entrance of the estuary to 5.2 m at Antwerpen (Figure 7.3). The total flood discharge of a tidal cycle (flood volume), which amounts to an average of 1100 $\times$ $10^6 m^3$ at Vlissingen, reduces to 70 $\times$ $10^6 m^3$ at Antwerpen. The fresh-water discharge of the Schelde river averages between 50 and 60 $m^3 s^{-1}$ from April to October and 160–180 $m^{3 s-1}$ from December to February. The average chlorinity of the water decreases from 18 $kg\,m^{-3}$ at Vlissingen to about 3 $kg\,m^{-3}$ at Antwerpen. At most locations the bed material of the Westerschelde consists of well sorted medium- to fine-grained sand. In deep channels the grainsize is generally coarser than on the shoals. In natural channels and shoal areas admixtures of clay are mostly less

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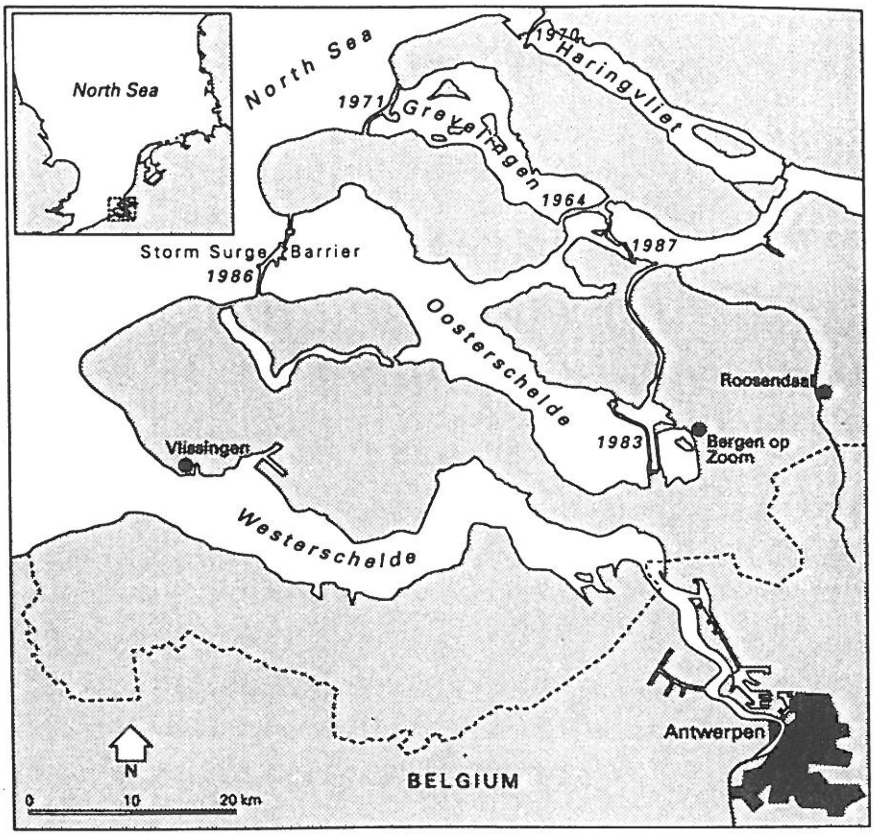


Figure 7.1 Estuaries and inlets of the SW-Netherlands, with dates of closure dams

than 3%, except for locations where older deposits (early Holocene/Tertiary) are exposed.

In the course of the Netherlands Delta Project (Watson and Finkl 1990), a series of coastal constructions were made to protect the SW Netherlands from a repeat of the 1953 storm-surge flooding. The inlets of the northern part of the system of estuaries have been closed by dams. At the entrance of the Oosterschelde a storm-surge barrier was built instead of a closure dam to save the ecology and tidal landscape of the estuary. The Westerschelde is not closed because of its importance as a waterway to Antwerpen, which requires dredging operations to be performed at some relatively shallow areas of the main channel. To keep pace with expanding shipping traffic, maintenance dredging activities have increased in the past decades up to about 12 million $m^3 a^{-1}$ at present. In the near future a further increase of dredging activities may be expected, related to a further deepening of channel bars in the navigation channel.

Human interference in this estuary is not something new. Humans influenced the

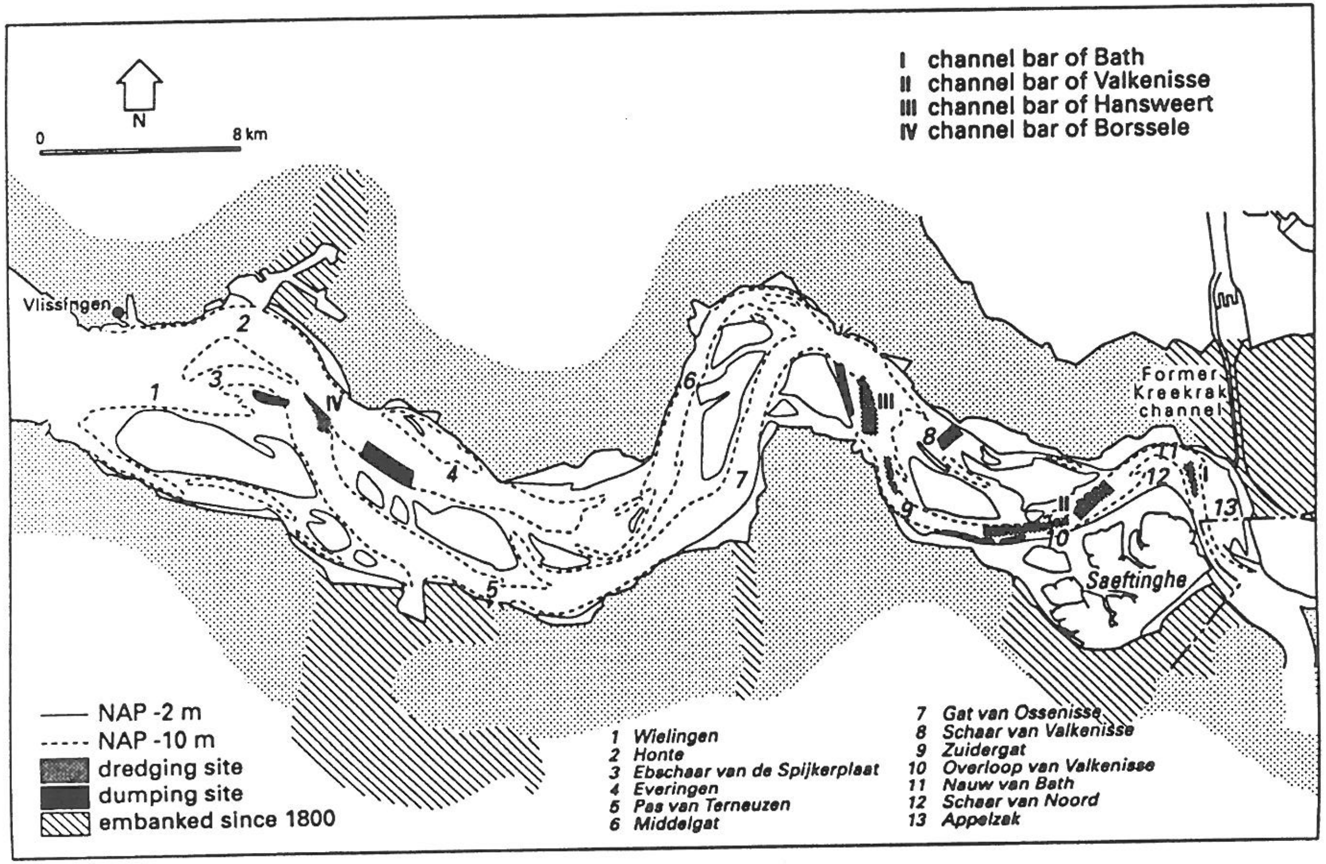


Figure 7.2 The Westerschelde in 1992

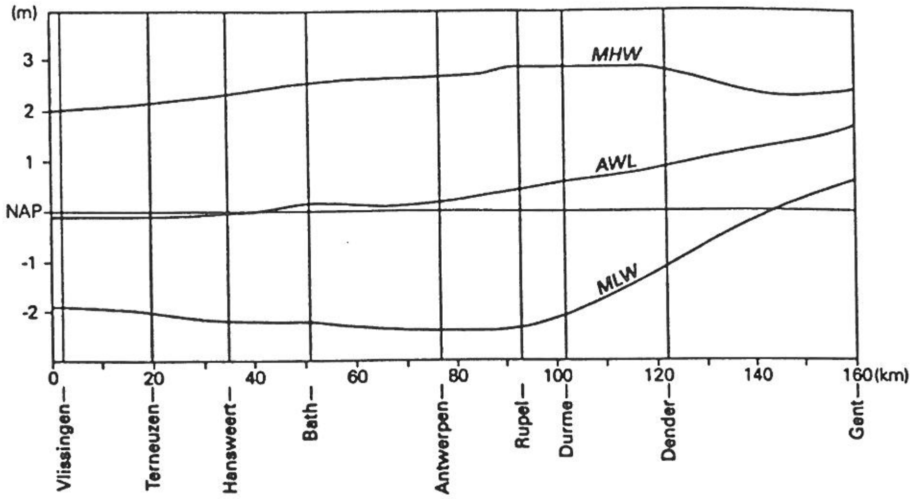


Figure 7.3 Mean High Water (MHW), Mean Low Water (MLW) and Average Water Level (AWL) in the estuary and the lower course of the Schelde river (NAP = Dutch Ordnance Level)

estuary from the moment it started to evolve. Ancient human activities resulted in the lowering of embanked areas, thus creating space for tidal areas. After dike breaches, the lowered polder areas could not be reclaimed and became part of a growing estuary. The purpose of this chapter is to describe and explain the evolution of the Westerschelde estuary by natural processes and increasing human interference.

7.2 PALAEOGEOGRAPHICAL BACKGROUND

The western part of The Netherlands is almost completely covered by a Holocene blanket of sediment, which locally reaches a thickness of 20–40 m. Its development took place under the influence of the rising sea, on a north-to-west dipping surface of Pleistocene deposits. To the west the Holocene sediment wedge is bounded by coastal barrier deposits. The coastal barrier originated during the Atlantic and Subboreal (Zagwijn 1986; Figure 7.4). At the same time, the relatively high elevated Pleistocene surface in the area of the present day Westerschelde became inundated by the rising sea level. Most of the Holocene deposits in this area were laid down by tidal channel systems behind this barrier. During the Atlantic, the barrier coastline retreated and it was still interrupted by many inlets (Figure 7.4). Along the western coast of The Netherlands, the barrier started to prograde by the end of the Atlantic or in early Subboreal times (Beets et al. 1992). Later, a gradual closure of most of the inlet gaps of the barrier took place in these areas. The

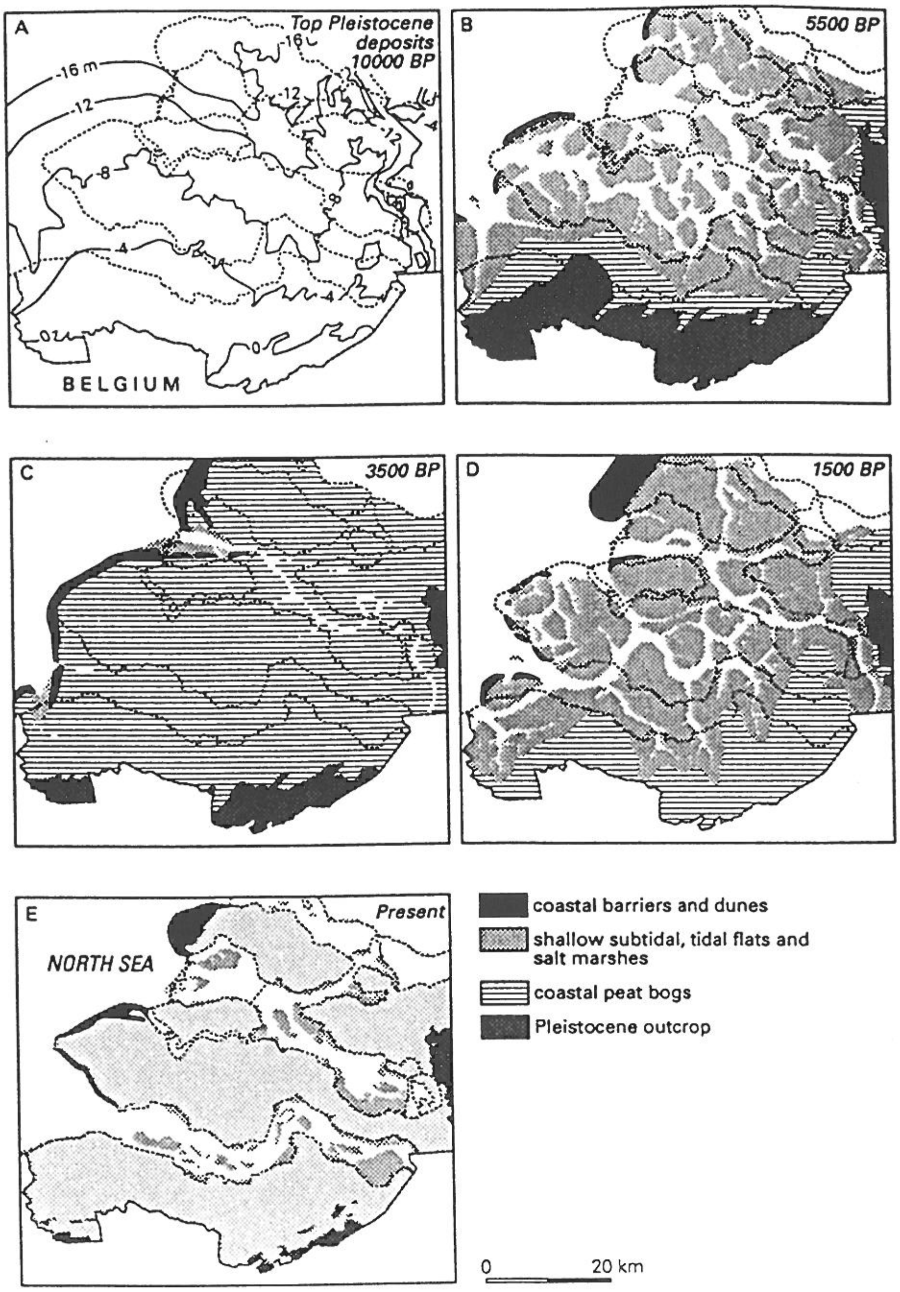


Figure 7.4 Paleogeography of the SW Netherlands (after Vos and Van Heeringen 1993)

closures were caused by a rapid filling of the inshore tidal basins (Calais deposits), made possible by a reduced rate of sea level rise. Barrier progradation is explained partly by sediment supply from degenerating ebb-tidal deltas in front of the inlets during the closure process (Beets et al. 1992). Most of the tidal landscape changed into an extensive fresh water marsh, which resulted in the formation of a thick peat layer (Holland peat). In the SW part of the Netherlands during Roman times, the barrier started to retreat (see Figure 7.4). It became breached at a number of places and new inlet systems evolved. After the second century AD, these systems expanded rapidly. Deep channels were cut and peat layers were removed by tidal currents in many places. Erosion in many areas was soon followed by sedimentation, and during early Mediaeval times many branches of the new channel systems were already completely silted up. However, at the same time, other parts of the tidal channel system were expanding, causing widespread erosion (Vos and Van Heeringen 1993).

Until recently, it was thought that the main ingressions were synchronous events (Zagwijn 1986). Based on this assumption, related deposits are currently classified chronostratigrafically in several Calais and Dunkirk stages. However, evaluation of new and existing archaeological and geological data in the SW-Netherlands (Vos and Van Heeringen 1993) shows that this transgression/regression model does not apply to the Dunkirk stages: in the area of the present day Westerschelde the latest ingression phase started in the ninth century, or even somewhat earlier. More to the north the inlets of the Grevelingen and the Haringvliet started to evolve in the 12th and 13th century respectively (Leenders 1986). The diachronous character of the ingressions excludes external triggers, such as an increase in the rate of sea level rise, to be the principal cause of the initiation of the ingressions as assumed, for example, by Hageman (1969). As far as the later Dunkirk incursions are concerned, human interference is an important factor. During Roman times, ditches were cut to improve the drainage of some marsh areas. Because of the dewatering, surficial peat layers oxidized and the land surface was lowered, which made the area more susceptible to floodings (Vos and Van Heeringen 1993). During the Middle Ages, the influence of humans in creating favourable conditions to the tidal incursions increased. Apart from the effect of artificially improved drainage, a more dramatic lowering of the land occurred in many areas by large-scale stripping of surficial (Holland) peat layers for mining salt and heating purposes; in Biervliet, a small town on the southern bank of the Westerschelde (Figure 7.5), in 1422 more than 300 salt factories were operating (Rottier and Arnoldus 1984).

After the initial start of a tidal incursion, several feed-back mechanisms promoted further expansion of the tidal channel system into the marsh area. The origination of tidal channels caused an improved drainage of nearby marshes, which resulted in a further lowering of these areas; also, owing to an increase in tidal prism, the channels widened at the expense of the original marsh, resulting in a further increase of tidal prism. The deepening of the channels, which accompanied the landward penetration of the channel system, reduces the energy dissipation of the tidal wave. This promoted higher and more devastating storm-surge levels, and lower low water levels, improving drainage and related lowering of peat areas.

7.3 HYDRAULIC EVOLUTION OF THE TIDAL BASIN

The Westerschelde estuary originated quite recently. It started as a new branch of a tidal channel system located in the western part of the present Westerschelde (Figure 7.4) that finally became connected to the Schelde river. During the 14th century the shipping route to Antwerpen started to divert to the Westerschelde (Denucé 1933), indicating the growing importance of the Westerschelde as a distributary of the Schelde river. In the 16th century the channel connecting the Schelde river through the Kreekrak (Figure 7.2) silted up, becoming shallow enough to be waded through at low tide (Van den Berg 1986). The abandonment of the Oosterschelde as a river distributary of the Schelde was finally completed artificially in 1867 and 1871 when two dams were built for a railway connection to Vlissingen.

As a result of warfare in the 14th to 17th century between Holland and Spain (Eighty Years War) and Britain and France (Hundred Years War), many dikes that had been erected along the margins of the Westerschelde during the Middle Ages were breached. This was not only due to poor maintenance; many dikes were breached deliberately, to discourage the enemy. The Westerschelde tidal area reached its maximum size in that century (Figure 7.5). In the past few centuries most of the land losses of the 14th to 17th centuries were reclaimed by embankment of newly formed supratidal marshes. Between 1800 and 1980 15 238 hectares were embanked (Technische Scheldecommissie 1984; Figure 7.2), a third of the tidal area in 1800.

According to an analysis of hydrographic maps drawn between 1878 and 1952 a net sediment import of 1.3 $10^6 m^3$ per year occurred. This import is related to the siltation of some branches of the Westerschelde and the growth of tidal marshes. The main channel system of the Westerschelde did not show any net loss or gain of sediment (de Looff 1983). At first sight this might look rather strange as a loss in tidal surface area should result in a loss of ebb and flood volume in the channels. This would result in a similar loss of channel cross-sectional area (see Figure 7.6), which would imply a considerable sediment import. This seeming discrepancy is explained by the fact that the reduction in size of the tidal area apparently was compensated by the simultaneous increase in the celerity and amplitude of the tidal wave.

The amplification of the tidal wave is illustrated in Figure 7.7. It is related to the disappearance of the branches and the reduction of intertidal areas along the margins of the Westerschelde, causing the average depth of the estuary to increase and making it more funnel-shaped. As a result, the energy of the tidal wave became less dissipated and more contracted, causing higher amplitudes, especially in the

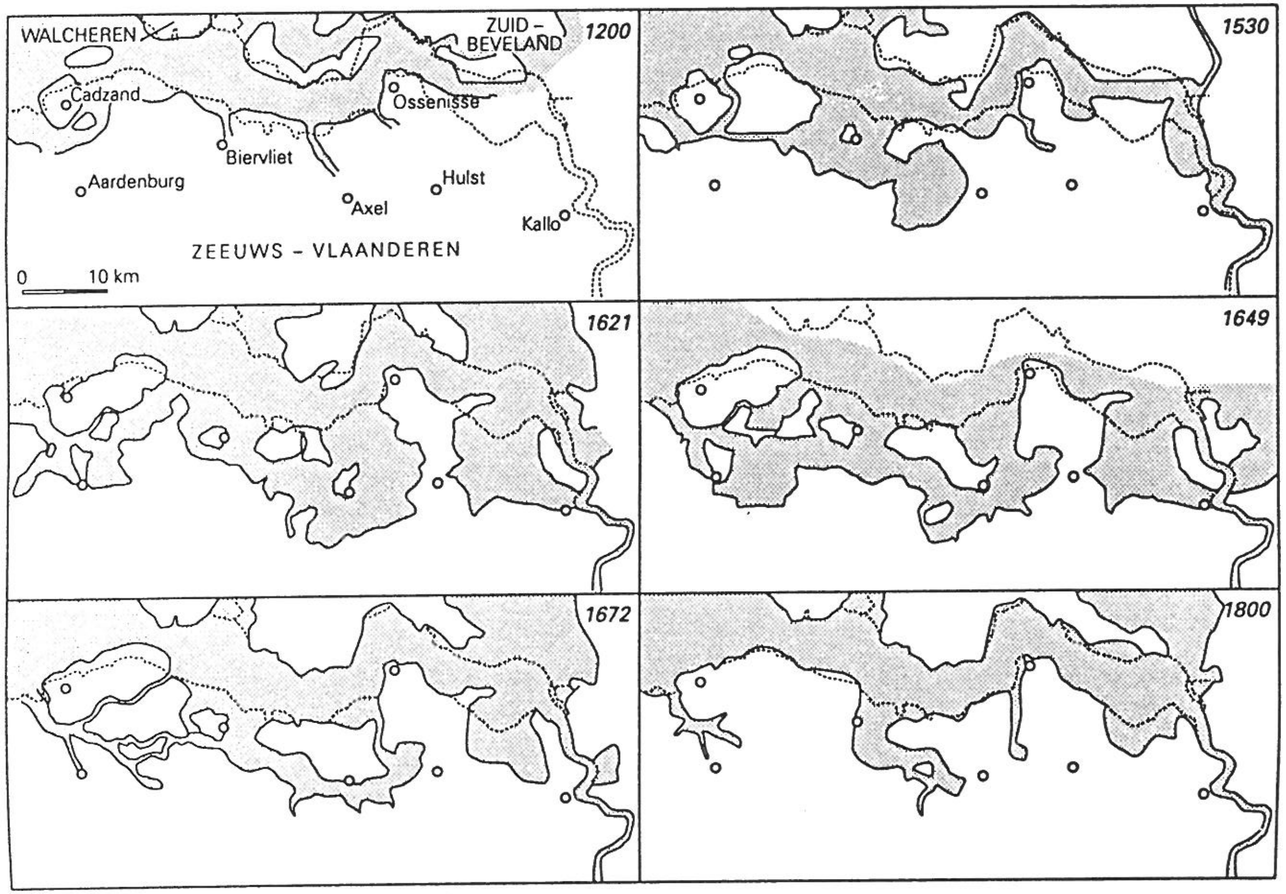


Figure 7.5 Boundaries of the tidal basin of the Westerschelde since AD 1200 (modified after Brand 1985)

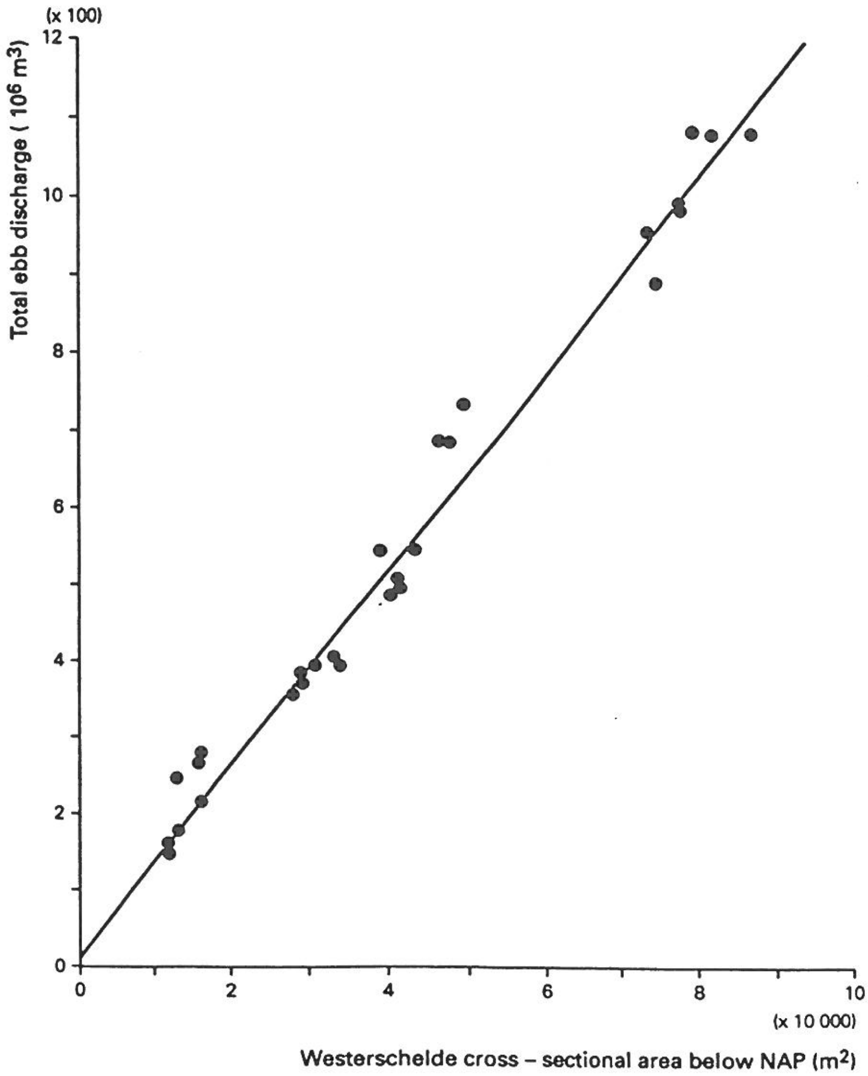


Figure 7.6 Channel cross-sectional area as related to ebb tidal volume (after De Jong and Gerritsen 1984)

inner part of the estuary. The increase of average waterdepth also resulted in a marked increase of the celerity of the tidal wave. In the 16th century, the travelling time of the highest point of the tidal wave from Vlissingen to Antwerpen was about 4.5 hours (Coen 1988). Now the difference in time is only 2 hours. This means that the natural wave period of the estuary at present allows a much better resonance of the tidal wave, which must have contributed to a further amplification of the tide in the basin. The artificial deepening of channel bars in the eastern part of the

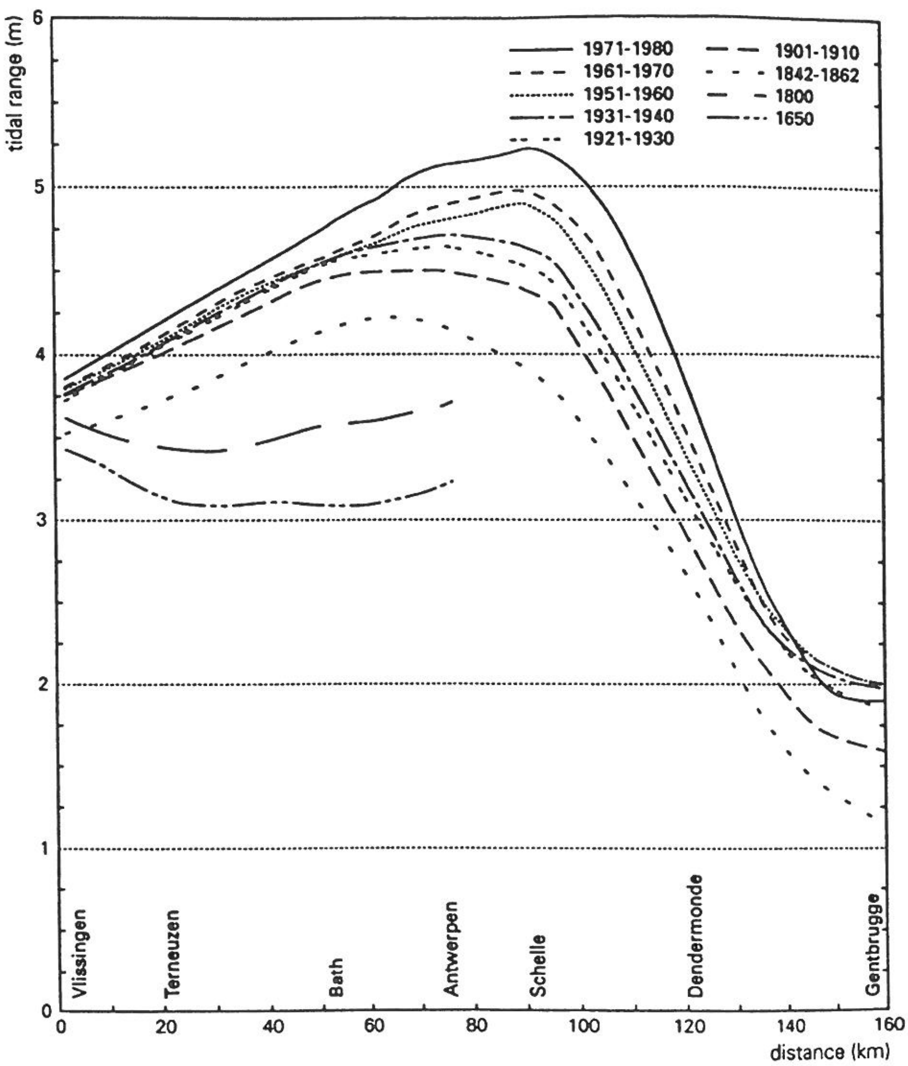


Figure 7.7 Amplitude of the tidal wave in the Westerschelde since AD 1650. Curves for 1650 and 1880 predicted, according to DUFLOW simulations. Remaining curves are derived from 10-yearly reviews of measured water levels along the Schelde estuary

Westerschelde by dredging produced a considerable reduction in the hydraulic resistance of the estuary, which caused a significant lowering of the tidal low water levels in this area, especially after 1970. Finally, some increase in the tidal amplitude resulted from an amplification of the tidal wave in the North Sea recorded during the past century (Figure 7.8). The reason for this amplification is still unknown (De Ronde 1983; Misdorp et al. 1990). The reduction of tidal prism

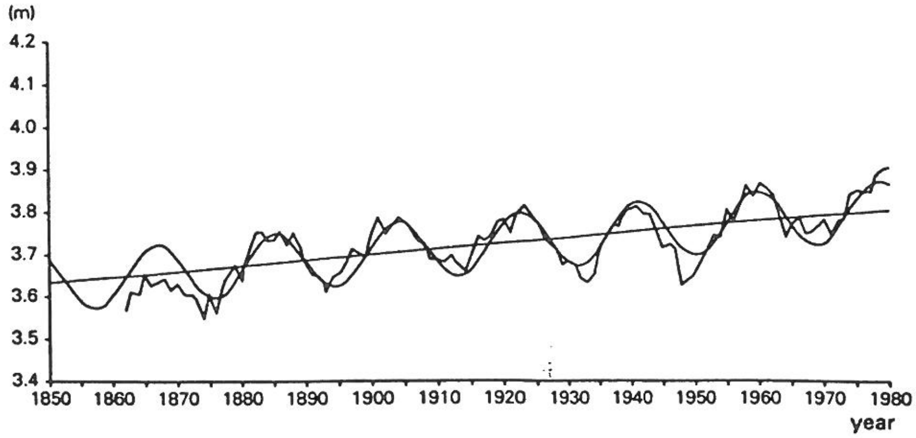


Figure 7.8 Amplitude of the tidal wave at Vlissingen since AD 1862 (after Technische Scheldecommissie 1984)

by loss in tidal area was not only compensated by the increase in amplitude of the tidal wave, but also by an increase in its celerity. In the 16th century, due to the low propagation rate of the tidal wave, high water at Vlissingen coincided with low water in Antwerpen. Now, the water level in Antwerpen is already well above the low water mark when high water is reached in Vlissingen. The increase in propagation rate of the tidal wave has resulted in a better filling of the tidal basin at high tide and thus an increase of tidal prism. Van der Spek (1993) studied the tide characteristics of two former situations of the Westerschelde (1650 and 1800) using the one-dimensional mathematical DUFLOW model (Spaans et al. 1989) and old charts and tide data. Although since 1650 the total tidal area of the Westerschelde reduced by 44%, the computational results suggest that the flood volume diminished by only 13%. From the effect of 44% loss of tidal area, 27% was compensated by increase in tidal range and 4% by increase in tidal wave celerity.

7.4 LONG-TERM SEDIMENT IMPORT AND TIDAL ASYMMETRY

At present, tidal inlets along the Dutch coast are restricted to the SW part and the chain of barrier islands connecting the North Sea with the Wadden Sea. During the Atlantic period a number of inlets were also present along the western part of The Netherlands. In Subboreal times, these inlets were closed as the tidal basin behind then was filled with marine sands and clay (Van der Spek and Beets 1992). The closure of this large basin was achieved in only several thousand years, notwithstanding the fact that sea level during the filling rose at a rate of 0.15 m or more per century. The annual import rate of sediment in the entire basin during this period is estimated at 4–5 million m^3 of sand and 5–7 million m^3 of mud, corresponding to a vertical accretion of 0.30 m per century (Van der Spek and Beets 1992). This illustrates that the basin was an efficient sediment trap. The large net rate of sediment import is not a special feature related to this former tidal basin, but seems to be a common characteristic of many tidal basins and estuaries. For instance, on the basis of hydrographic charts of 1927 and 1967, a net import of 15.2 million $m^3$of sediment into the tidal basin of the Friesche Zeegat (Northern Netherlands) was calculated (Oost and De Haas 1993). This represents a vertical accretion of 0.18 m per century, which is slightly more than the present rate of sea level rise of 0.11 m per century (Misdorp et al. 1990). The net sediment import of the Westerschelde during the past century amounted to almost 1.4 million $m^3 a^{-1}$ on average, corresponding to an average vertical accretion of 0.30 m per century, surpassing the relative sea level rise by about a decimetre.

Two mechanisms account for the sediment trap efficiency of coastal plain tidal basins, such as the basins mentioned above: asymmetry of the tidal wave at the entrance of the basin and settling lag effects. The first mechanism refers to the net import of sand, the second mainly concerns the import of mud. Coastal plain tidal basins are generally found along the margin of shallow seas. Here, the tidal wave crest propagates at a higher velocity than the wave trough. As a result the rising part of the wave surface becomes increasingly steeper, and the falling part steadily flatter. In the case of the Dutch coast, the tidal wave becomes progressively more asymmetric as it propagates from south to north along the coast. In the westernmost part of the Wadden Sea, the asymmetry is temporarily less pronounced, because the tidal wave approaches this area from the relatively deep, central part of the North Sea. At the entrance of tidal basins, the steeper water-level gradient at flood causes higher inshore directed tidal flow velocities during flood as compared to the ebb. As stressed by Dronkers (1986) this is the major cause for the occurrence of greater maximum current velocities during flood than during ebb in the Dutch tidal basins.

In the case of a tidal basin without shoals that emerge at low tide, this tidal asymmetry will result in a net import of sand. Because the transport of sand is proportional to a third (or higher) power of the flow velocity the sand transport during flood is not compensated by the sand transport during ebb. However, if emerging shoals are present in the tidal basin, an important counteracting effect occurs. In the case that large areas of a tidal basin consist of shoals, the maximum of the flood discharge will shift to a later stage in the flood period at a relatively high water level, during which the shoals become flooded. Such a shift means an increase in cross-sectional area of the main channels at the moment of maximum discharge, which implies a reduction in flow velocities. On the other hand the presence of large tidal flats may enhance the maximum ebb current in these channels, as noted by Speer and Aubrey (1985). The decrease in water level on the shoals lags behind the fall in the large channels (Dronkers 1986). As a result, the maximum of the ebb discharge shifts to a later stage of the tidal cycle, to a lower water level. The effect is, as shown by model computations by Friedrichs et al.

(1990), that the ratio of flood to ebb sand transport decreases with increasing amount of shoal area.

In general terms, the deformation of the tide by the presence of shoals means a decrease of flood current velocities and an increase in ebb velocities, which counteracts the net import effect by tidal wave asymmetry at the seaward boundary of the estuary. One could imagine a kind of equilibrium condition of the amount of shoal area in a tidal basin, in which the morphological effect of the shoals on the tide would be just enough to eliminate the import effect due to tidal wave asymmetry. This would enable the prediction of equilibrium hypsometry as a function of basin geometry and tidal wave characteristics at the entrance of the basin.

Such an equilibrium is not expected because of the second important mechanism of sediment import, the settling-lag and scour-lag effects as described by Postma (1967) and Van Straaten and Kuenen (1957). Both effects favour a net transport of mud particles into a tidal basin and into tidal marshes. The lag effects refer to the import of mud into estuaries, whereas the tidal wave asymmetry effect refers to sand import. This means that theoretically two morphology-related stages of infilling of a coastal plain tidal basin can be distinguished, which can be presented in a schedule as shown in Figure 7.9. The rate of infilling of basins in their first stage of evolution increases with increasing asymmetry of the tidal wave. This might explain the rather extreme rate of filling of the Holland Basin in Subboreal times. The model suggests that the rate of filling of a tidal basin in its second stage is related to the availability of (suspended) mud. Some supporting evidence of this is found in the SW Netherlands. The Oosterschelde and the Westerschelde – both mature stage tidal basins in the sense of the model – show a remarkable difference in suspended mud concentration. During 1972–1975 the mean mud concentration

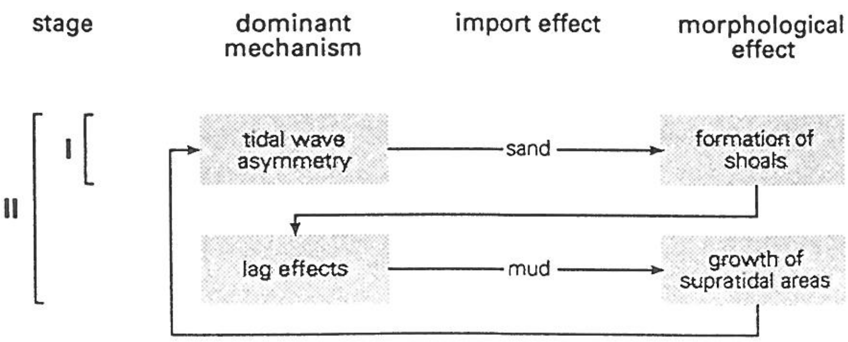


Figure 7.9 Fill processes in small tidal basins: (I) initial stage: infilling dominated by the tidal wave asymmetry effect (formation of shoals emerging at low tide); (II) mature stage: channel and shoal morphology in 'dynamic equilibrium': infilling caused by lag effects (growth of supratidal areas, resulting in a reduction of intertidal shoal area and thus restoring some of the tidal wave asymmetry effect)

measured during calm sea in the Oosterschelde was about 30 mg l^{-1}; in the Westerschelde the concentrations were about twice as much (Terwindt 1977). This occurs because the Westerschelde is a real estuary with a characteristic turbidity maximum due to (estuarine) density circulation, whereas the Oosterschelde has no significant fresh-water inflow and therefore lacks a turbidity maximum. The difference in the suspended mud concentration is in accordance with the rate of reduction of the size of the two basins as a result of the embankment of marshes during the past century; the tidal basin of the Westerschelde reduced at an annual rate of 0.18%, the rate of reduction of the Oosterschelde basin was six times smaller.

The amount of sediment deposited between 1880 and 1950 in shallow areas along the margins of the Westerschelde is estimated at $100 \times 10^6 m^3$. This rapid sedimentation and related expansion of tidal marshes in the Westerschelde is

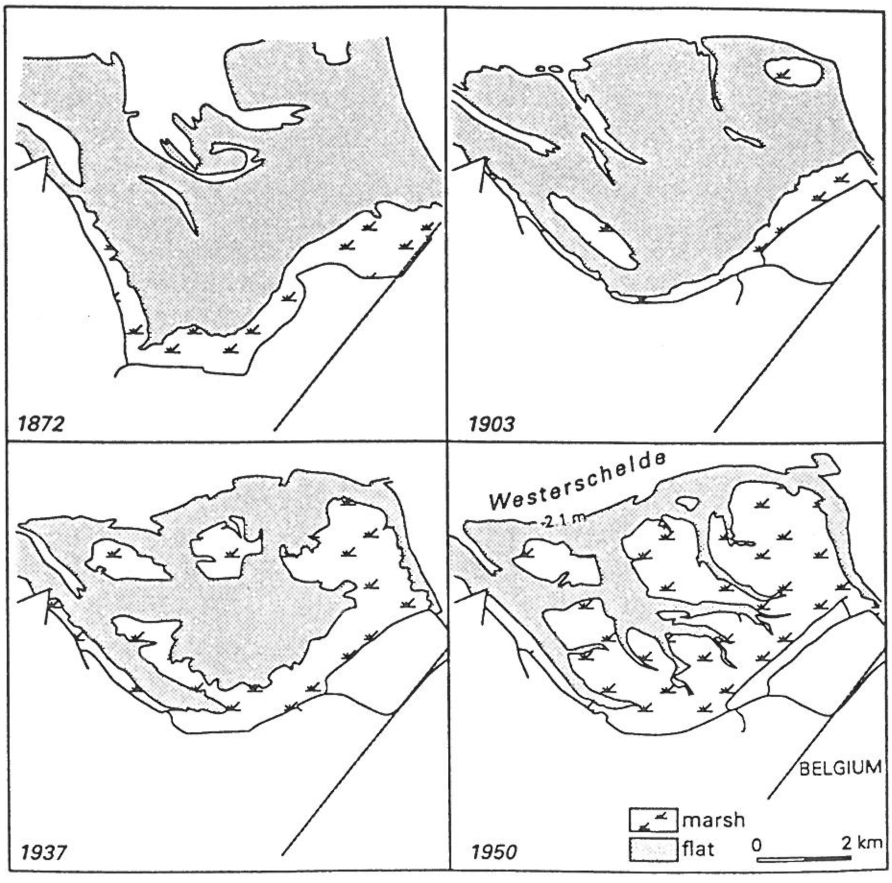


Figure 7.10 The Drowned Land of Saeftinghe since 1872 (modified after Sponselee and Buise 1979)

illustrated by the Saeftinghe salt marshes, located in the eastern part of the estuary (Figure 7.2). The area was embanked during the Middle Ages (Figure 7.5). In 1584, during the war against Spain, the dikes of the polder were deliberately breached by Dutch troops in an effort to prevent the siege of Antwerpen, but Antwerpen was taken and a large polder area became part of the Westerschelde tidal system. In the following centuries, salt marshes developed and part of the lost land was reclaimed (Figures 7. 2 and 7.10). The process of sedimentation and expansion of salt marshes is still going on. According to detailed topographical measurements, a net deposition of about $25 \times 10^6\,m^3$ occurred in the period 1949–1992; during the past 30 years the accretion was $0.013\,m\,a^{-1}$ on average (Krijger 1993). Spatial differences in the rate of sedimentation are indicated in Figure 7.11. Accumulation in channels was generally faster than in marsh areas. The extreme sedimentation in the westernmost channel is possibly related to the proximity of a dumping site of dredged spoil in the adjacent main channel area. In the period 1965–1990 more than $12 \times 10^6\,m^3$ of sand dredged from channel bars in the shipping route to Antwerpen was dumped at this location (Van den Berg et al. 1991).

The quasi-equilibrium condition at which the sand import effect of the tidal wave asymmetry at the entrance of the basins is eliminated by the morphological effect of shoals is not just a function of the available shoal area but the amount of shoal area that is flooded or drained at the same time. In the case of large basins, such as the Westerschelde, a considerable time lag exists between the flooding of the shoals near the entrance and intertidal areas at the landward end of the basin. In

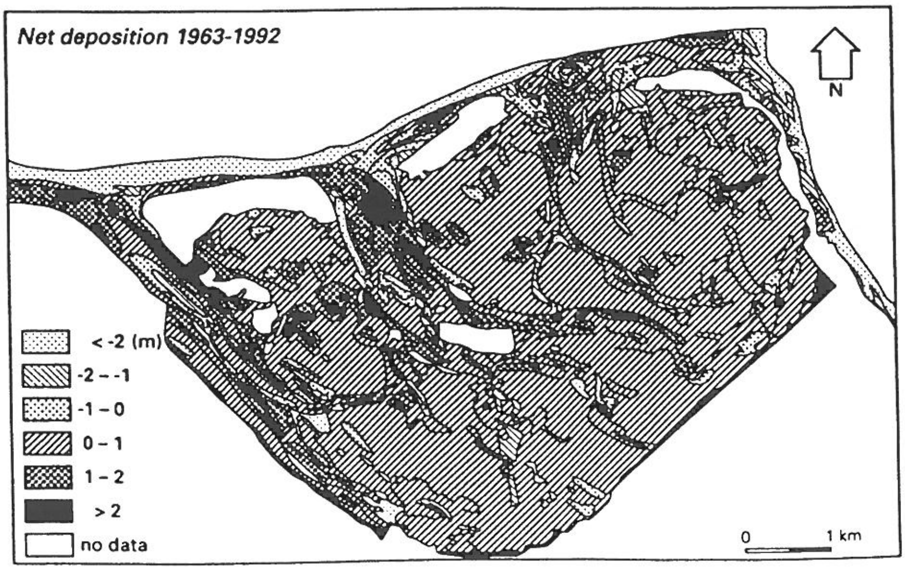


Figure 7.11 Spatial differences of net sedimentation in the Drowned Land of Saeftinghe, 1963–1992 (data Rijkswaterstaat)

such a basin an increase in the total amount of shoal area generally will result in a decrease of the average water depth of the basin and therefore a slowing down of the propagation of the tidal wave. An increase in the total amount of shoal area may not always result in an increase of area that is flooded at the same time. In the Westerschelde during the past centuries, the opposite seems to have occurred. According to Van der Spek (1993) the total amount of shoal area (between NAP −2 m and NAP + 2 m) reduced from 340 million m^2 in 1650 to 200 million m^2 in 1800 and 90 million m^2 in 1968. However, the model simulations of the three situations show that the effect of flooding of shoals as expressed in a peak of flood discharge near high water level is most obvious in 1968 (Figure 7.12). The total amount of shoal area decreased, but the total area that flooded simultaneously increased. This is explained by the dramatic increase of the propagation rate of the tidal wave in the Westerschelde discussed before. However, the larger extension of the shoals in 1650 caused a more retarding ebb in 1650. It seems that both flood and ebb currents reached higher maximum values in 1650 than at present. However, the ratio of maximum flood to maximum ebb current reduced from 1.30 to 1.21, which suggests that the Westerschelde in 1650 was a more sand-importing system than it is now.

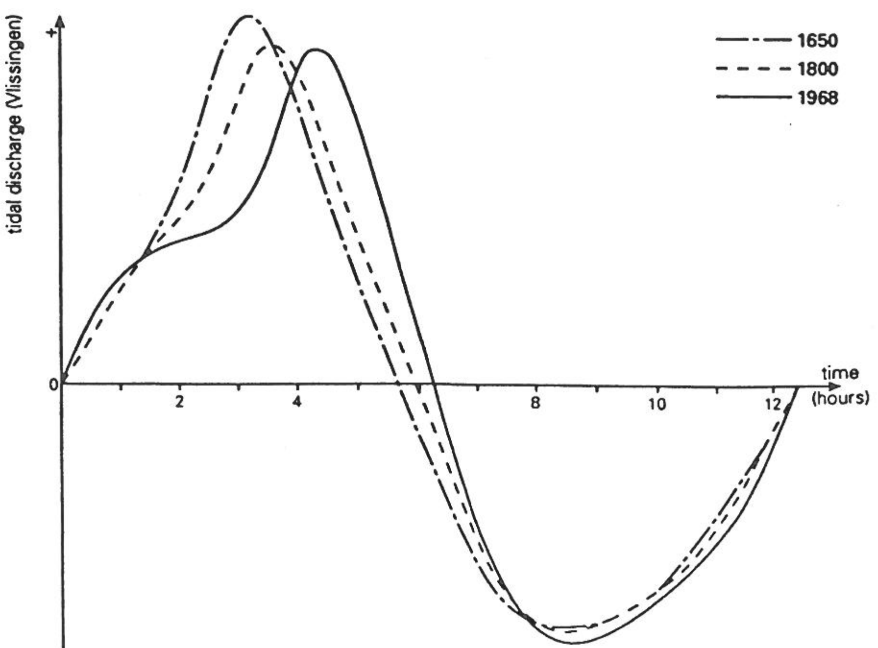


Figure 7.12 Tidal discharge during the average tidal cycle at Vlissingen according to DUFLOW simulations. Based on data of Van der Spek (1993)

7.5 RECENT MORPHOLOGICAL BEHAVIOUR OF THE CHANNELS AND SHOALS IN THE WESTERSCHELDE

The present morphology of the Westerschelde is representative of a mature tidal basin in its second stage of evolution, according to the model described earlier. The overall morphology consists of a system of mutually evasive ebb and flood channels separated by (inter)tidal shoals (Van Veen 1950). The main ebb and flood channels show great differences in morphology. The ebb channels exhibit a meandering pattern, with relatively deep bars. The flood channels are relatively straight channels more or less parallel to the general alignment of the estuary. Generally the bars at the end of the flood channels are shallower than the bars in the ebb channels. These differences in morphology are probably related to an asymmetry in the ebb and flood discharge cycle. The draining ebb flow reaches its maximum discharge near average water level (NAP-level). The flood reaches its maximum discharge at the time that the shoals are inundated. Owing to this asymmetry, the ebb is a less diverging flow than the flood flow, resulting in the relatively deep bars in the ebb channel. As a second result the ebb current causes most of the bend migration of the larger channels, whereas the flood flow tends to cross-cut these channel bends.

These different characteristics are illustrated in Figure 7.13 by the location and shifts of the thalwegs of the main channels since 1800. Until approximately 1930 the morphological evolution of the channel and shoal system was dominated by the shift of ebb channels due to meandering process. The annual migration rates in channel bends were in the order of tens of metres. Around 1930 most ebb channels had reached the embankments along the Westerschelde. Further migration of the channel thalwegs caused a steepening of the channel banks along the estuary, resulting in an increasing risk of dike breaches by bank failures. Failure of the channel banks, i.e. slides with more or less circular failure surfaces, sometimes involving more than a million cubic metres of sediment, has been observed at several locations along the Westerschelde. Along some stretches of the coastline additional protections of gravel or slag are made, down to the toe of steep channel bank slopes, to eliminate the threat of dike breaches by slope failures. In the near future these measures will also be extended to areas without a direct thread to dikes, in order to safeguard valuable saltmarsh areas. Bank failures also occur along steep slopes along the margin of intertidal shoals (Figure 7.14).

Unless further movement is obstructed by coastal defence structures, ebb channel bends migrate in a seaward direction. This meandering process is often accompanied by an expansion of the bend. Because of the resulting increase in channel length, small connecting channels in the inner bend of the meander develop. These connecting channels often originate in the bar-area of the flood channel. At one location such a small channel developed into a new major channel (indicated by A in Figure 7.13). This new channel gradually took over part of the tidal discharges of the expanded ebb channel, resulting in large sedimentation in the

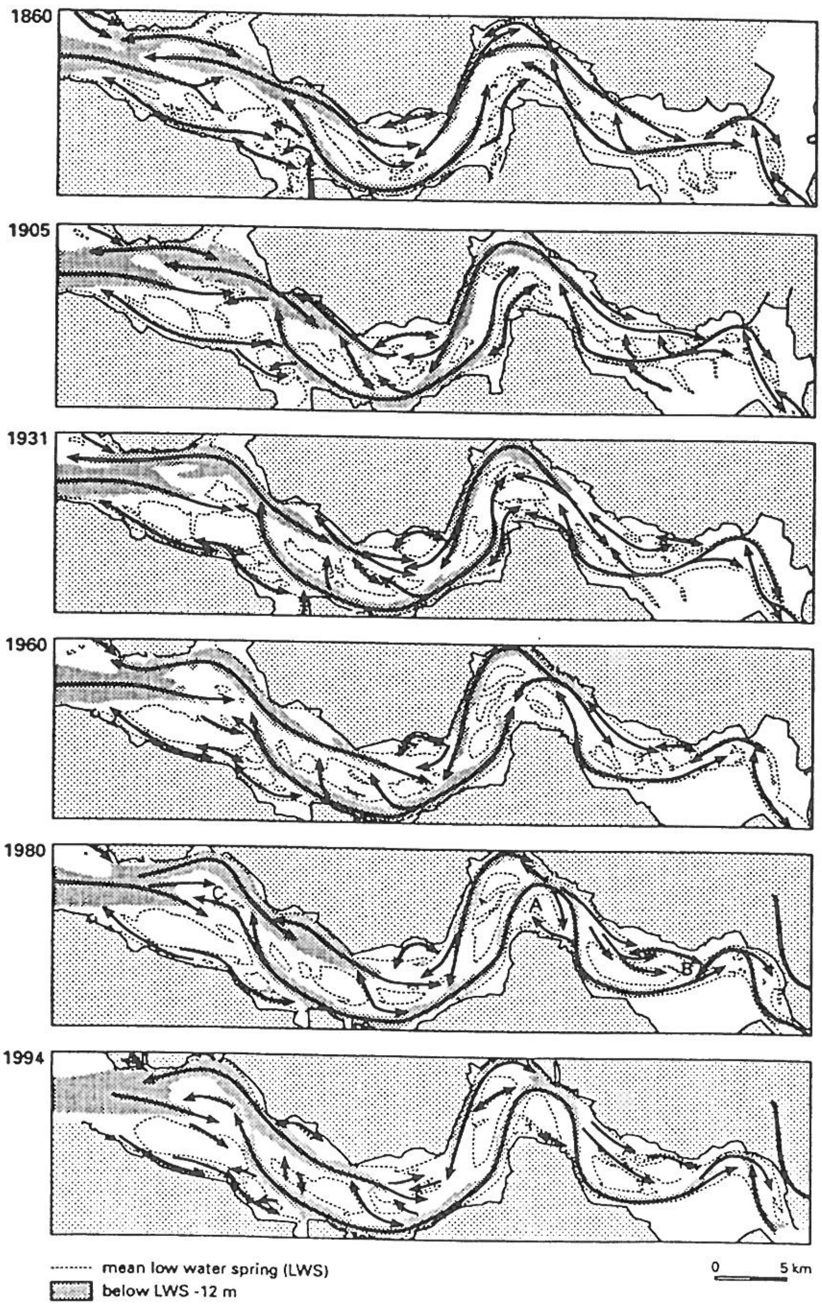
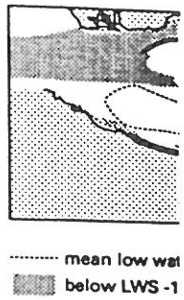


Figure 7.13 Location of channel thalwegs in the Westerschelde since 1860



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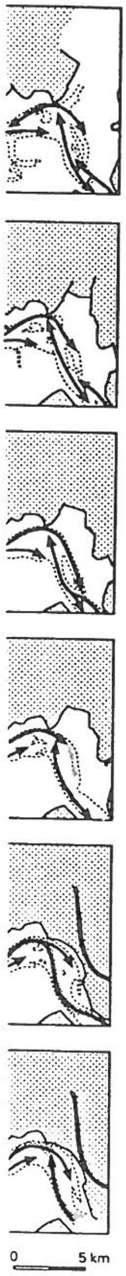

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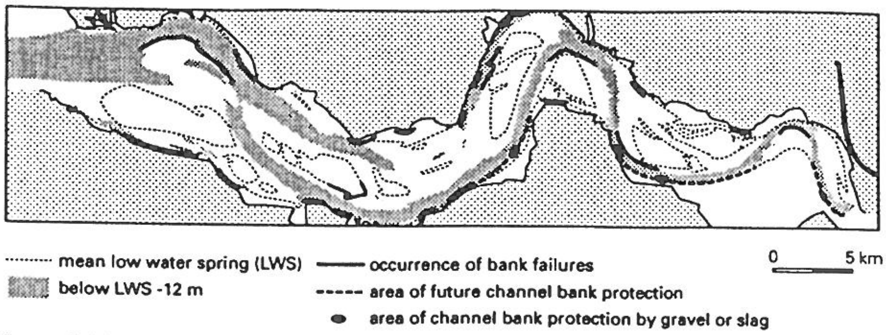


Figure 7.14 Occurrence of coastal defence structures reaching more than 10 m below mean sea level and locations of regular bank failures

older channel. This entire cycle of bend expansion and final bend cut-off lasted more than 100 years. At two other locations (B and C in Figure 7.13) similar connecting channels developed, although these channels did not develop into new major channels. At location B migrating connecting channels with a lifetime of less than a decade occurred (Kleinjan 1938; Sterling and Roovers 1967). Since approximately 1930 these migration cycles have been obstructed by dredging. The connecting channel at location C originated in the early 1960s and rapidly expanded and migrated in a northerly direction. The development of connecting channels at locations B and C noticeably influences the dimensions of the bars in the main ebb channel (Kleinjan 1938; Bliek and Ruijter 1994).

The development of a new major channel from a small connecting channel is rather exceptional. Generally, the connecting channels between the main channels remain small, but they are the most dynamic elements of the channel system and are found at many places. Connecting channels originate due to water level differences between the main channels. These water level differences are primarily due to the differences in channel dimensions (e.g. channel length, cross-sectional area) between the main ebb and flood channels. In addition, water level differences between the main channels may exist due to the Coriolis force, loss of momentum of the tidal flow or centrifugal forces (Figure 7.15). Probably, in most cases, more than one process is operating. Most connecting channels are marked by rapid lateral migration (up to 100 m a^{-1}). These rapid migration rates are due to the sharp bend at the places where the connecting channel splits from the main channel. Owing to the migration, the channel shifts from the position with a maximum water level gradient to a less optimal location. This will reduce the size of the channel and eventually lead to its disappearance. In the meantime, a new connecting channel is formed at the place of maximum water level gradient. These cyclic processes of origination, migration and degeneration of connecting channels are found at various places in the Westerschelde. An example of the cyclicity of connecting channels along the margin of the Nauw van Bath is shown in Figure 7.16. Besides differences in dimensions of the main channels, the water surface slopes here are

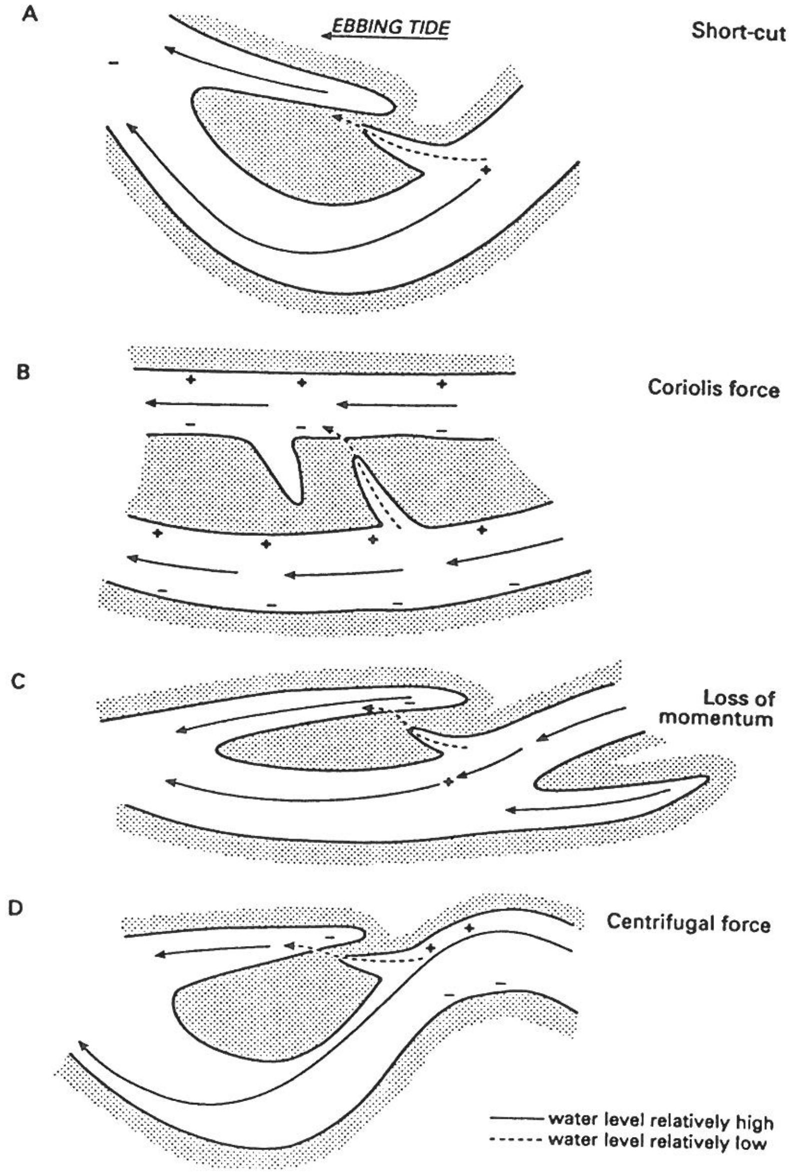
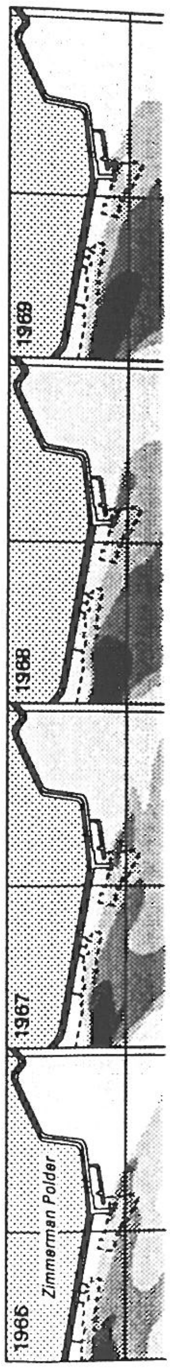


Figure 7.15 Cause of cross-shoal water level difference and the existence cross-connecting channels

possibly enhanced by a combination of centrifugal forces, Coriolis force and loss of momentum. Generally, the influence of connecting channels on the banks of the estuary is negligible.

The cross-sectional surface of ebb and flood channels is proportional to the



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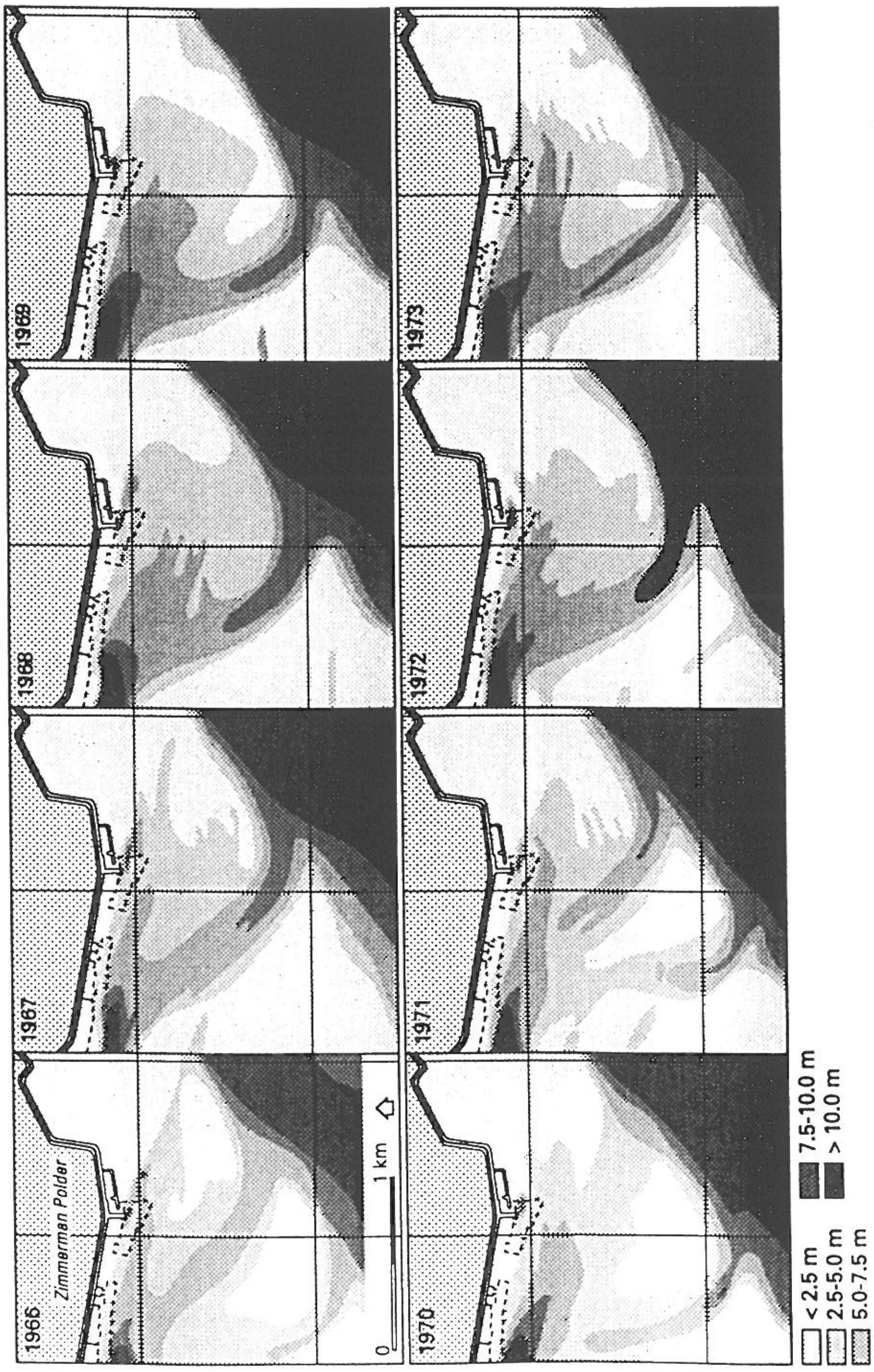

Figure 7.16 Cyclicity of cross-connecting channels along the margin of the Nauw van Bath main ebb channel

volume of the dominant tide (Figure 7.6). However, the cross-sectional area is larger at places where an ebb channel in downcurrent direction reunites with a flood channel or where connecting channels are present. Here the ebb flow expands and the channel becomes relatively shallow. Especially in the eastern part of the Westerschelde the natural depths at these bars in the main ebb channel is insufficient for navigational needs. Because of the increase in the size of ships, the depth of the bars was increased artificially from NAP -10 m after world war II, to NAP -14.5 m at present (Figure 7.17). A second artificial deepening to NAP -16 m is planned for the near future. In order to maintain the bars at the desired depth, the magnitude of the dredging also increased (Figure 7.17). Most of the dredged spoil is disposed at a number of dumping sites inside the tidal system (see Figure 7.2).

The system of tidal channels and flats in the Westerschelde can be subdivided into five bend groups. Each bend group consists of a meandering ebb channel and a straight flood channel, separated by (inter)tidal flats and connected by one or more connecting channels. Each of these bend groups is marked by specific morphological changes. In the remaining part of this chapter the major morphological changes and human interferences are summarized. The analysis of morphological behaviour of the channels and shoals is based on detailed five-yearly soundings of the Westerschelde from 1965 onwards.

The most easterly located bend group is formed by the ebb channel Nauw van Bath and the flood channels Schaar van Noord and Appelzak (Figure 7.2). In this area, the first dredging activities started around 1930. These dredging activities obstructed the formation of large migrating connecting channels between the ebb channel and flood channel. Until 1960 migrating connecting channels also occurred between the Nauw van Bath and the flood channel Appelzak. A guide wall that was built in the early seventies to conduct the ebb flow, resulted in the final disappearance of the connecting channels and slight sedimentation in the flood channel Appelzak. The artificial deepening of the bars in the main channels resulted in an enlargement of the adjacent part of the ebb channel. Between 1965 and 1980 the channel volume below NAP -2 m increased by more than 25%. The average channel depth increased by approximately 1.5 m (Jeuken 1993).

The second bend group encloses the ebb channels Overloop van Valkenisse and the Zuidergat, and the main flood channel Schaar van Valkenisse. In this area approximately 5 million $m^3 a^{-1}$ is dredged. Most of the dredged spoil has been disposed at the eroding outer channel bend of the Zuidergat and Overloop van Valkenisse. Despite the dumping, the erosion rate is approximately $5 \, m \, a^{-1}$. Most of the disposed sediment is rapidly removed by the tidal currents (Jeuken 1994). The artificial deepening of the ebb channel bars caused a similar enlargement of the adjacent parts of the ebb channel as in the first bend group. The disposal of large volumes of dredged material at the entrance of the flood channel Schaar van Waarde induced an increase of the local tidal flat volume (above NAP -2 m) of more than 30% between 1975 and 1985. Since 1955 the flood channel Schaar van

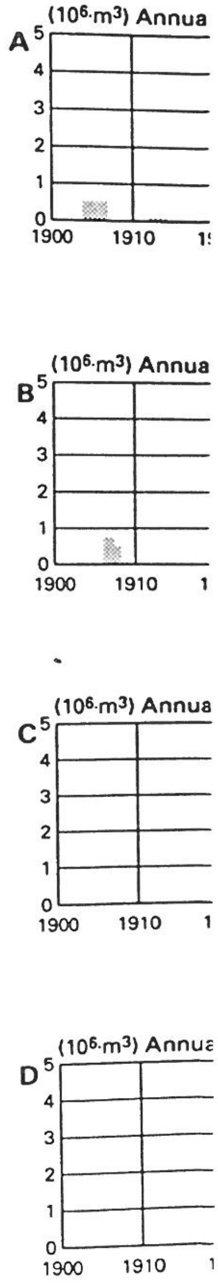

Figure 7.17 Annua
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water at spring tide.

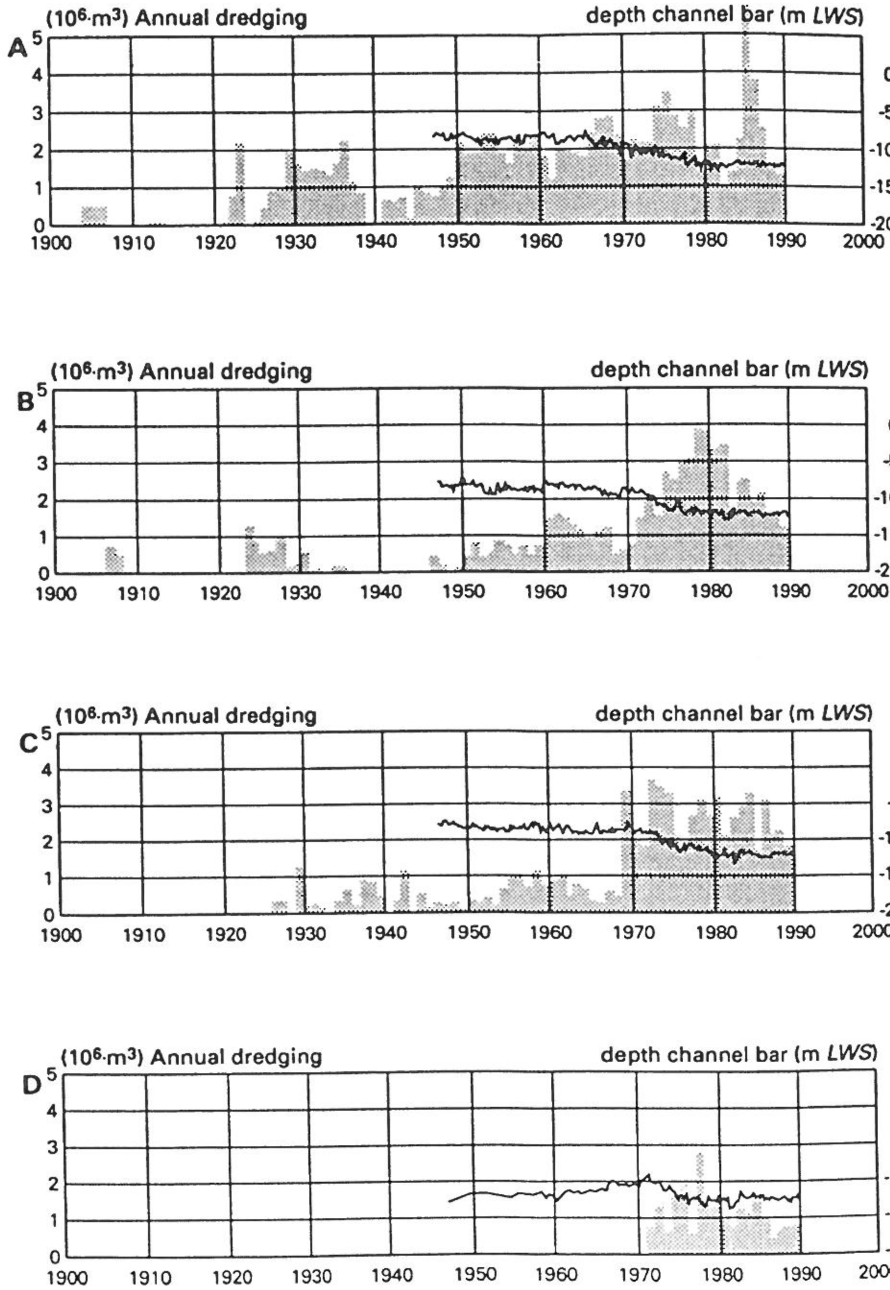

Figure 7.17 Annual dredging and the minimal depth of the channel bars at (A) Bath, (B) Valkenisse, (C) Hansweert and (D) Borssele. Depths in metres with respect to mean low water at spring tide. For location of channel bars, see Figure 7.2

Valkenisse gradually rotated in a southwesterly direction over a distance of approximately 900 m. Migrating connecting channels have been present in the bar-area of the flood channel since 1985. The lifetime of these connecting channels is approximately 7 years.

The morphological processes in the third bend group, Middelgat – Gat van Ossenisse, are dominated by the process of bend cut-off as described earlier. The meandering and expansion of the Middelgat has been going on since at least 1800. The actual bend cut-off, initiated by the formation of a small connecting channel, started in 1951. Between 1951 and 1970 this connecting channel rapidly expanded forming a new major channel. As a result, the tidal volume through this channel increased at the expense of the tidal volume through the ebb channel Middelgat. A second consequence of this bend cut-off was that large volumes of sand could be stored in the Middelgat. Between 1965 and 1990 the channel volume (below NAP −2 m) of the Middelgat decreased by approximately 35 million m^3, a reduction of the channel volume of 20 % (Jeuken 1993). The intertidal flat volume between the main channels increased by approximately 40 %. The channel axis of the northern part of the new channel is slightly rotating. The migration tendency is small due to the limited freedom of movement (imposed by the embankments along the estuary).

The fourth bend group (Everingen–Pas van Terneuzen) is probably the most stable channel system when considering the major morphological changes. The volumetric changes of the main ebb and flood channel between 1965 and 1990 are below 6% (Jeuken 1993). Also the ebb and flood tidal volumes remained stable. The tidal flat volume increased between 1965 and 1985 by 15%. Since 1955 the outlet of the ebb channel Pas van Terneuzen has slightly expanded in a southwesterly direction over a distance of approximately 500 m. Although the net changes in channel volume are small, the reworking of sediment is probably large due to the presence of five connecting channels. The connecting channels in the bar-area of the flood channel are particularly dynamic. Annual migration rates of the connecting ebb channel amount to 100 m and more. Three connecting channels are cross-connecting channels between the main channels. They owe their existence to cross-shoal water level differences (Figure 7.15A and C). The migration rate of these connecting channels, about $40\,m^3\,a^{-1}$, is considerably smaller than the migration rate of the connecting channels in the bar area of the flood channel.

The fifth bend group consists of the ebb channel Honte and the flood channel Wielingen. The gradual migration of the ebb channels Honte and the outlet of the Pas van Terneuzen (Figure 7.2) implied an increase of water surface slopes across the bar-area of the flood channel. This caused the formation of connecting channels in around 1960. The morphological evolution of the bend group is dominated by the expansion and migration of this connecting channel since 1960. The connecting channel started to degenerate in 1988. New small connecting channels have formed in the bar area of the flood channel since 1990.

7.6 FURTHER DEEPENING OF CHANNEL BARS IN THE NEAR FUTURE

In order to improve further the navigation possibilities of large vessels, the minimal depth of the main shipping route to Antwerpen will be increased from 14.5 to 16.5 m in the near future. If the present strategy of disposal of dredged spoil at nearby shallows away from the main channel is followed, the present amount of 12 million $m^3 a^{-1}$ of maintenance dredging could increase to 15 or 20 million $m^3 a^{-1}$. Initially, much more sediment must be dredged to reach the desired design of the navigation channel. This volume of sediment is far too large to be stored at the present dumping sites. Also, it is questionable whether natural processes are able to remove the increased amount of dredged material off the dumping sites. These areas may therefore gradually become choked, eventually causing dramatic and rather unpredictable changes to the remaining channels and shoals and the sediment dynamics of the estuary. Therefore several possible schemes for the maintenance of the navigation channel are being studied by the Board of Ways, Waterways and Harbours of Zeeland province, together with the Institute of Nature Conservation. The main objective of these schemes is to improve the navigation on the Westerschelde with minimum dredging effort in such a way that the characteristic system of flood and ebb channels in the long term is safeguarded. One of these ideas is to increase the tidal prism of the estuary. This would increase the natural depth of the channel bars. A reduction of the dredging may also be reached by a more sophisticated way of morphologically oriented removal and disposal of material.

An increase the tidal prism can be achieved in two ways: (1) by giving some polders back to the tidal system after lowering their surface down to the low water line and (2) by mining some of the dredged material instead of dumping it back into the system. The dredging activities are largely concentrated in the eastern part of the Westerschelde.

Most of the material dredged is dumped at nearby locations. One of the envisaged strategies of morphologically oriented dredging is to transport and dump the sediment at more remote locations, in the western part of the Westerschelde. The resulting increase of travelling time of the sediment to compensate the loss by dredging might reduce the sedimentation rate at the channel bars, thus reducing the dredging effort. Other possible reductions of dredging may be found by employing a dredging that follows better the natural alignment of the channel system. In addition to this the morphology adjacent to the channel bar could be adapted by the dumping of dredged spoil, in such a way that the tidal flow becomes more concentrated over the channel bar.

At present the sediment import of the Westerschelde is very small compared to the sediment volumes that circulate in its five channel bend groups. This fact may indicate a delicate equilibrium, that might be disturbed by side-effects of future navigation channel maintenance strategies. Therefore the possible consequences of these plans, or a combination of these, to the sediment system as a whole must be known before implementation. The possibilities of predicting the consequences of a dramatic change in dredging activities and maintenance strategy to the sediment dynamics of the estuary are still very limited, as no reliable mathematical morphodynamic simulation models are available. Therefore any change in strategy will be made stepwise. In this way it is hoped that possible undesired developments can be identified early, to be able to minimize these effects by adapting the maintenance strategy accordingly.

7.7 CONCLUSIONS

From its origins, less than a millennium ago, the evolution of the Westerschelde estuary has been influenced by man. The expansion of the estuary in the 14th to 17th century was mainly an inadvertent effect of land use. On the other hand the large reclamation of the former land losses in the past centuries was made possible by the natural process of rapid accretion of marginal flats and saltmarshes. In the past decades the increasing dredging and dumping activities mark a change to deliberate man-made modifications. As a reaction to this, significant changes in the overall morphology have occurred, such as the increase in height of some large shoals in the eastern part of the estuary. In the near future the minimal depth of the channel bars will be increased from 14.5 to 16.5 m. In order to reduce the effects of a further deterioration of the natural environment by this interference, several alternative dredging strategies are being considered. Since the middle of the 17th century the size of the tidal basin of the Westerschelde has reduced by more than 40%, but the tidal prism has not reduced, because the loss of tidal basin storage was compensated by an amplification and acceleration of the tidal wave in the estuary.

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