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COASTAL AND MARINE ENGINEERING AND MANAGEMENT
COMEM

MORPHOLOGY OF THE EASTERN SCHELDT EBB TIDAL DELTA

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Delft University of Technology
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Abstract

The Eastern Scheldt tidal basin and its ebb tidal delta have changed drastically in the recent centuries under the influence of natural processes and human interventions. A Storm Surge Barrier, one of constructions within framework of Delta Project in the Eastern Scheldt, is considered as the largest impact to changes in hydrodynamics and morphology of the ebb tidal delta.

The barrier was built in 1987 to maintain the tide and to protect the area from flooding. The barrier closes under severe storm surge conditions and remains open during normal conditions to preserve the tide-dominated character of the ecosystem. However, this storm surge barrier caused a reduction of tidal volume and tidal current in the Eastern Scheldt. Since 1987, there has been a remarkable reduction of the tidal prism by 30%, of the average tidal range by 12% and of the average tidal current velocities by 33%. As a result, sediment export from the basin towards its ebb tidal delta has ceased. This led and still to changes in morphology of the ebb tidal delta. In order to adapt to changes in tidal volume, the tidal channels become sinks of sediment and this sediment has been and still is taken from the tidal shoals nearby. Sediment volume of these shoals therefore has decreased drastically. The deposition in channels and erosion on the shoals caused a number of negative effects to ecology, safety, navigation, recreations and fishery in the Eastern Scheldt.

To analyse the morphological developments of the ebb tidal delta before, during and after the implementation of the Storm Surge Barrier in the Eastern Scheldt, bathymetry maps which present the changes in deposition and erosion parts in the ebb tidal delta in every four years (from 1960 to 2004) were used.

In summary, the morphology of the Eastern Scheldt ebb tidal delta experienced enormous changes due to the Delta Project. These changes comprise shoaling and reorientation of channels- from updrift to downdrift (northward) migration of channels, landward migration of shoals, development and diminishing of ebb and flood chutes and development of scour holes near the entrance of the storm surge barrier. As a result, it would take a long time (centuries) to establish a new dynamic equilibrium between hydraulic conditions and geomorphology in the Eastern Scheldt inlet.

Key words: Eastern Scheldt, ebb tidal delta, morphology, storm surge barrier.

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Chapter 1. Introduction

1.1. Problem definition

The Eastern Scheldt located in the southwestern part of the Netherlands has changed significantly in the recent centuries under the influence of natural processes and human interventions. A Storm Surge Barrier, one of constructions within framework of Delta Project in the Eastern Scheldt, is considered as the largest impact to changes in hydrodynamics and morphology of the ebb tidal delta.

A combination of high tide and water level set up due to a severe storm surge in 1953 led to the inundation of large parts of the southwest of the Netherlands. There was an enormous loss in human life, numbers of livestock and damage of land caused by salt-water infiltration. Consequently, the Delta Project was implemented by closing three of four tidal inlets: the Haringvliet, the Grevelingen, and the Eastern Scheldt. The original plan to close off the Eastern Scheldt from the North Sea by a solid dam, thereby creating a fresh water lake was altered in 1976. This situation caused discussion between protection of ecological and economic value of this tidal system and protection from flooding.

The barrier was built in 1987 to maintain tidal characteristics and to protect the area from flooding. The barrier closes under severe storm surge conditions and remains open during normal condition to preserve the tide-dominated characters of the ecosystem. However, this storm surge barrier caused a reduction of tidal volume and tidal current in the Eastern Scheldt. Since 1987, there have been remarkable reductions of tidal prism by 30%, of the average tidal range by 12% and of the average tidal current velocities by 33%. As a result, sediment export from the basin towards its ebb tidal delta has ceased. This led and still to changes in morphology of the ebb tidal delta. In order to adapt to changes in tidal volume, the tidal channels become sinks of sediment and this sediment has been and still is taken from the tidal shoals nearby. Sediment volume of these shoals therefore has decreased drastically. The deposition in channels and erosion on the shoals caused a number of negative effects to ecology, safety, navigation, recreations and fishery in the Eastern Scheldt.

1.2. Objectives and research questions

To get insight into the historical development of Eastern Scheldt, the following objectives have been defined.

- ✓ Analyse the impacts of the implementation of the storm- surge barrier to hydrodynamic and morphological characteristics of the study area.
- ✓ Get more insight into the bathymetry of the ebb tidal delta and the morphology pre-barrier and post- barrier (1986- present)

- Main research question
  What is the behavior of the ebb tidal delta under influence of human interventions over different periods: before, during and after the implementation of the Storm Surge barrier?
- Sub research questions
  What are the processes influencing to the development of the ebb tidal delta?

1.3. Research approach

To fulfill the objectives mentioned above, the approach used for this study is:

1. Literature study in the Eastern Scheldt and its ebb tidal delta such as tide, wave and sediment transport processes.
2. Study consequences of barrier construction to the tidal basin, changes in its tidal and morphological characteristics
3. Historic evolution of the ebb tidal delta: bathymetry maps which present the changes in deposition and erosion parts in the ebb tidal delta in every four years (from 1960 to 2004) were used.

1.4. Thesis outline

Basic structure of this thesis is comprised 6 chapters:

Chapter 1. Introduction gives an overview of problems and objectives of the study and methodology

Chapter 2. Literature review of coastal inlet discusses tide, wave and sediment transport, which have important impacts to morphology of tidal inlet.

Chapter 3. Description of the study area: presents general hydrodynamics and morphodynamic characteristic of the study area, consequences of the barrier also are discussed in this chapter.

Chapter 4. Historical development of ebb tidal delta of the Eastern Scheldt; In this chapter, changes of the ebb- tidal delta caused by natural processes and closure of the inlet are determined.

Chapter 5. Synthesis: summary of results from the previous chapter.

Chapter 6. Conclusions and recommendations this chapter contains a summary of the overall results of this study including recommendations.

Chapter 2. Literature review of coastal inlet

2.1. Tidal inlet

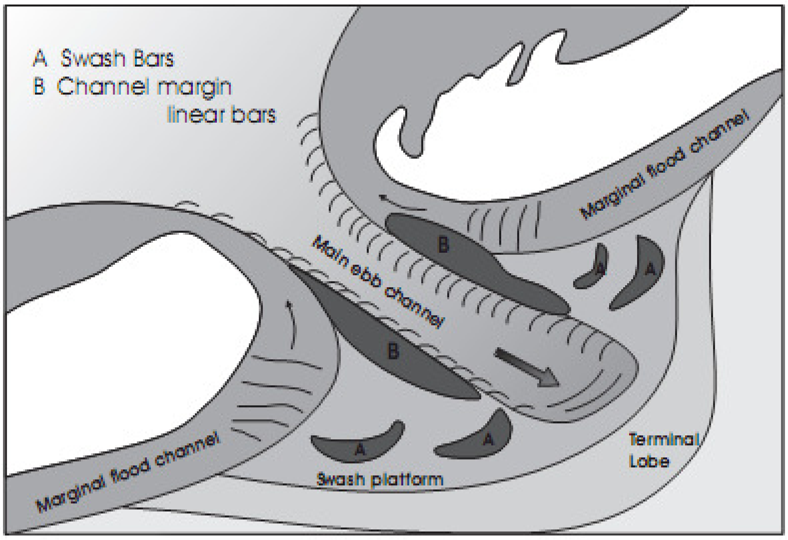


Figure 2.1. Tidal inlet morphology (Elias, 2006)

- *A main ebb channel is dominated by the ebb tidal currents.*
- *Marginal flood channels are dominated by the flood tidal currents.*
- *A terminal lobe is located at the end of the main ebb channel where sediment settles due to diminishing of the ebb velocities.*
- *Swash flat-forms are broad shallow sand flat-forms located on the both side of the main ebb channel*
- *Swash bars are formed and migrate onshore due to wave breaking generated currents and transports.*
- *Channel margin linear bars are built by the interaction of the ebb tidal currents and waves*

A tidal inlet is an interruption of the shoreline through which water and sediments is exchanged between the open sea and the back-barrier basin. A dynamically stable inlet channel is maintained by tidal currents (Escoffier, 1940).

Sediments eroded from the inlet, and supplied by littoral drift, accumulate in tidal deltas at the seaward and at the landward side (the ebb-tidal and flood-tidal delta respectively) where flow segregates and velocities diminish beyond the sediment transport threshold after passing through the narrow inlet throat. Swash bars and channels exhibit a highly dynamic behavior; their positions are continuously changing by time.

2.2. Ebb tidal delta morphology

The ebb tidal delta is a sediment accumulation seaward of the inlet throat. It is formed primarily by sediment supplied by the ebb tidal currents and destructed by wave action. The sediment volume confined in the ebb tidal delta relates to the tidal prism.

$V_o = c.P^{1.23}$ (1)

Where: V_o is the ebb-delta sand volume (m^3), c an empirical constant and P the tidal prism magnitude (m^3)

Large ebb shoals and small flood shoals generally develop in areas with large tides and small waves. The deposition is mainly caused by ebb currents and sediment is transported offshore by the ebb current in the main ebb channel located in the middle of the inlet. Since the velocity decreases further away from the inlet the sediment finally deposits. The small waves usually modify the size and shape of the ebb shoal (Hayes, 1980)

2.3. Tide

Tide is a deterministic process, constituted by the rising of Earth's ocean surface caused by the interaction of the Moon and the Sun on the Earth. In the open sea one may not detect tidal motion, but near the coasts the effect of tides is amplified (Skinner and Porter, 1995), making it noticeable. On almost all coasts the rhythmic tidal rise (flood) and fall (ebb) of water can be observed (Woodroffe, 2002) and is of considerable importance to coastal studies, not only through the effects of tidal currents, but also as it spreads the range and influence of marine processes over a wider area (Carter, 1988), such as in tidal flats and estuaries.

The tides are long waves (Woodroffe, 2002) of extremely long periods and they behave as shallow water waves. Its translation involves large scale water mass and energy fluxes, resulting in current generation (oscillating tidal streams) (Carter, 1988 and Wikipedia), and sediment transport.

Each tide is a sum of a number of components, called harmonics. Each of these components corresponds to one of the relative astronomical motions between Earth, Sun and Moon (Brown et. al., 1989). The main lunar component M2 has a 12.42 h period and the main solar component S2 has a 12 h period. When a tide wave enters a coastal environment, distortions of the wave occur, due to the shallow water, and new harmonics are generated, with smaller periods, as M4 (6.21h period) and M8 which most of the times are sufficient to explain most of the variance in shallow water tidal curves (Dyer, 1997 and Carter, 1988).

2.3.1. Tidal asymmetry

Tidal asymmetry directly controls transport patterns of coarse sediment. If the maximum flood velocity is higher than the ebb velocity then it is called flood dominant and the system tend to import sediment and vice versa.

The following equation illustrates the effect of the interaction of the M2 tidal current and its M4 overtide causing the tidal asymmetry:

$$\frac{S}{c{u^3}_{M2}} = \frac{3}{4}\left(\frac{u_{M4}}{u_{M2}}\right)\cos\varphi_{M4-2} \quad (2)$$

Where: S sediment transport

c coefficient

u_{M2} the amplitude of the M2 tidal current

u_{M4} the amplitude of the M2 tidal current

φ_{M4-2} the phase lag $\varphi_{M4} - 2\varphi_{M2}$ between M2 and M4

If $\cos\varphi_{M4-2}$=1 then flood dominant leading maximum net import sediment and if $\cos\varphi_{M4-2}$=-1 then ebb dominant, the system exports sediment.

2.3.2. Tidal prism

Tidal prism consists of the volume of water exchanged in a tidal cycle. It is estimated as a product of the surface area of the system measured up to the upper limit of the estuary and the tidal amplitude (Carter, 1998). Large tidal prisms can induce large well-developed ebb tidal delta.

There is a relationship between volume of ebb tidal delta, volume of channel and tidal prism

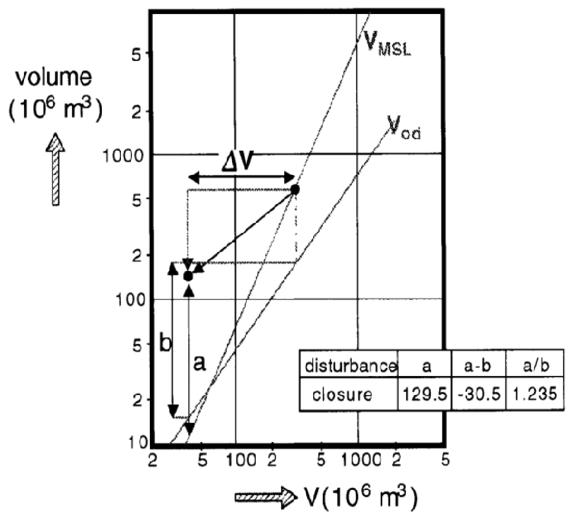


Figure 2.2. Morphologic relationships (Source: J. Bosboom and M.J.F Stive, 2010)

The volume of sand confined in the ebb-tidal delta relates to the tidal prism (Walton and Adams, 1976):

$$V_{od} = c.P^{1.23} \qquad (3)$$

Where: Vod is the ebb-delta sand volume (m^3), c an empirical constant and P the tidal prism magnitude (m^3)

The relation of sediment volume of channel and tidal prism is defined by the following equation

$V_c = C_V . P^{3/2}$ (4)

Where: Vc is the channel water volume (m^3), Cv an empirical constant and P the tidal prism magnitude (m^3)

For example, the closure of the tidal basin will result in a reduction of the channel volume Vc and tidal prism. The inlet will adapt to the new situation. Changes in tidal prism have larger effect on the equilibrium channel volume than the ebb tidal delta sand volume because of the larger exponent. If the tidal prism decreases then shallower channels and smaller of shoals should appear.

2.4. Wave

Waves are an important factor for sediment transport on the ebb tidal delta. The ebb tidal delta volume might be related to tides or tidal prism but waves redistribute the sediments and contribute to the sediment by-passing mechanism. Waves contribute directly to the sediment transports via currents due to radiation stresses generated by wave breaking of obliquely incident waves and due to wave asymmetry. Indirectly waves enhance bed-shear stresses and stir-up sediment, allowing more sediment into suspension to be transported by the tidal- and wind-driven flow.

Direction of waves influences the geometry of ebb tidal deltas: asymmetry (downdrift or updrift migration) and protrusion. The asymmetry can also be caused by the interaction of alongshore tidal currents with the inlet tidal currents. The development of asymmetry and its orientation will depend on the relative importance of the two factors.

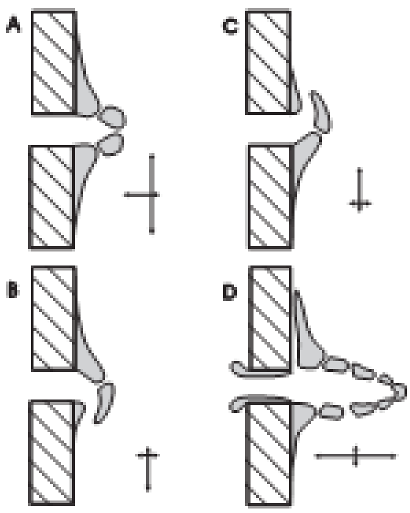


Figure 2.3. Representation of relative forces of cross-shore and longshore currents

(Soure: Elias, 2006)

In the figure 2.3, A is wave dominated because wave forces in this case is stronger than tide forces whilst D is tide dominated. As known, wave energy tends to move sediment shoreward, therefore wave-dominated ebb-tidal deltas (A) are pushed close to the inlet throat while tide-dominated ebb-tidal deltas (D) extend offshore. For B and C, wave forces overwhelmed tidal forces so the asymmetry of the ebb tidal delta depends on wave direction. In B case, wave comes from updrift to downdirft, therefore, the ebb tidal delta tends to downdirft migration and vice versa for C case.

2.5. Secondary flow

A secondary flow component is caused by the curvature of the flow in bends and due the Coriolis Effect. This secondary flow causes an upward flow in the inner bend and consequently an upward sediment transport. This may lead to an increase of sediment transport towards the shoal. The secondary flow due to curvature is independent on the flow direction, while the Coriolis Effect is in the Northern Hemisphere always to the right looking in the flow direction. Hence, the curvature induced secondary flow and the Coriolis Effect may reinforce or weaken each other, depending on the direction of the flow.

The curvature induced secondary flow does not change sign and is in the upper part of the water column always directed away from the centre of curvature flow; in lower part always towards it. Hence, it is contributed to maintenance of the shoal.

Wave induced currents

Due to refraction, the waves tend to converge toward the top of the shoal. As the waves break on the seaward slope of the shoal, they dissipate and generate wave force. The water will flow over the shoal in the direction of the force. Water level variations exist around the shoal due to wave height gradient. Water flow over the shoal until it reaches the channel behind the shoal.

2.6. Sedimentary processes

2.6.1. Sediment transport

Longshore sediment transport: The sediment moving along a coastline under the action of the waves and the long shore currents is transported in several modes:

- Bed load transport: either in sheet flow or rolled along the bottom;
- Suspended load: carried up within the fluid column and moved by currents ;
- Swash load: moved on the beach face by the swash.

Littoral transport can occur in two alongshore directions, depending on the wave direction. Typically the longshore transport at a site will consist of positive drift for one or more seasons, and negative drift for the remainder of the year. The net drift is the sum of the positive and negative components. The gross drift is the sum of the drift magnitudes. All of these parameters can be important for a coastline.

Cross shore sediment transport: If the long shore sediment transport is mostly due to the wave induced longshore current then cross shore transport is a result of the water motions due to the waves and the undertow. However, the coupling between the hydrodynamics and the sediment transport is not all that well understood.

Seasonal shoreline changes are usually considered to be in response to the greater incidence of storm during winter and the associated seaward transport and storage in near shore bar features. With the greater wave heights associated with storms, the bar forms farther offshore where the water is deeper and the entire scale of the bars is likewise increased, requiring a greater volume of sand, which is provided in part by erosion of the subaerial portion of the beach profile.

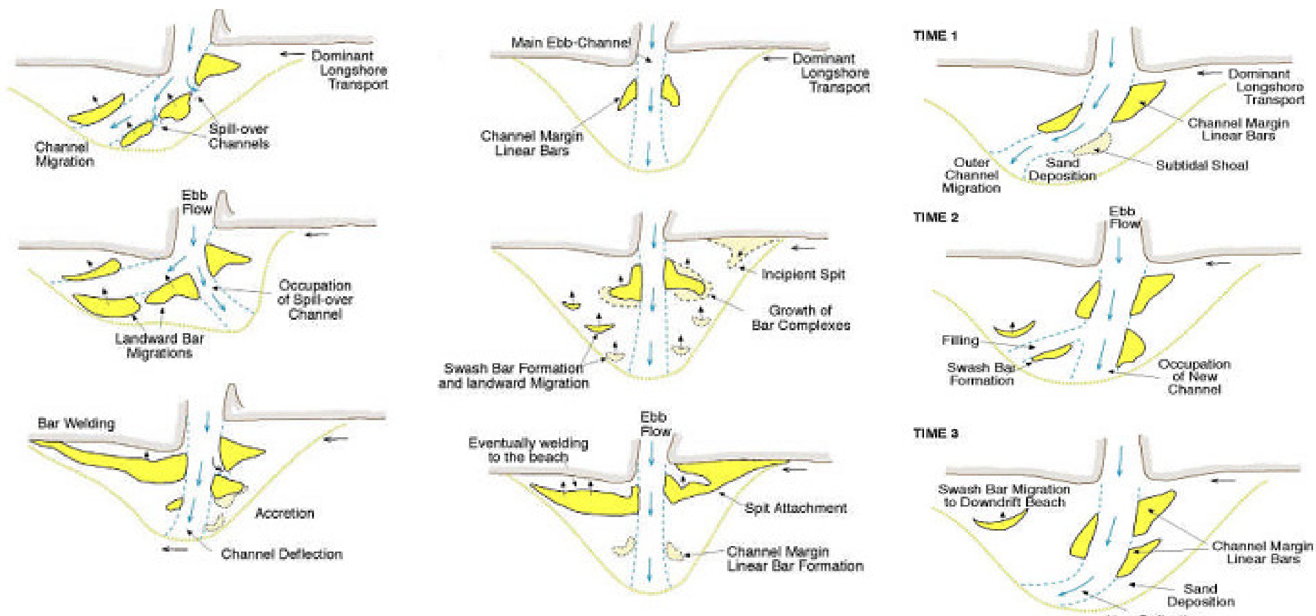
Sediment transport is determined by the product of sediment concentration and flow velocity. The sediment concentration depends on several aspects like the stirring of sediment by waves and flow velocity and the settling velocity of the sediment. Flow velocity causes bed shear stress. When the bed shear stress is above a critical bed shear stress, which is a function of the grain size, the sediment will go into suspension. Thus sediment transport has a non-linear relation with flow velocity:

$S = c.u$; $c \sim \tau.u \sim u^2$ then $S = c.u^3$

Where S is the sediment transport, c is the sediment concentration, u is the flow velocity and is the bed shear stress.

2.6.2. Sediment bypassing mechanism

Natural inlet bypassing occurs when sediment is transported by waves and currents from the updrift side of an inlet to the down-drift side. This process is the result of interaction between the longshore transport and inlet currents which force the sediment around the edge of the ebb shoal promoting stability of the down-drift shoreline. FitzGerald et al. (2000) presents mechanisms by which sand is transferred to the down-drift shoreline as following conceptual models (Figure 2.4):



Model 1: Cyclic ebb- tidal delta breaching *Model 2: Stable inlet process* *Model 3: Outer channel shifting*

Figure 2.4. Conceptual models of natural sediment bypassing

(Source: FitzGerald et al, 2000)

Model 1 - Cyclic Ebb-tidal Delta Breaching: Ebb-tidal delta or ebb-shoal breaching is the process when sand is bypassed through migration of the main ebb channel. The longshore sediment transport causes a sediment buildup on the updrift side of the inlet which deflects the ebb channel. This process can go on until the main ebb channel runs almost parallel with the down drift shoreline and it causes significant erosion. It is not efficient for the water to flow this way so gradually, or during a single storm event, the flow will be diverted and start to flow over the sand accumulation and finally break the tidal delta. The former channel will be filled with sediment due to decreased water flow through it and soon all the water will go through the new channel. The rest of the delta forms a large bar complex which, through onshore movement, migrates to the down-drift beach.

Model 2 - Stable Inlet Processes: A stable inlet should have a main ebb channel that does not migrate and has a stable inlet throat position. At those kinds of inlet sand bypassing can occur. Swash bars, which form in the distal part of the ebb shoal of sand transported in the ebb channel, lump together and form a large bar complex that migrate landward to the down drift shoreline. The reason for this is the dominance of net landward flow in the swash zone since during flood the current gets reinforced by the swell waves and during ebb the ebb current gets retarded by the swell waves.

Model 3 - Outer Channel Shifting: This mechanism of inlet sediment bypassing is similar to ebb-tidal delta breaching, but is limited to the seaward end of the main ebb channel and involves smaller volumes of sand. In this process, the inner portion of the main channel remains in a fixed position while the outer channel is deflected down-drift because of preferential accumulation of sand on the seaward, updrift side of the swash platform. As the outer portion of the channel becomes more deflected, which at some inlets can produce a right-angle bend, flow through the outer portion of the channel becomes increasingly less efficient. Eventually, a new channel is cut through the distal portion of the ebb delta that shortens the pathway of flow. Cutting of a new channel is commonly initiated during high spring tides when peak flows occur in the channel. The sand that had been located on the updrift side of the outer channel and is now on the down-drift side has bypassed the inlet.

Chapter 3. Description of study area

3.1. Introduction to the Eastern Scheldt

The Eastern Scheldt, located in the southwestern part of the Netherlands, is one of the estuarine branches of the delta for the rivers Rhine, Meuse and Scheldt (Smaal and Nienhuis, 1992). The Eastern Scheldt originally was a tidal estuary that transports fresh water from the Rhine/Maas Rivers and the Scheldt to the North Sea. But the Eastern Scheldt lost its connections with the Scheldt River and is no longer as an estuary due to connecting and scouring of the Western Scheldt in the 14th century. The tidal system of the Eastern Scheldt consists of a tidal basin and its ebb tidal delta. Since 1987, the tidal basin is bound by the storm-surge barrier in the west and by the Oesterdam and the Philipsdam in the east.

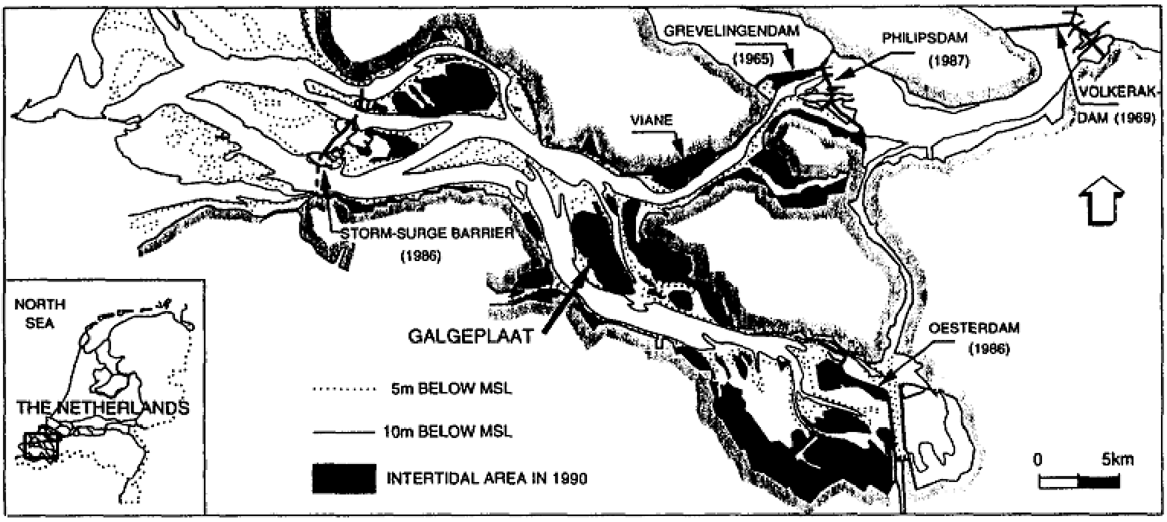


Figure 3.1. Map of the Eastern Scheldt (Souce: Mulder, 1994)

The Delta Project has significantly influenced on tidal characteristics and morphology of the Eastern Scheldt system. Before closure, the basin was 55km long; it was shortened by 5km after implementation of constructions. The inlet width of the Eastern Scheldt is 7.5 km and the widest cross-section is 10.5 km. The geomorphology of the basin is characterized by a complex system of meandering tidal channels, tidal shoals, mud flats and salt marshes. Three main channels connect the Eastern Scheldt with the sea comprising of the Hammen, the Schaar and the Roompot.

In Eastern Scheldt, the ebb tidal delta consists of a network of ebb and flood dominated channels and sandy shoals that extend up to 15km into the North Sea. The channels in the ebb tidal delta can reach a depth of 37 meters below NAP. The tops of the tidal flats are typically located between 1 and 3m below NAP. (C. de Bok, 2002)

After the closure, the total surface area of the Eastern Scheldt is 351 km^2, of which 118 km^2 are tidal flats and 6.27 km^2 are salt marshes. The western and central sections have large sandy shoals and are relatively deep with tidal gullies up to 55 m. In contrast, the eastern section is relatively shallow with mussels and other macrobenthos species in the post-barrier period are 13.1, 10.7 and 5.0 g ash-free dry weight. The economic functions of the Eastern Scheldt comprise shellfish cultures and fisheries, recreational use and navigation. The cultivation of mussels is executed on 22.53 km^2 of marked lots; 3.4 km^2 in the eastern section is used for storing and cleansing the mussels before further processing takes place. The cultivation of flat oysters (*Ostrea edulis*) has declined dramatically since 1979 due to the Bonamia disease. (Smaal & Nienhuis, 1992)

3.2. Consequences of the Storm Surge barrier at the Eastern Scheldt inlet

The barrier consists three sections across the main channels of the inlet, namely, the Schaar, the Hammen and the Roompot. There are 63 gates, each hinged between piers founded on mats on top of artificially densified subsoil. All elements were pre-fabricated with 17500 ton weight and 40m high piers. The construction started in 1978 and was successfully completed in 1986. (Huib de Vriend, 2004)

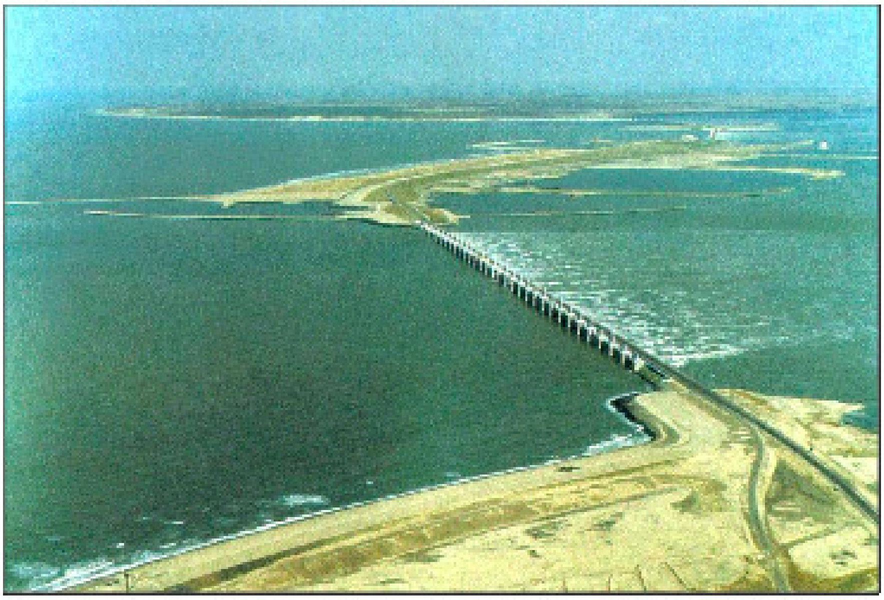


Figure 3.2. Storm-surge barrier under normal conditions (Source: Huib de Vriend, 2004)

The barrier structure with a lot of gates forms an obstacle to the tide and leads to a reduction of the tidal motion. The reduction of the tidal motion largely impacts to intertidal areas within the basin. It causes a decrease of bed relief inside the basin and also leads to a decrease of marshland and mudflats bordering the basin. The loss of intertidal areas also has negative effects for recreation and shellfish fishers. The siltation of the channels causes less water depth for the navigation of ships. Due to the lower high water levels and the absence of extreme high waters, inundation time of marsh decrease and there is less time available for the deposition sediment at the top. It means a change of bed surface structure (more consolidated) and vegetation cover (more terrestrial). In these erosion areas, there is not only loss of habitat but also peat layers get exposed and produce large amount of fine organic material that causes an increased turbidity of the water in the basin. Moreover, for the areas cut off from the tidal basin by the compartmenting measures, reduced water circulation has led to eutrophication from nearby agricultural land and then causes algae blooming. (Huib de Vriend, 2004).

The construction of the storm-surge barrier diminished the cross sectional area of the channels of the inlet of the Eastern Scheldt from 80,000 m^2 in 1984 to approx. 17,900 m^2 in 1987 (Louters et al. 1998). There then have been remarkable reductions of tidal prism by 30%, the average tidal range by 12% and the average tidal current velocities by 33%. As a result, sediment export from the basin towards its ebb tidal delta has ceased. This leads to changes in morphology of the ebb tidal delta.

Moreover, the barrier caused discontinuous tidal currents between seaward and landward side at the inlet. At the seaward side of the storm surge barrier larger velocities occur during ebb than during flood and the opposite happens at the landward side. It leads to a development of scour holes at the both side of the barrier. These scour holes are known as a cause for limited sediment import. These scour holes possibly block the sediment transport into the Eastern Scheldt basin. During flood the sediment is trapped in the scour holes and during ebb the sediment is flushed out of the holes in the direction of the North Sea.

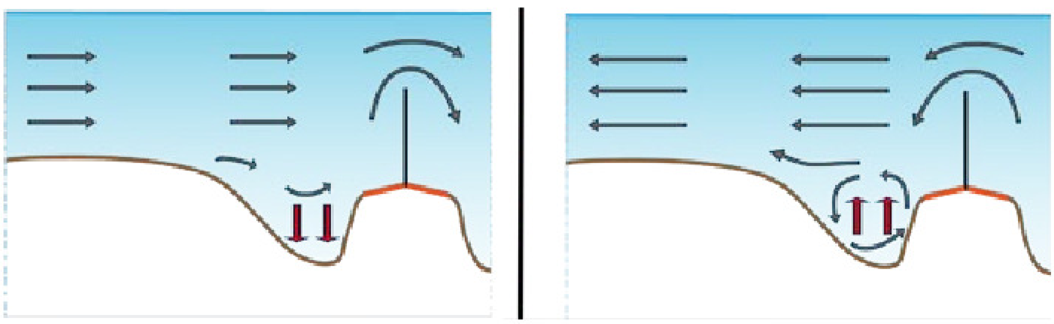


Figure 3.3. Sedimentation during flood (left) and erosion due to turbulence during ebb (right) at a outer scour hole (Source: L. Hoogduin, 2009)

3.3. Hydrodynamics in the Eastern Scheldt

3.3.1. Tide

Total mean tidal volume in the Eastern Scheld basin is about by 880 million m^3. Maximum velocities on ebb and flood vary on average tides from 0.35 m/s in the northern branch, 0.75 m/s in the eastern part and up to 1.0 m/s in the western part. The residence time of the water is about 20 tidal periods near the mouth, 100 in the central part and roughly 200 near the Oesterdam and Philipsdam (Smaal & Boeije, 1991)

The mean tidal range varies from 2.5m near the mouth to 3.4m in the landward part of the basin. The maximum current velocities vary from 1-1.5m/s in the tidal channels to 0.2-0.4 m/s in the shallow areas on the flats and shoals. (C.de Bok, 2002)

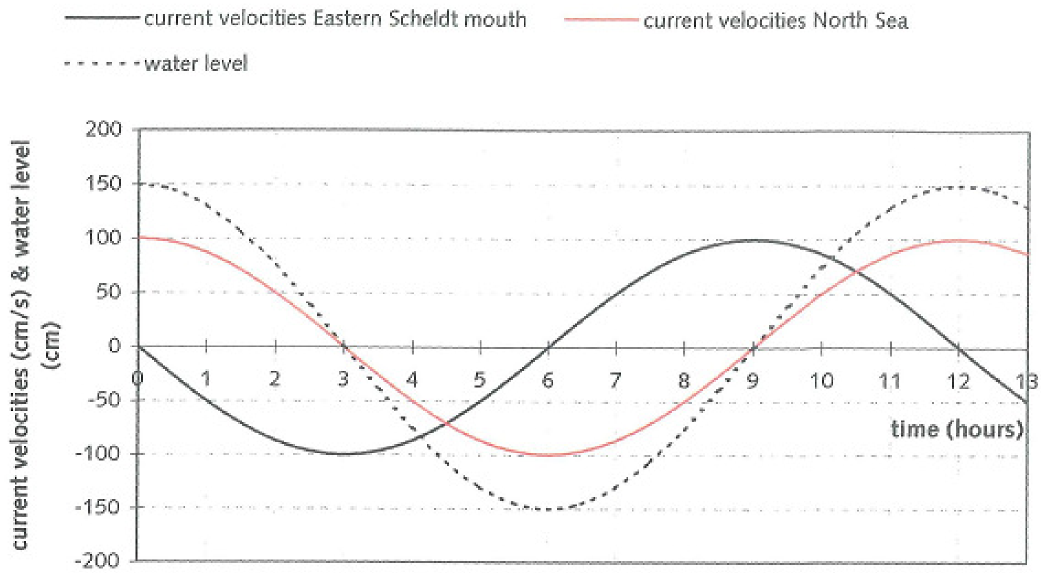
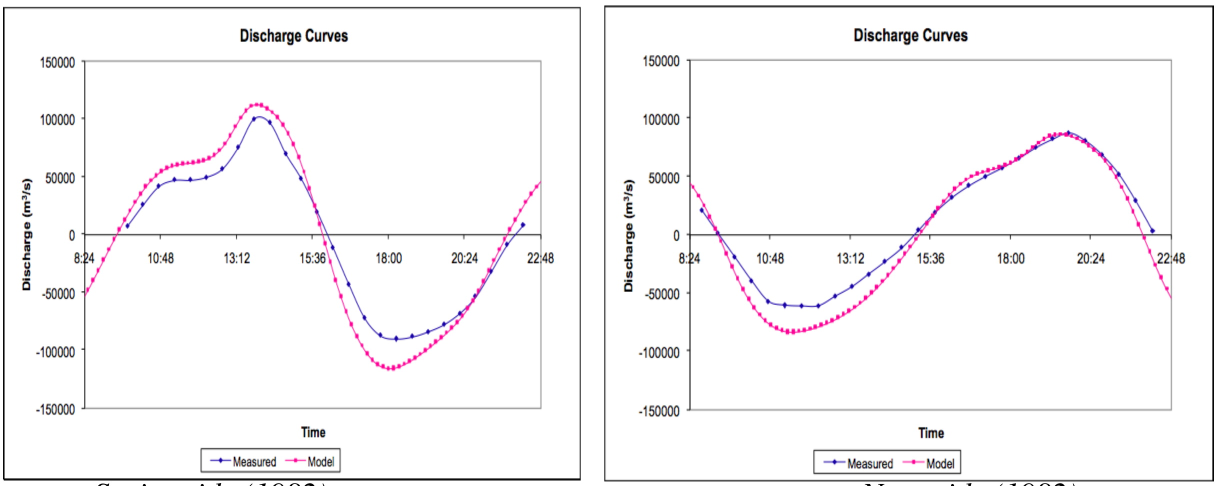


Figure 3.4. The water inlet in the inlet and the current velocity at the North Sea and in the inlet of the Eastern Scheldt (C. de Bok, 2002)

The tidal wave inside the basin has the character of a standing wave with the surface elevation and current velocity nearly 90^{o} out of phase. In contrast, the tidal wave at sea has a progressive character, with the surface elevation and current velocity nearly in phase with each other.

The difference between flood and ebb duration implies that the average flow velocity at flood differs from the average ebb velocity, because of the equal flood and ebb discharge. In the Eastern Scheldt, the flood period is larger than the ebb period, resulting in a larger maximum ebb flow velocity than maximum flood velocity. Thus it is ebb dominant. The estuary tends to export sediment from the basin seawards.



Spring tide (1982) *Neap tide (1982)*

Figure 3.5. Tidal currents at spring and neap tide measured at cross section near the barrier

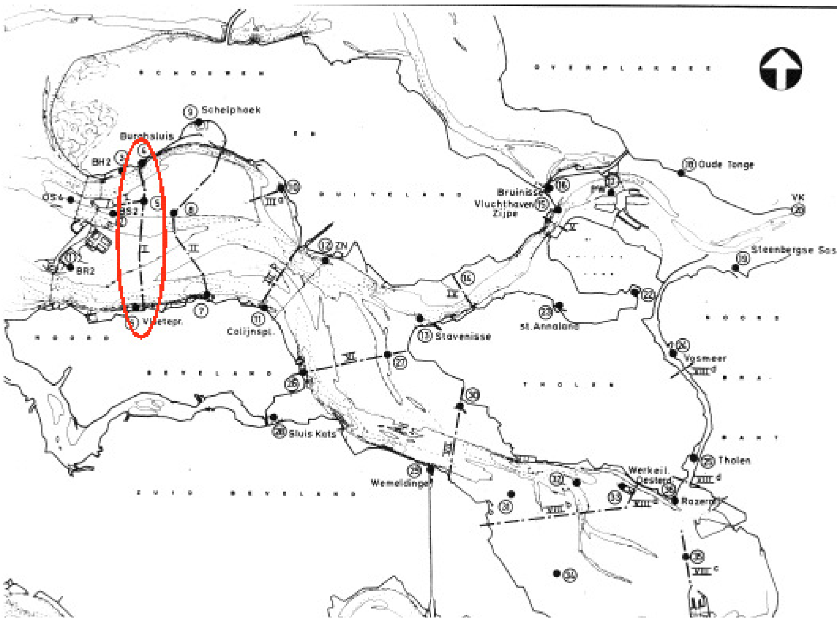


Figure 3.6. Cross section where measured tidal currents

In the Eastern Scheldt, flood velocity during spring tide is higher than during neap tide. During spring tide there is a larger water depth on the shoal. Therefore there is a higher sediment transport capacity due to higher velocities during spring tide which yields an extra shoal building capacity compared to neap tide.

3.3.2. Wind wave

The wind regime along the south-western coast of the Netherlands shows seasonal variations. The prevailing winds are from a westerly direction, with an average velocity varying from 8m/s near the mouth of the Eastern Scheldt to approximately 6.5m/s in the Marollengat, in the East.

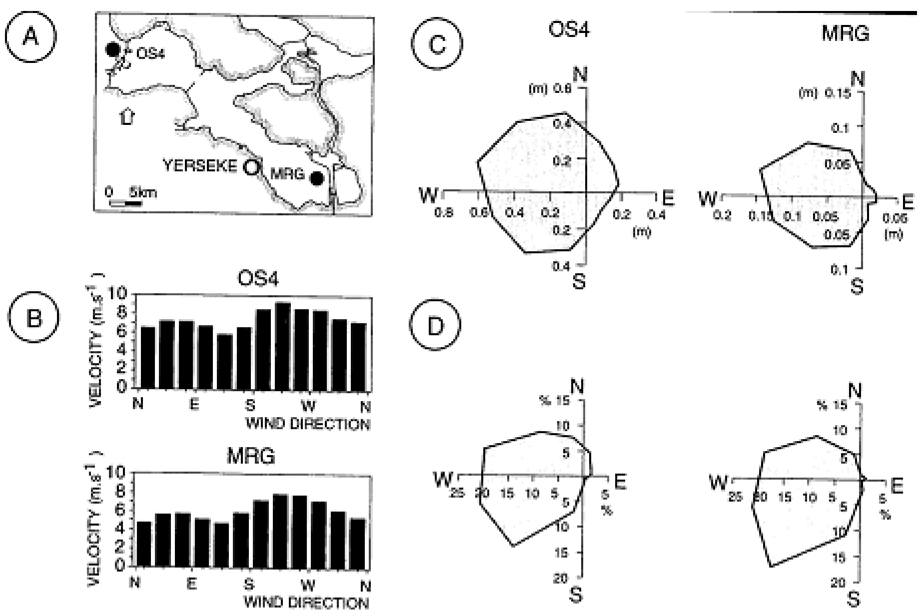


Figure 3.7. Wave and wind characteristics of the Eastern Scheldt system (1977-1990) ***a) Location of station OS4 and MRG. b) Average wind velocity. c) Average significant wave height [m]. d) Proportional wave energy distribution for different wind directions. (Louters et al. 1998)***

The Eastern Scheldt Storm Surge barrier blocks most of from offshore incoming waves. Hence the majority of the short waves are locally wind generated. Wave records indicated that in the prevailing SW-NW winds the average significant wave height decreases from about 0.4m near the mouth to 0.1m in the landward part of the Eastern Scheldt. The dominant wave energy flux is from the southwest. (Louters et al. 1998)

Table 3.1. Wave climate measured at Schouwenbank (SCHB) from 2005 to 2009

H_{sig} (m)	Direction class (degrees)												
	15	45	75	105	135	165	195	225	255	285	315	345	Total
<1	8.01	2.94	1.02	0.56	0.46	0.61	1.43	4.03	8.25	5.74	7.59	12.39	53.02
1<2	4.32	0.70	0.14	0.03	0.04	0.10	0.57	8.00	8.00	2.79	3.98	6.66	35.33
2<3	0.39	0.01	0	0	0	0	0.06	2.24	2.96	1.06	1.16	1.98	9.85
3<4	0.02	0	0	0	0	0	0	0.13	0.38	0.35	0.31	0.33	1.52
4<5	0	0	0	0	0	0	0	0.01	0.05	0.06	0.06	0.07	0.26
>5	0	0	0	0	0	0	0	0	0	0.02	0	0	0.02
Total	12.73	3.64	1.16	0.59	0.50	0.71	2.06	14.40	19.63	10.01	13.11	21.44	100

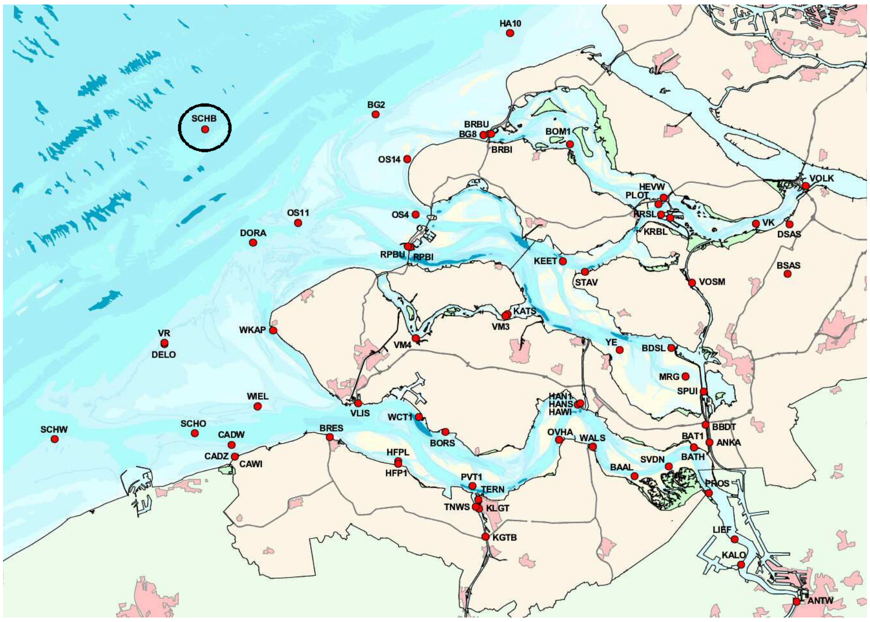


Figure 3.8. Schouwenbank (SCHB) location

Since changes in offshore wave energy along the coast small compared to differences in tidal prism between the inlets, the magnitude of the tidal prism determines the variation in overall shape of the ebb tidal deltas. Inlets with a large tidal prism show updrift asymmetrical ebb deltas, whereas inlets with a small tidal prism have downdrift asymmetrical ebb deltas. In the Eastern Scheldt, the increase of tidal prism of about 25% since the last century will have changed the relative importance of wave to tide.

3.3.3. Sediment transport

The Eastern Scheldt basin has been a sand exporting system for a long time. The constructions of Zandkreekdam, Veersegatdam, Grevelingendam and Volkerakdam led to an increase of tidal volume. Hence the Eastern Scheldt basin kept exporting sand. (Mulder and Louters 1994). However, since 1987 due to the barrier, no sediment from the North Sea is imported, thus the intertidal areas within the basin are eroding.

Prior to the construction of barrier, the erosion and deposition on the ebb tidal delta were been related to the developments within the basin (Van de Berg, 1986). However, after the closure of the inlet by the storm surge barrier, the exchange sediment between the basin and the ebb tidal delta are mostly impossible.

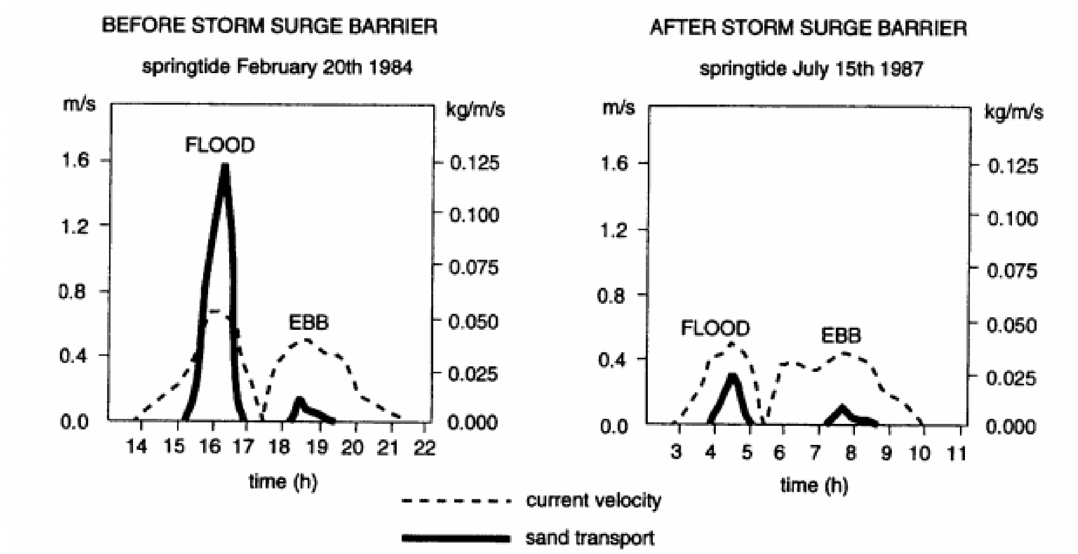


Figure 3.9. The dramatic reduction in sediment transport due to the construction of barrier at Galgeplaat tidal shoal under normal conditions (Louters, 1998)

The flood currents have decreased after construction of the barrier; it makes a decrease in sediment transport. Furthermore, the flood currents are in charge of shoal building, as a consequence, less sediment is brought by the flood currents to build the shoals.

3.3.5. Summary of changes in hydrodynamic due to human interventions

Hydrodynamic characteristics of the Eastern Scheldt changed due to the Delta Works. When construction of Grevelingen dam (1962-1964) was completed, part of its tidal prism was added to Eastern Scheldt tidal system. The same thing happened for closure of the Volkerak in 1969.

The construction of the storm-surge barrier causes a discontinuity of tidal range between on the seaward side and landward side. Tidal range is greater on the seaward because of the resistance of barrier. Tidal amplitude increase eastwards from the barrier, from a mean of 2.47m near the barrier to 2.98m in the northern branch and 3.39m at the southeast end near the Oester dam. (Vroon, 1994)

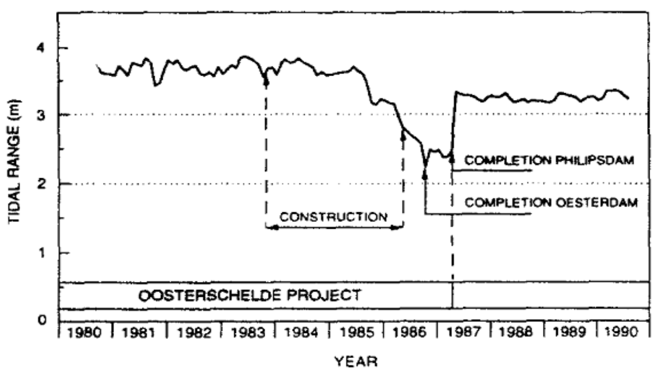


Figure 3.10. Changes in mean tidal range in the central part of the Eastern Scheldt due to the Delta Project (Mulder, 1994)

Table 3.2. Changes in hydrodynamic characteristics of Eastern Scheldt (Brinke et al., 1994)

	Pre-barrier	Post-barrier	% change
Total surface area (km^2)	452	351	-22
Intertidal surface area (km^2)	183	118	-36
Tidal volume (10^6 m^3)	1283	915	-29
Average current velocity (m/s)	1.2	0.8	-33
Residence time water (days)	50	100	+100
Fresh water input (m^3/s)	70	25	-63
Salinity (%o)	>25	>30	+15
Average tidal range (Yerseke) (m)	3.7	3.25	-12
Average concentration suspended matter (mg/l)	25	15	-40

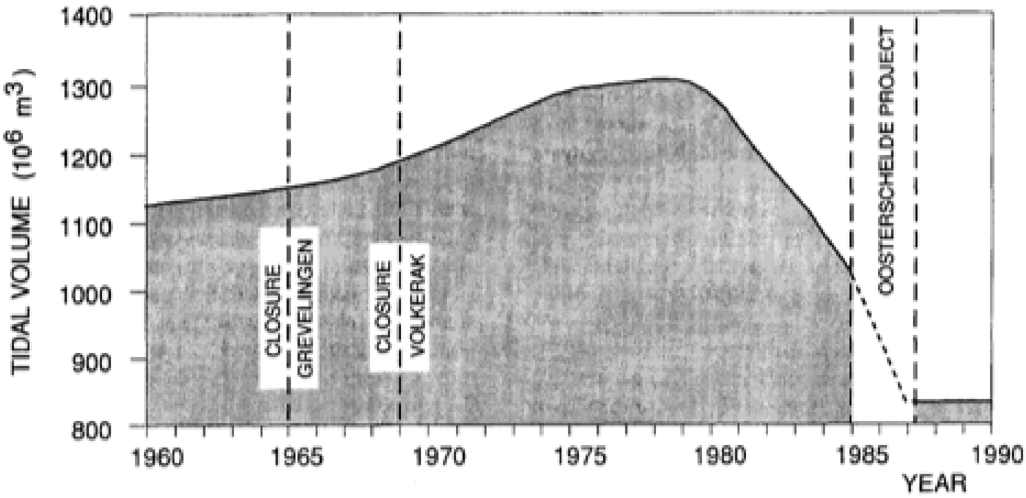


Figure 3.11. Change in tidal volume at entrance of the Eastern Scheldt in recent decades (Source: Louters et al., 1993)

During the construction of the Delta Works, the tidal volume, tidal current velocities and the tidal range gradually decreased. The closure of the Oesterdam (1986) and the Philipsdam (1987) led to a decrease of tidal volume of almost 30%, but led to an increase in tidal range. In addition, due to the decrease in tidal volume, the current velocities in the Eastern Scheldt have been reduced by about 30% but locally there are much higher reductions up to 80%.

3.4. Morphologic characteristics of the Eastern Scheldt

The Eastern Scheldt project caused a significant change in the hydrodynamic characteristics of the basin. Consequently, it leads to changes in morphology of the basin. From 1964 to 2004, morphological developments were dominated by the adaptations to the changes in the tidal flow that resulted from constructions within the tidal basin and storm surge barrier. The size of the tidal basin and the tidal amplitude within the basin are altered and has resulted in changes in the tidal prism.

3.4.1. Ebb- tidal delta

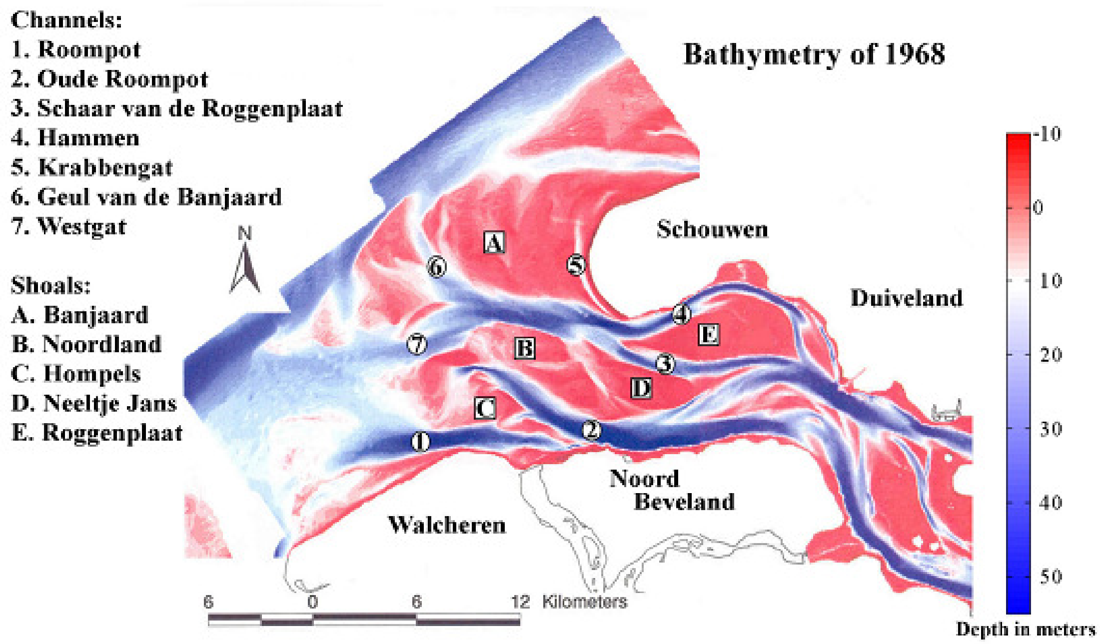


Figure 3.12. The ebb tidal delta of the Eastern Scheldt in 1968

The ebb tidal delta of the Eastern Scheldt is approximately delineated by the -10m AOD contour. To the North East, it connects with the ebb tidal delta of the former Grevelingen inlet that was closed in 1971. While to the south it merges into the ebb tidal 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 -23m AOD. The average maximum height of the tidal shoals in the ebb tidal delta decreases as they get closer to the sea. (Louters, 1998)

The completion of the Eastern Scheldt Project in 1987 caused enormous changes in hydraulic conditions and initiated a large-scale transformation in the geomorphology of the tidal basin and the ebb tidal delta. Since 1987, the tidal prism has decreased by 30% and the average tidal range by 12%. Tidal current velocities have decreased by 20-40% in the western and central parts of Eastern Scheldt, and by 80-100% near to the closure dams in the land ward end of the basin. Thus, sediment export from the basin towards its ebb tidal delta has decreased. As mentioned, due to the reduction of tidal volume the sediments in the deeper parts of channel composed increasingly of silt and mud while tidal shoals and salt marshes are showing distinct erosion. (Louters, 1998)

The changes in sediment volume show contrary trends before and after 1987. Before 1987, intertidal areas inside the basin were eroded while the sedimentation was happened in the ebb tidal delta. In the period 1960-1989, tidal basin lost a total of approximate 120 million m^3 of sediment, while the ebb tidal delta showed a net total deposition of 34 million m^3. The major source was presumably erosion of the Eastern Scheldt tidal basin. The negative trend in the sediment budgets of the ebb tidal delta during the implementation suggests a slight reduction in size of the ebb tidal delta. (Louters, 1998)

3.4.2. Intertidal areas (shoals)

Initial formation of shoals is caused by tidal currents. Once shoals grow above the subtidal level 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.

Galgeplaat located in the central part of the Eastern Scheldt basin, is one of the fastest eroding shoals of the Eastern Scheldt. Before the construction of the storm surge barrier the Galgeplaat showed characteristic spatial variations of erosion and sedimentation between locations at the upper and lower parts of the shoals. There are also spatial variations between more and less wind and/or wave exposed edges. (Mulder and Louters 1994)(Hoeven 2006). Since completion of the engineering works, tidal current velocity and tidal range at the shoal have been reduced, leading to a significant reduction in sediment transport. The area of the Galgeplaat has decreased from 10 km^2 in 1985 to 9.64 km^2 in 2001. This is a decrease of 3.6%. (Ingrid Das, 2010)

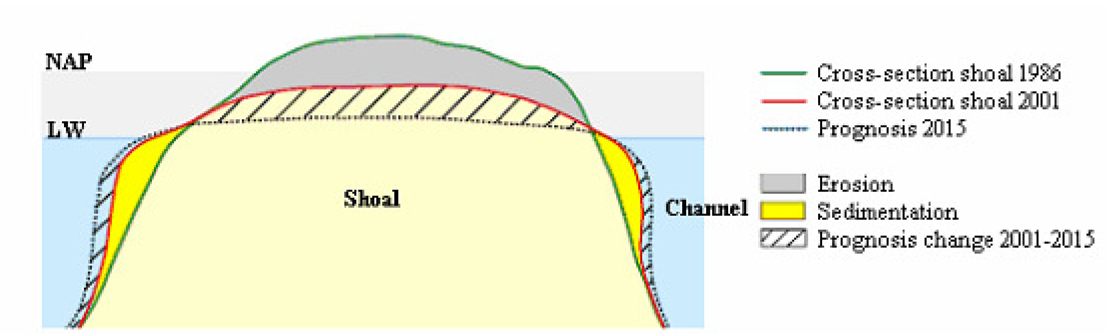


Figure 3.13. Erosion of the shoal and deposition of channel (Source: Ingrid Das, 2010)

3.4.3. Long- term morphologic changes

The reduction of the tidal amplitude in the Eastern Scheldt has led to a significant reduction of the flow velocities, especially in the deeper channels. This must lead to a morphological response. As the cross sectional area of a channel is approximately proportional to the magnitude of the tidal prism.

If the tidal prism decreases, the channel will tend to trap sediment and reduce their cross section area. This sediment is generally imported through but as long as this imported material has not reached its destination in the basin, the channels take sediment from the shoals to reduce their cross-section. Under equilibrium conditions, there is a long term balance between the constructive forces of tidal effects (build shoals up) and the deconstructive forces of wind wave effects (eroding shoals). Therefore, the reduction of tidal motion in the channels leads to the decrease of tidal build-up whilst wave action brings sediment of the shoals into the surrounding channels. Thus, the shoals temporarily lose sediment.

In summary, to reach a new morphodynamic equilibrium, any significant shift in hydraulic conditions has to result in a proportional adaptation in channel cross section: erosion after a tidal volume increase, sedimentation after a decrease.

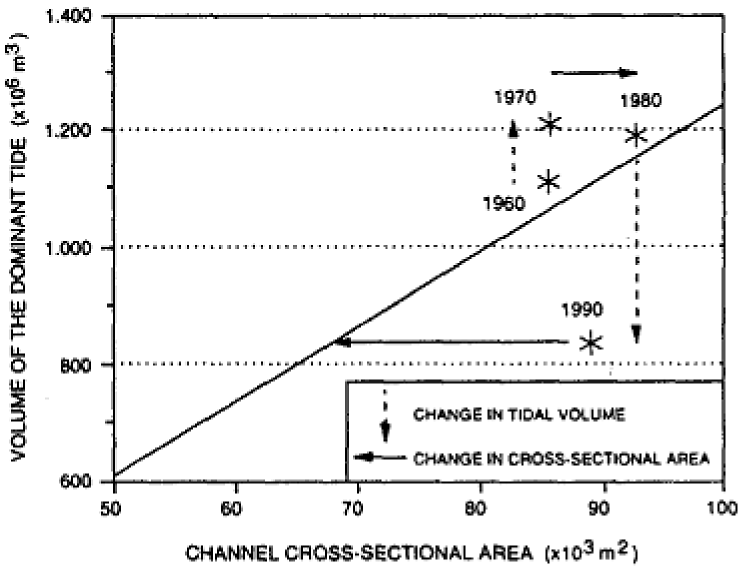


Figure 3.14. Morphodynamic equilibrium relationship between tidal volume and cross sectional area in the Eastern Scheldt (Mulder, 1994)

The system close to the morphodynamic equilibrium in 1960 has changed since the implementation of the Grevelingen and Volkerak Dam during 1960 -1970. These structures have caused an increase of tidal volume and resulting in an increase of cross sectional areas between 1970 and 1980. Since 1986, the decrease of cross section due the construction of Storm Surge Barrier has led the decrease of tidal volume by 30% and this causes sedimentation in the channels and the development of scour holes.

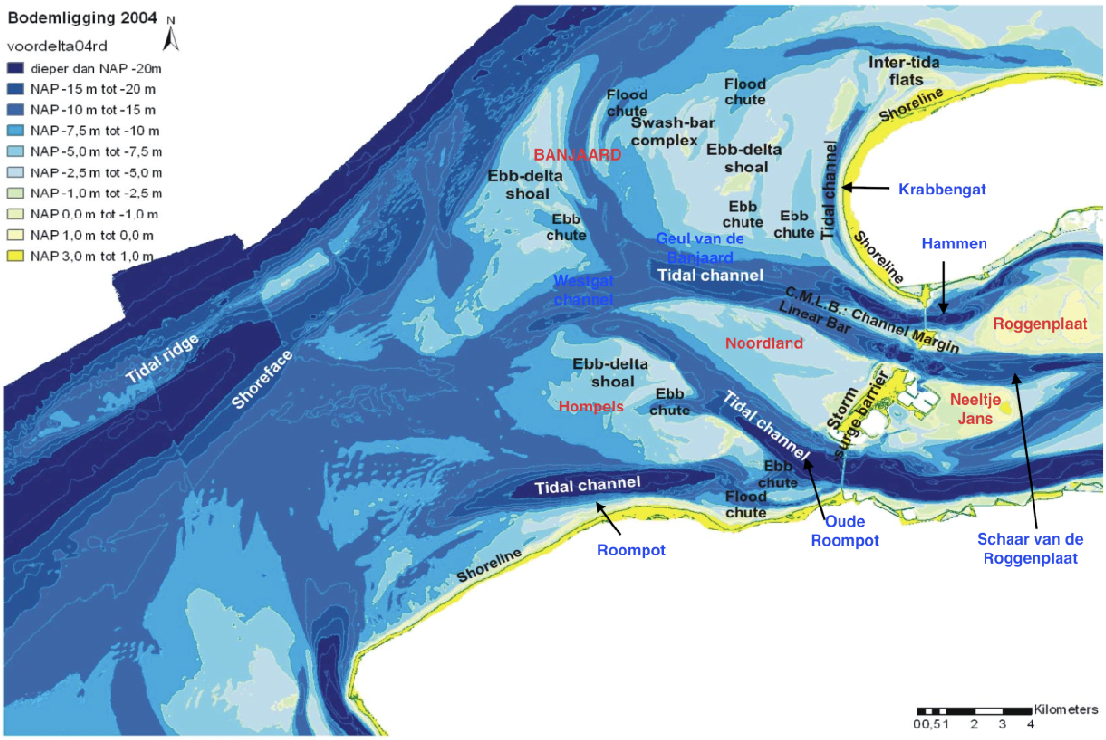
The given relationship (Fig 3.14) shows that the system will tend to a new equilibrium state by sedimentation. To establish a new morphodynamic equilibrium in the Eastern Scheldt channels, total sediment import requires about by 400-600 Mm3 (Mulder, 1994). This amount of sediment is more and less equal to the sediment, which has been eroded from the Eastern Scheldt basin due to an increase of tidal volume over the period

1872-1987. It means that after the recent decrease of tidal volume, time required to reach a new equilibrium will be several centuries. Because sediment transport capacity is product of sediment concentration and tidal current velocity with power of magnitude 2-5 (Van Rijn, 1987). Thus, an increase of tidal current velocities resulting from increases of tidal volume, morphological changes increases exponentially and vice versa. So if the previous time the Eastern Scheldt has taken one century then the present situation with the cutting of sediment supply from the basin will take several centuries to transport the same a mount of sediment.

Chapter 4.Historical development of ebb tidal delta of the Eastern Scheldt

The morphological developments on the ebb tidal delta of the Eastern Scheldt are dominated by the adaptations to the changes in the tidal flow. As mentioned in the previous sections, the changes in the tidal flow resulted from the construction of the storm- surge barrier as well as the constructions within the basin. It leads to the changes in the size of tidal basin, tidal amplitude and tidal prism.

The shift of channels in the ebb tidal delta should have corresponded with relative forces of the cross-shore and longshore currents (tide and wave forces). Another factor has important influence on evolution of ebb tidal delta that is tidal prism. If tidal prism increases then the channels become deeper and longer. It might lead to presence of new channels and vertical accretion, seaward expansion of the tidal shoals and vice versa if tidal prism decreases.



Morphological elements on the Eastern Scheldt ebb- tidal delta in 2004

Figure 4.1. Morphological elements on the Eastern Scheldt ebb tidal delta in 2004 (Cleveringa, 2008)

Shoals:

1. Banjaard
2. Hompels
3. Noorland
4. Neetltje Jans
5. Roggenplaat

Channels:

1. Roompot
2. Oude Roompot
3. Schaar van de Roggenplat
4. Hammen
5. Krabbengat
6. Geul van de Banjaard
7. Westgat

The morphological changes of the ebb tidal delta comprise the development, migration and diminishing of tidal channels, the formation and migration of swash bars and formation and leveling of ebb and flood chutes.

4.1. Influences of Delta Works to the tidal prism of the Eastern Scheldt

Works of the Delta Project that influence on hydrodynamics as well on morphology in the Eastern Scheldt can be seen as below. (C.de Bok, 2002)

- 1965: Grevelingen Dam was finished, located on the tidal divide between the Eastern Scheldt and the Grevelingen.
- 1967: Start construction Eastern Scheldt storm surge barrier
- 1969: Volkerak Dam was completed.
- 1983-1986: Placement of the piers and gates in the inlet
- 1986: completion of Philips Dam and Oester Dam and Storm Surge Barrier

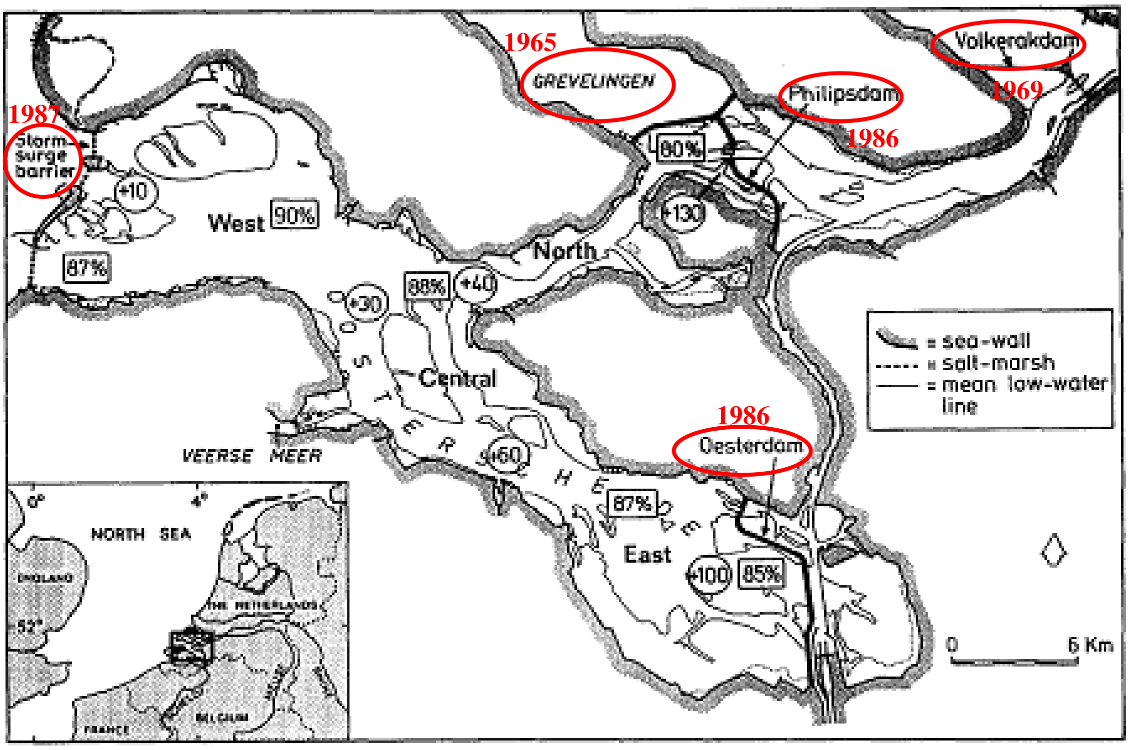


Figure 4.2. Hydrodynamic changes due to Delta Works: Number in square presents reduction of tidal range and number in circle illustrates increase of residence time (Source Vroon, 1994)

Changes in hydrodynamics of the ebb tidal delta Eastern Scheldt have interaction with each period of Delta Works Project. In 1965, since Grevelingen Dam was built on the natural tidal divide between the Eastern Scheldt and the Grevelingen, there had no change in the basin area. Thus it was no significant effect on tidal prism and hydrodynamics and morphology.

When the Volkerak Dam was finished in 1969, the water discharge from Rhine river was cut off from the Eastern Scheldt. Thus, the water motion in the Eastern Scheldt is dominated by tidal flow and the Eastern Scheldt is rather a tidal basin than estuary. Furthermore, due to the completion of Volkerak Dam, basin area increase from A = 3.51 108m^2 to A = 3.89 108m^2. It means that the tidal prism in the Eastern Scheldt increases.

From 1977 to 1986, hydrodynamics in the Eastern Scheldt had great changes due to combination effect of decreased basin area and reduction in cross sectional area. The construction of the Philips Dam and the Oester Dam resulted in decrease of basin area and the progressive reduction of cross sectional area at the inlet is caused by the storm surge barrier. These lead to decrease of tidal prism and sedimentation in the channels and erosion of shoals occur.

Since 1987, when the Storm Surge Barrier was completed, there have been remarkable reductions of tidal prism by 30%, the average tidal range by 12% and the average tidal current velocities by 33%.

4.2. Sediment volume

The change in sediment volume shows contrary trends before and after 1987. Before 1987, the sediment budget of the basin was negative while one in the ebb tidal delta was positive. In the period 1960-1989, the tidal basin lost a total of approximate 120 million m^3 of sediment, while the ebb tidal delta shows a net total deposition of 34 million m^3. The major source was presumably erosion of the Eastern Scheldt tidal basin. The negative trend in the sediment budgets of the ebb tidal delta during the implementation suggests a slight reduction in size of the ebb tidal delta. (Louters, 1998)

4.3. Morphological evolution of the ebb tidal delta

In order to analyse in detail the evolution of the ebb tidal delta, four sections in the area have been chosen as below.

- ✓ Section I is chosen at inlet of the Eastern Scheldt system, in this section the development of the scour holes and changes of the Hammen, Schaar van de Roggenplat and Oude Roompot changes of the Noordland and Neeltje Jans shoals will be considered.
- ✓ Section II, III will focus on migration of channels, chutes and shoals: the Hompels and Banjaard shoal at updrift and downdrift of the inlet.

✓ Section IV is chosen to study seaward extension of shoals and channels.

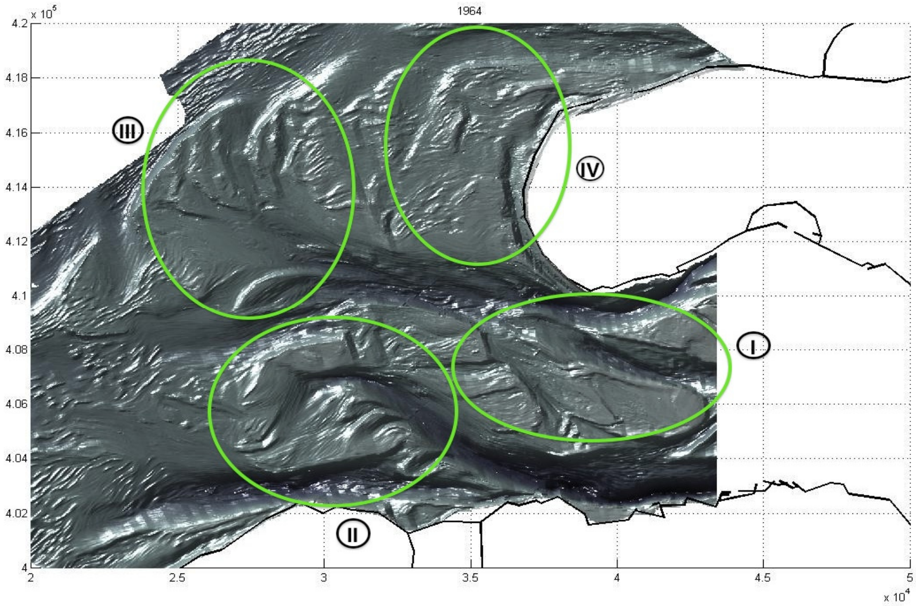


Figure 4.3. Divided sections of the Eastern Scheldt ebb tidal delta

4.3.1 Pre- intervention (Prior to 1964) - Natural developments

Originally the Eastern Scheldt had one major channel (the Hammen channel), which was narrow. During mediaeval times, storm incursions and flooding widened the estuary. Hence, the tidal prism must have increased by many hundreds of millions of cubic meters. (Van den Berg, 1986)

After 1600AD the increase of tidal discharge resulted in the development of a second major channel, the Roompot, leading to a coastal retreat of Noord-Beveland and a further widening of the mouth of the estuary. Most of the eroded sediment must have been transported to the sea and has contributed to the extension of the tidal delta. (Van den Berg, 1986)

During the 20th century, a third major channel has developed, the Schaar van Roggenplaat, which is running Northwest to South East between the Hammen and the Roompot. This channel has anticlockwise rotation.

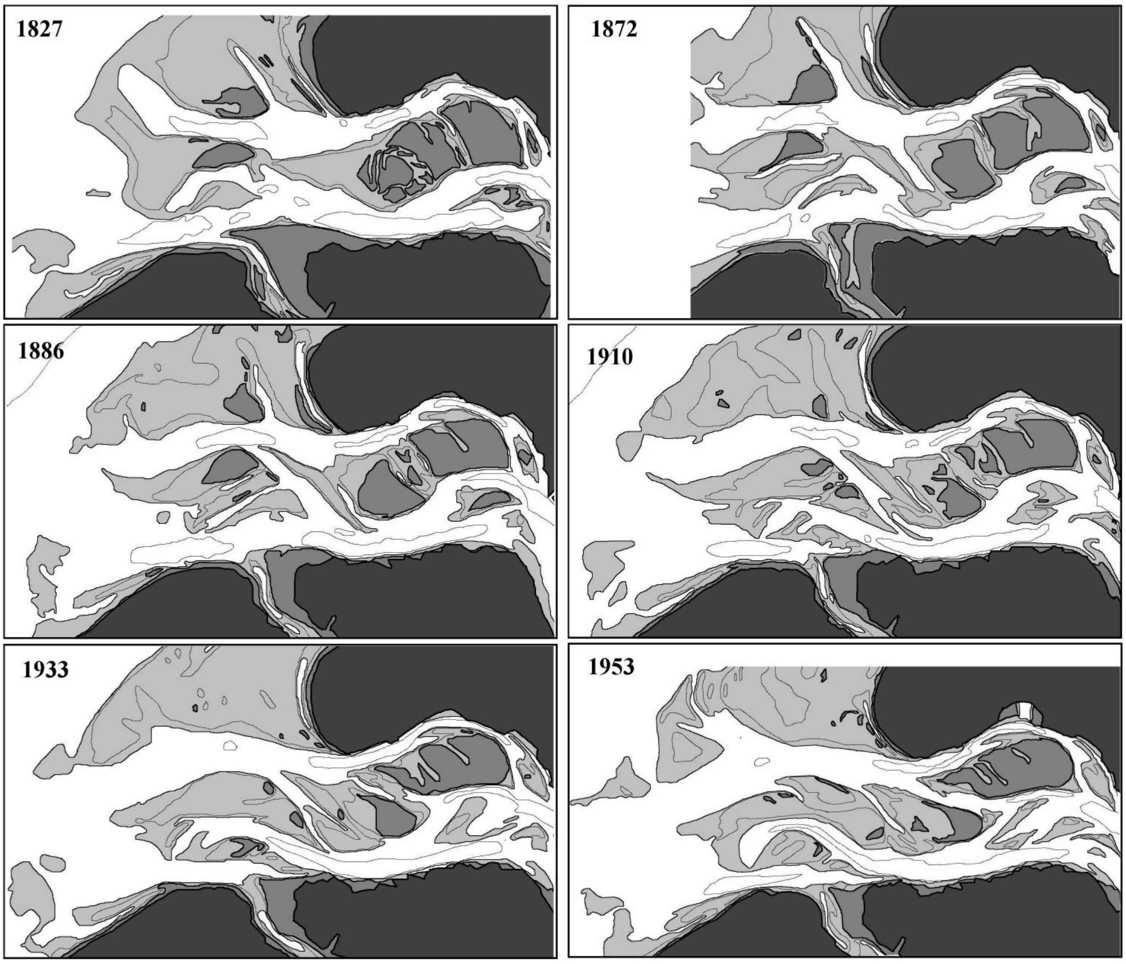


Figure 4.4. Evolution of the Eastern Scheldt ebb tidal delta from 1827 to 1953

(Source: Haring, 1978 and Eelkema, 2009)

From 1827 to 1960, the ebb tidal delta was shifted from a downdrift- oriented system (Northern side of inlet) to a more centrally oriented system and the cross sectional area tended to increase slightly. Over this period the tidal velocities through the inlet were larger than the equilibrium velocities. It led to the erosion and enlargement of the inlet. The larger velocities could have been caused by an increase in tidal prism which resulted from flooding in the basin.

In the period 1960-1964

Since 1960 some of the closures of the Delta Project have influenced on the tidal prism and other tidal characteristics in the Eastern Scheldt. Before the construction of Grevelingen Dam in 1962- 1964, a small part of the ebb discharge from the Krammer-Volkerak area passed through the Grevelingen inlet. But when the Grevelingen Dam was completed, these water masses were added to the tidal volume of the Eastern Scheldt. The tidal volume in the Eastern Scheldt, therefore, slight increased in this period (Van den Berg, 1986). However, there had less morphological changes in this period.

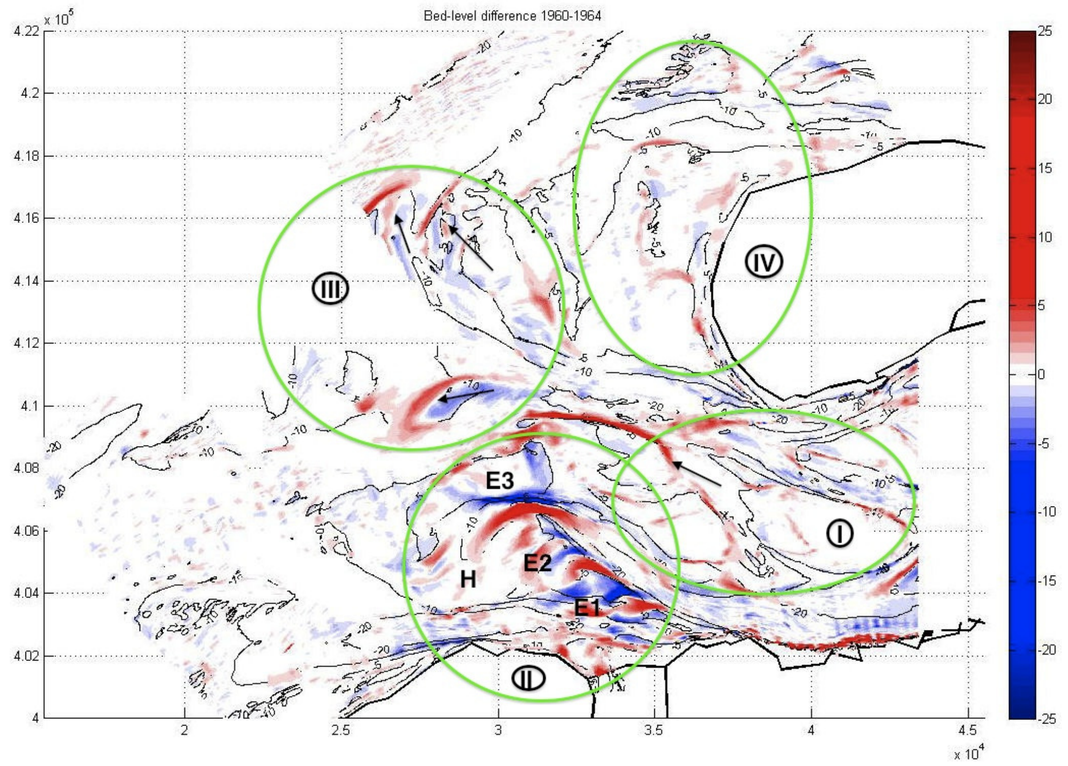


Figure 4.5. Bed level difference in the Eastern Scheldt between 1960 and 1964

- ✓ In section I and III, some shoals and channels had seaward migration.
- ✓ In section II, there was a presence of cyclic developments of ebb chutes (E1, E2, E3) on the shoal at the updrift (Southern side) of the inlet. This cyclic behavior was more distinct than the situation in 1953 (Figure 4.4). This could be caused by the increase of tidal volume.
- ✓ In the section IV, no clear morphological activity could have been found.

4.3.2. During intervention (1964 -1986) - Increased tidal prism

The sedimentation surplus of the ebb tidal delta over the 1960-1980 period, resulted in a seaward expansion of the delta front. General eroding and expanding ebb channels in the delta occur during this period.

The ebb channels of Westgat and Oude Roompot have expanded rapidly towards the sea. The tidal delta front displays a similar seaward expansion which is spectacular in the northwest where protruding terminal lobes of ebb shields form part of it.

The seaward expansion of the Oude Roompot channel is predominantly achieved by channel bend erosion in the westernmost part of the channel. The fast erosion by the ebb current of the outer bend is compensated by deposition in the inner bend. The sill between the Oude Roompot and Westgat channels is eroded by currents that cross the bar caused mainly by the ebb current. As a result, the Oude Roompot and Westgat channel have been connected since 1972.

In the period 1964-1968

The Grevelingen Dam built in 1965 on the Northern side of the inlet has caused a increase of tidal volume. It means tidal channels in the ebb tidal delta become deeper and wider to adapt to the new tidal volume. In contrast, tidal shoals are built up due to increase of net sediment flux.

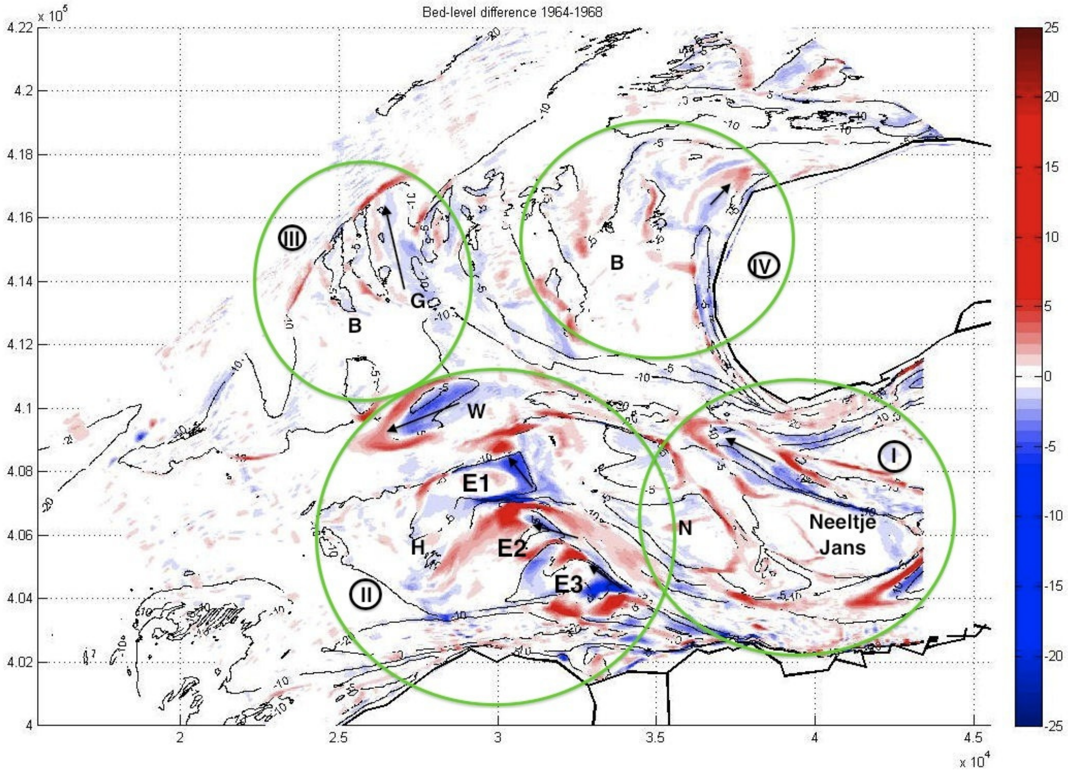


Figure 4.6. Bed level difference in the Eastern Scheldt between 1964 and 1968

✓ In section I
Sedimentation occured on the tidal shoals in and outside of the inlet (the Neeltje Jans and the Noordland (N)). The Schaar van de Roggenplaat eroded and part of the sediment was transported to the sea.

✓ In section II
Most of ebb chutes and tidal channels in the ebb tidal delta were eroded and had seaward migration. The cyclic behavior has still developed (E1, E2, and E3). Sedimentation started at the Hompels shoal (H).

✓ In section III

Slightly increase in sediment volume of the Banjaard shoal (B) and the Geul van de Banjaard channel (G) was shifted toward the sea.

- ✓ In section IV

  Small deposited sediment was remarked at the Banjaard shoal. The northward extension of the Krabbengat channel occurs.

In the period 1968-1972

The completion of the Volkerak Dam caused an increase of the Eastern Scheldt area. It resulted in an increase in tidal volume. Then the increased tidal volume causes erosion on the channels and sedimentation on the tidal shoals. This sedimentation will result in the decrease of the tidal prism. In term of outer delta, the sand volume increases as the tidal volume increases.

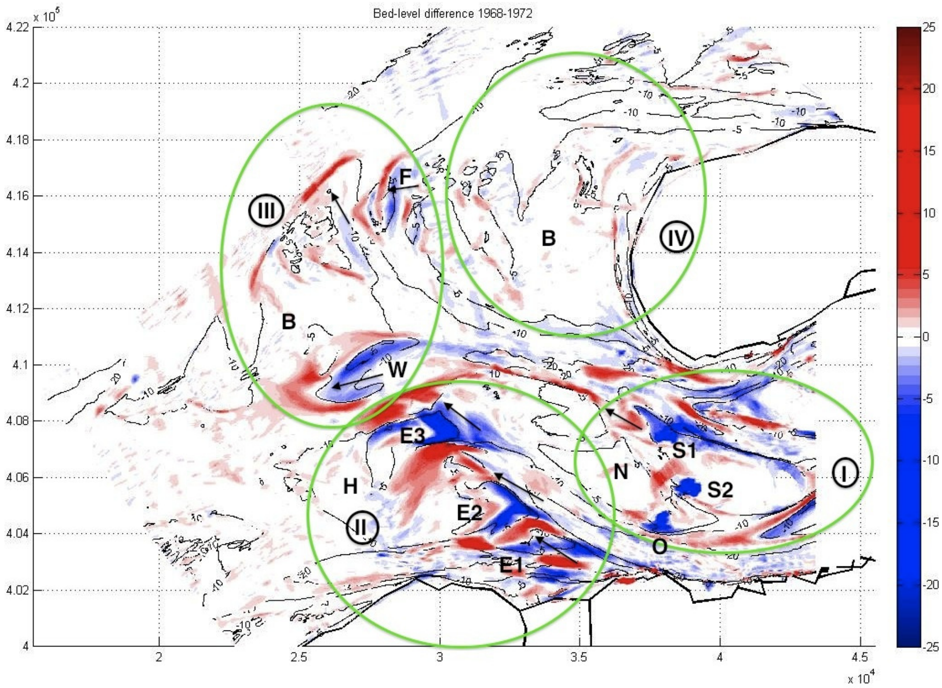


Figure 4.7. Bed level difference in the Eastern Scheldt between 1968 and 1972

- ✓ In section I

  Near the entrance, there has been a remarkable erosion of the Schaar van de Roggenplaat (S) tidal channel and smaller erosion of the Hammen channel. The eroded sediment was transported toward the sea and caused infilling in the outer end of these two channels. There was start of barrier construction (from 1967) so the erosion holes in the Oude Roompot (O) and in the Schaar van de Roggenplaat channel (S1, S2) near the construction area could be seen.

- ✓ In section II

  Due to increase in tidal prism, the stronger cyclic development of ebb tidal chutes (E1, 2, 3) on the Hompels shoal has been found. Seaward migrations occur in these tidal channels. Especially, the excessive seaward migration of the Oude Roompot resulted in its breakthrough towards of the Wesgat in 1972.

  The sediment eroded from the channels Roompot (R) and Westgat (W) contributed significantly to building up of the Hompels (H) shoal and the Banjaard (B) shoal respectively.

- ✓ In section III

  The Banjaard shoal (B) was expanded seaward.

  New flood chute (F) was formed near the Banjaard shoal. This flood chute also was eroded and migrated seaward.

- ✓ In section IV

  There was no active morphological change. Small landward accretion in the part near to the shoreline of the Banjaard shoal occured. Besides, slight erosion in the outer end of the Krabbengat channel was found.

In the period 1972-1976

No significant changes due to the Delta Works have been found. But the gradual increase of tidal volume in the previous period still influenced on morphologic activities of the ebb tidal delta. Tidal channels kept widening and deepening and the tidal shoals had vertical accretion and seaward migration.

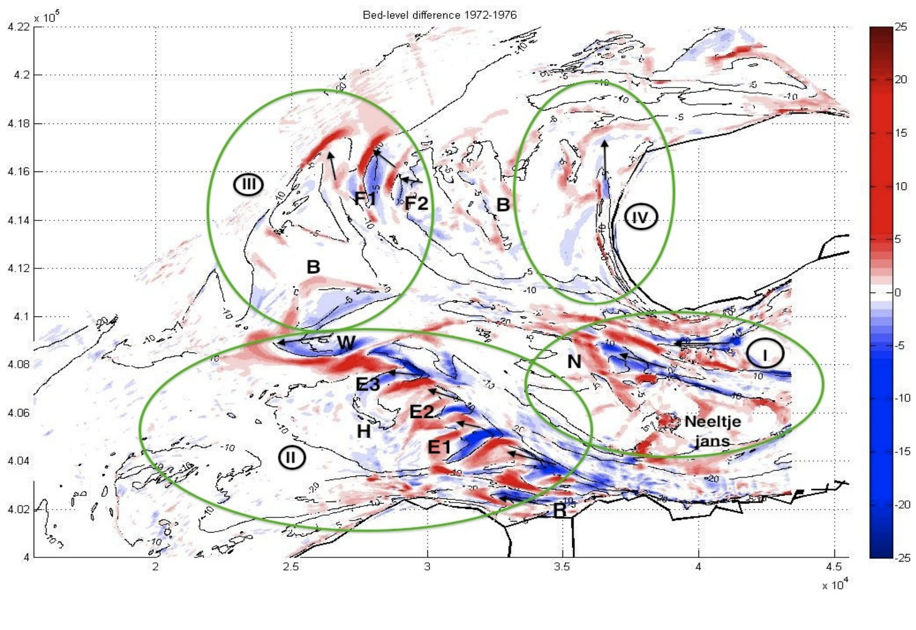


Figure 4.8. Bed level difference in the Eastern Scheldt between 1972 and 1976

- ✓ In section I
  The Hammen and the Schaar van de Roggenplaat tidal channels remained eroding and the sediment was used to build up the shoals near by such as the Noordland shoal (N) in the ebb tidal delta and the Neeltje Jans intertidal shoal inside the basin.

- ✓ In section II
  The Hompels shoal (H) had more accretion in this period thanks to extensive erosion of the ebb chutes. The cyclic behavior could be seen obviously. Moreover, the Roompot channel (R) still contributed sediment for building this shoal because of erosion in the channel.
  Further southern migration of the Westgat channel (W)

- ✓ In section III
  Another flood chute (F2) was created near the previous flood chute (F1) and the sediment taken from two of them, was transported toward the sea.

  On the Banjaard shoal, the southern part was accreted by sediment from the Westgat channel (W). Meanwhile the northern part of this shoal was built up by sediment taken from the Geul van de Banjaard channel.

- ✓ In section IV
  Sediment from the Krabbengat channel was brought further to the North and the result is a contribution to sedimentation of channel near the Grevelingen inlet.

A decreasing tidal volume between 1977 and 1986

Completion of the Oester Dam and the Philips Dam from 1977 to 1986 caused a decrease in basin area because they isolated two parts of the former Eastern Scheldt basin. It leads to decrease in tidal range in sections behind these dams. Completion of storm surge barrier in 1986 caused a dramatic decrease in the cross section area. It means tidal range decreases firstly then tidal volume and tidal prism also decrease.

In the period 1976-1980

In this period, tidal volume decreased gradually due to closure of the channel Geul and activities of Delta works Project. However it still remained higher level compared to the tidal volume in 1960 when there was no influence of Delta Works to the tidal basin. As a result, erosion in the tidal channel and sedimentation at the tidal shoals were continuing but at smaller rate and then reverse trend could happen as tidal volume has further decrease.

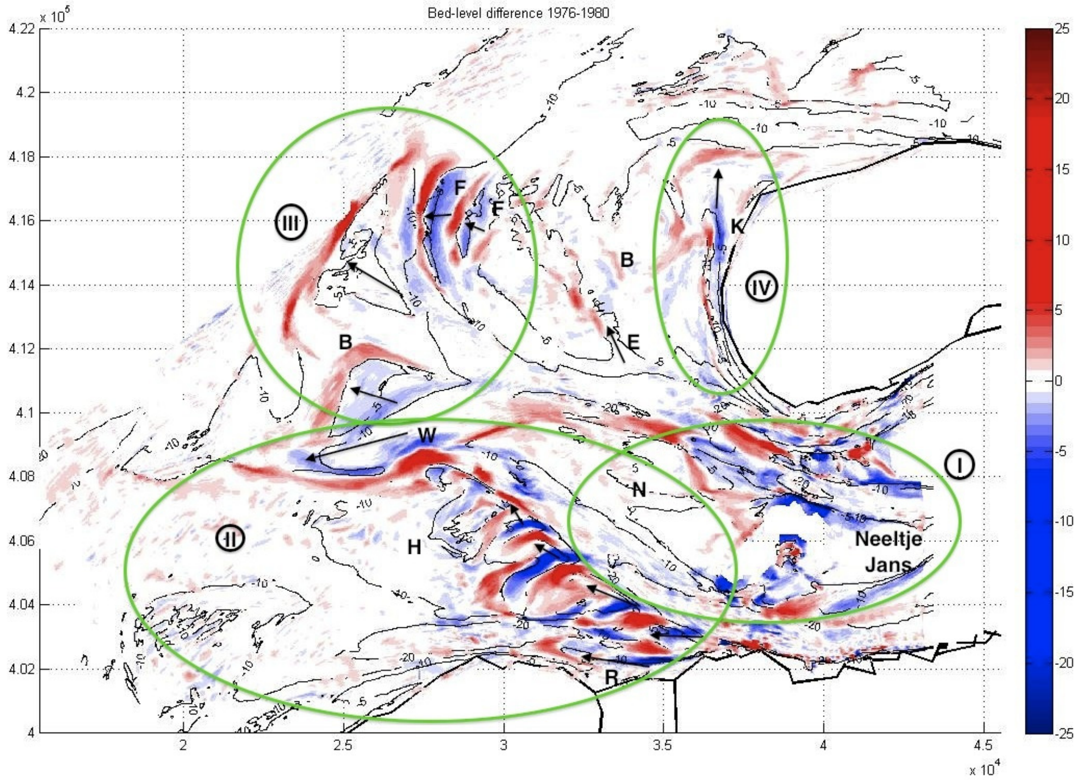


Figure 4.9. Bed level difference in the Eastern Scheldt between 1976 and 1980

✓ In section I

There was further influence of the storm surge barrier to morphology in the Eastern Scheldt. More erosion in the areas near the construction, no more accretion on the Neeltje Jans shoal and less sediment was brought to the Noordland shoal (N) outside the basin.

✓ In section II

The ebb chutes and the Roompot channel still were eroded and migrated toward the sea. The Westgat channel (W) continued the southern migration, however, the sediment eroded from this channel was still used to maintain the Banjaard shoal (B)

✓ In section III

Both sides of the Banjaard shoal (northern and southern side) kept accretion and migration further to the seaward.

The two flood chutes remained and migrated toward the sea.

✓ In section IV

The Krabbengat channel (K) was shifted further to the North. New ebb chute (E) was created at the Banjaard shoal. This ebb chute was formed from the tidal channel Geul van de Banjaard which flows near the shoal.

In the period 1980-1984

The tidal volume decreased rapidly because of placement of piers and gates in the inlet and the storm surge barrier was completed.

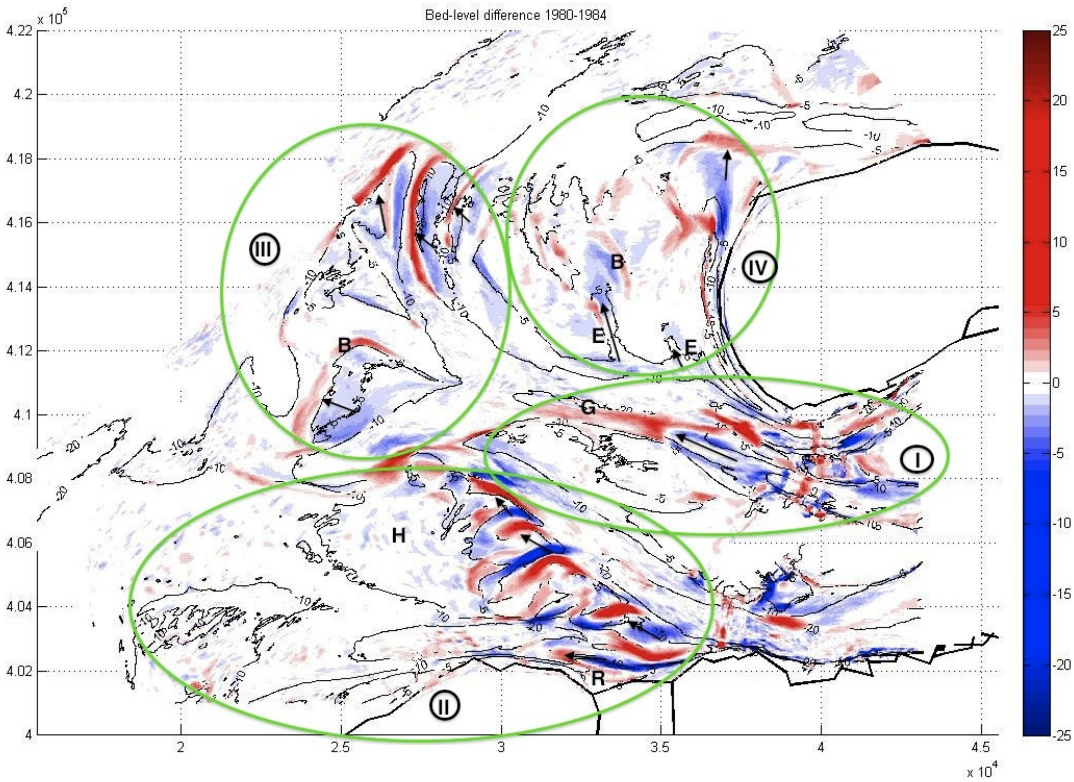


Figure 4.10. Bed level difference in the Eastern Scheldt between 1980 and 1984

- ✓ In section I

  Reduction of maximum depth in tidal channels and the Geul van de Banjaard (G) channel had sedimentation. The Geul van de Banjaard (G) channel slightly migrated toward the North.

- ✓ In section II

  Ebb chutes at the Hompels shoal (H) decreased erosion and less sediment were transported away.

- ✓ In section III

  The Banjaard shoal kept shifting toward the sea.

- ✓ In section IV
  The new created ebb chute (E) at the Banjaard shoal was developed and shifted to the north whereas another ebb chute was formed near to the previous one.
  The northward extension of the Krabbengat channel and the shoal still occur.

4.3.3 Post- intervention (1986 to present) - Decreased tidal prism

After completion of the Storm Surge barrier in 1987, tidal prism decreased rapidly by 30% and then remained stable in recent decades. This tidal prism is much smaller compared to one before implementation of the Eastern Scheldt Project. The ebb tidal delta becomes too large to the tidal prism. The ebb tidal delta therefore has eroded and will continue to erode until a equilibrium is reached. Recently, slow morphological activities indicates that basin tend toward a large-scale equilibrium.

There are some abandoned tidal channels in the northern part of the basin (section IV). On the former ebb tidal deltas of Haringvliet and Grevelingen some tidal channels have lost most of their tidal volume due to the closure of these inlets. After the closures, their tidal channels were filled with fine sediment.

The landward migration of the ebb tidal delta shoals and northward migration of major tidal channels in the Eastern Scheldt has noticed after closure of the inlet. There are depositions in tidal channels and erosion of the scour hole near the entrances of the storm surge barrier.

In the period 1984-1988

Since 1986, tidal prism decreases and shoals have shown distinct vertical erosion while rate of sediment supply from the basin has slowed. The net sediment flux thus has reversed and an erosive trend of shoals has begun.

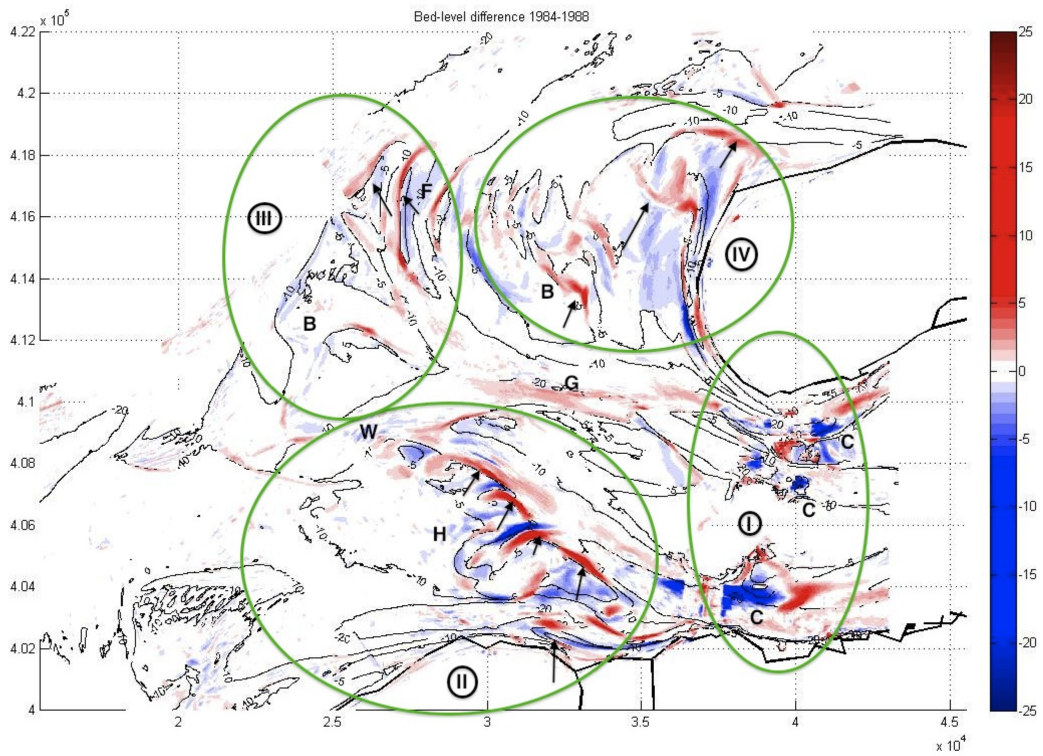


Figure 4.11. Bed level difference in the Eastern Scheldt between 1984 and 1988

- ✓ In section I

  Deep scoure holes (C) have developed in the tidal channels near the entrance of the inlet named the Hammen, Schaar van de Roggenplaat and Oude Roompot. In contrast, the Geul van de Banjaard channel was shoaling.

- ✓ In section II

  The cyclic behavior has ceased, the seaward migration of ebb chutes has gone. The sediment from the ebb chutes and tidal channels at the Hompels shoal (H) now tend to northward extension. This may result from stronger influence of wave (coming from Southwest direction) as tide force has decreased due to the decrease of tidal volume. The Hompels shoal (H) no longer is built up by sediment from channels and erosion even occurred on some part of the shoal.

- ✓ In section III

  The Banjaard shoal (B) has stopped accreting, small erosion even occurred at the seaward side of the shoal. However, at northern part of the shoal remained seaward extension. Besides, the flood chute (F) flowed through the shoal and cut away a small part of the Banjaard shoal.

- ✓ In section IV

  The Krabbengat channel tended to shift to the northward. The northward extension of the Krabbengat channel during this period was more active than the previous periods. This could be explained that the channel reached too close to channel at Grevelingen inlet and it became easier to fill up the channel.

  The Banjaard shoal (B) shifted to the landward.

In the period 1988-1992

Since 1988, the tidal volume of the Eastern Scheldt basin remains the same. Besides, the hydrodynamics has no many changes leading to less morphological changes. Slow morphological activities shown since 1988 indicate that the ebb tidal delta is tending to a new equilibrium. However, the ebb tidal delta is still far from equilibrium because the lack of morphodynamics comes from the decrease in flow and the cutting of the sediment supply from the basin.

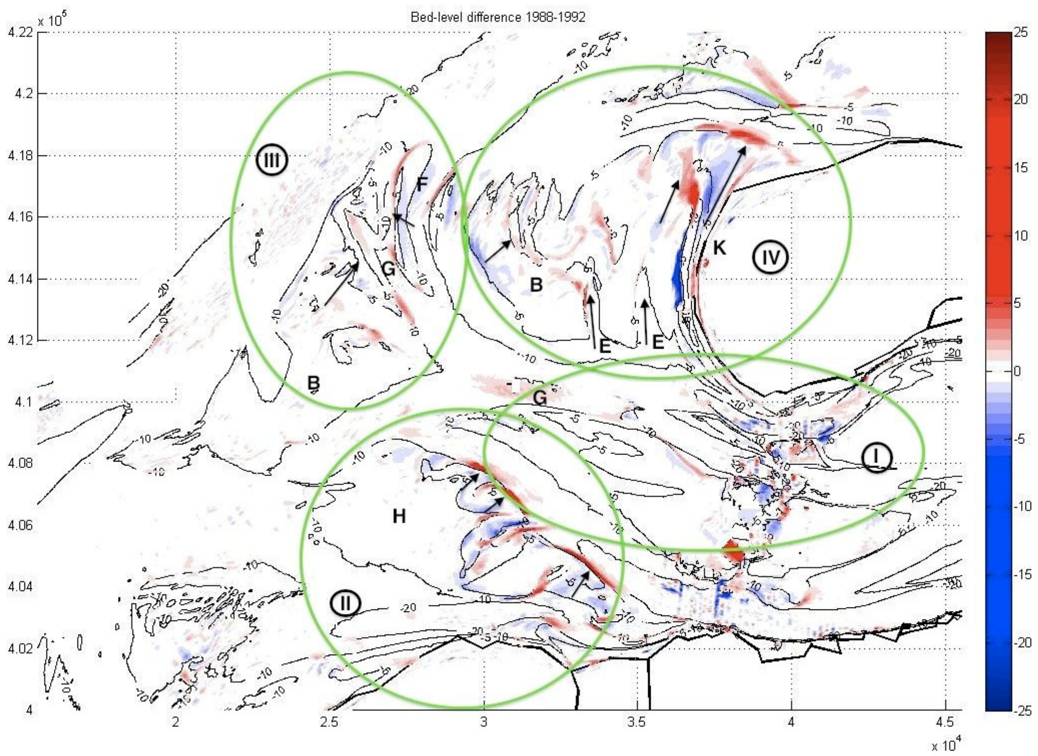


Figure 4.12. Bed level difference in the Eastern Scheldt between 1988 and 1992

- ✓ In section I

  There were no significant changes in morphology in this period. The Geul van de Banjaard (G) was shoaling along the Noordland shoal.

- ✓ In section II

  The Hompels shoal (H) was eroding; it leads to a degrading of the shoal. This eroded sediment was transported to the north due to wave force.

- ✓ In section III

  Decrease in depth of the flood chute (F) however small amount of sediment remained transport to the sea. Thus, the flood chute still had seaward migration.

  The Banjaard shoal (B) has stopped seaward extension and begun shifting to the landward.

- ✓ In section IV

  The erosion of the southern side of the Banjaard shoal (B) occurred. Furthermore, the active development of two ebb chutes at the tidal shoal Banjaard indicated the continuing erosion of the shoal. These ebb chutes were directed further to the North.

  The northward migration of the tidal channel Krabbengat kept causing sedimentation in the channel near the Grevelingen inlet.

  The Banjaard shoal has a gradual landward shift. The erosion of the southern part of the shoal occurred while the sediment was deposited in the northern side of the shoal. It is resulted from waves pushing the bed form eastward.

In the period 1992-1996

Major changes of hydrodynamics and morphology of the ebb tidal delta in the previous period was continuing from 1992 to 2004. The degrading of the Banjaard and Hompels shoals could be seen more evident by time. Most of channels are shoaling resulting a remarkable reduction of their maximum depths.

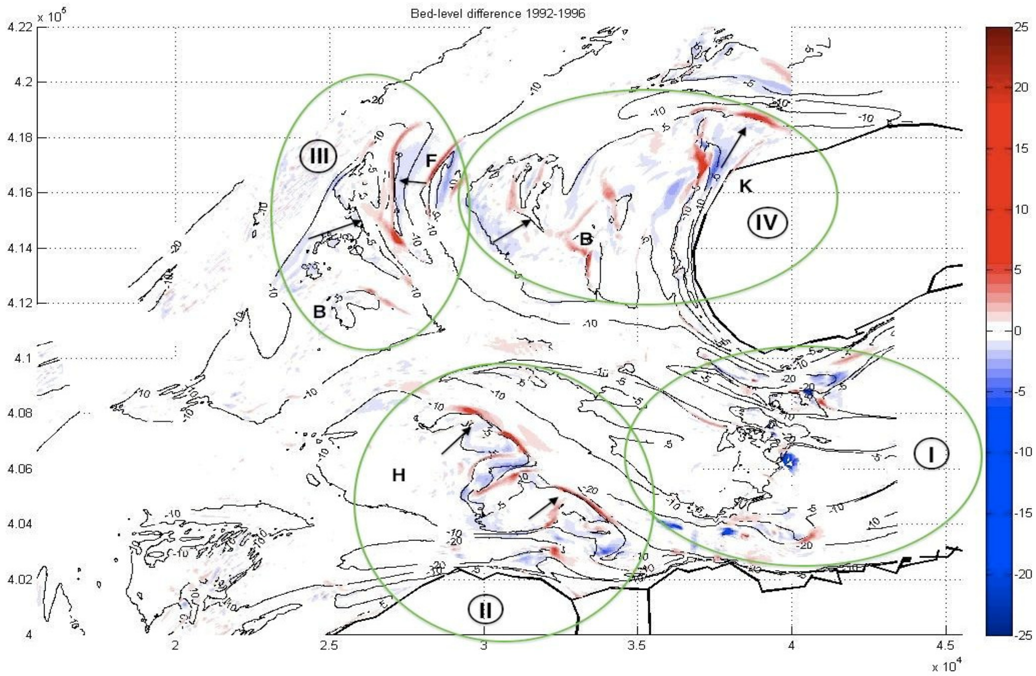


Figure 4.13. Bed level difference in the Eastern Scheldt between 1992 and 1996

In the period 1996-2000

From 1992 to 2000, when morphological activities in 3 sections: I, II and IV has decreased due to the decrease of tidal volume, the morphological changes in section II even increased. There has been an increase in erosion of the Banjaard shoal. This could be resulted from exponential relation of sediment transport and tidal current. As mentioned in previous chapter, decrease of tidal current will lead to exponential decrease of sediment transport. Thus, when tidal volume (tidal current) decreased, morphological changes will have to take a longer time to adapt the change in hydraulic condition. It means that the increase activities to find a equilibrium in the section III (1992-2000) was a respond to the decrease of tidal volume in previous periods. Moreover, no sediment supply from basin also accelerated the shoal erosion.

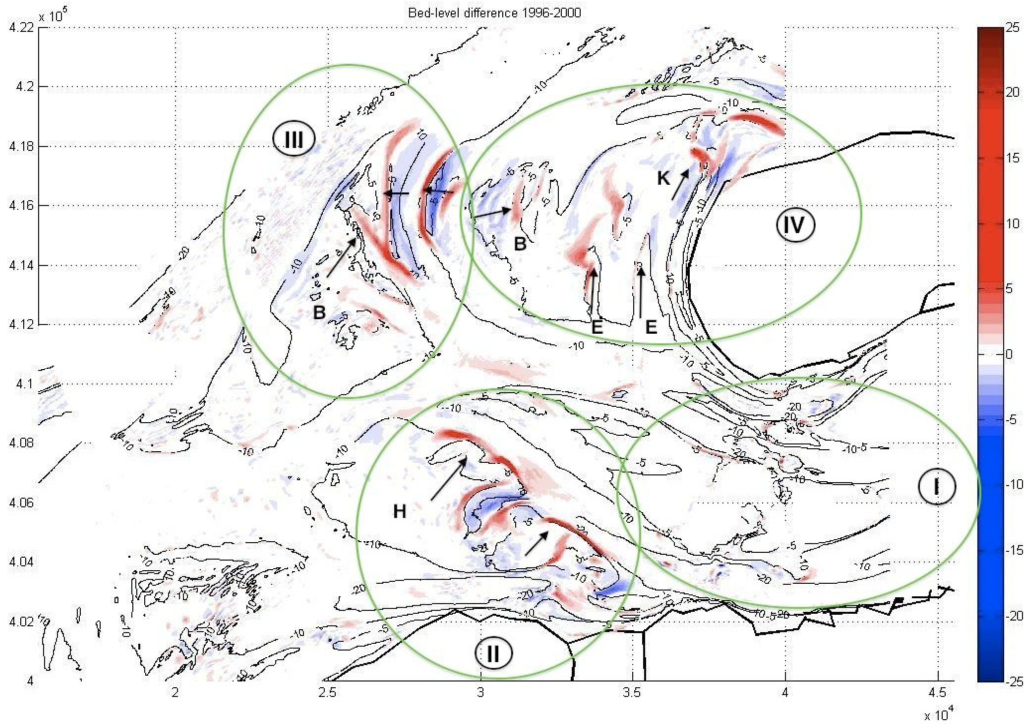


Figure 4.14. Bed level difference in the Eastern Scheldt between 1996 and 2000

In the period 2000-2004

No noticeable changes in morphology could be found in this period. The slow morphologic activities show the Eastern Scheldt is now tending to a new equilibrium. But as discussed, it is still far from the equilibrium.

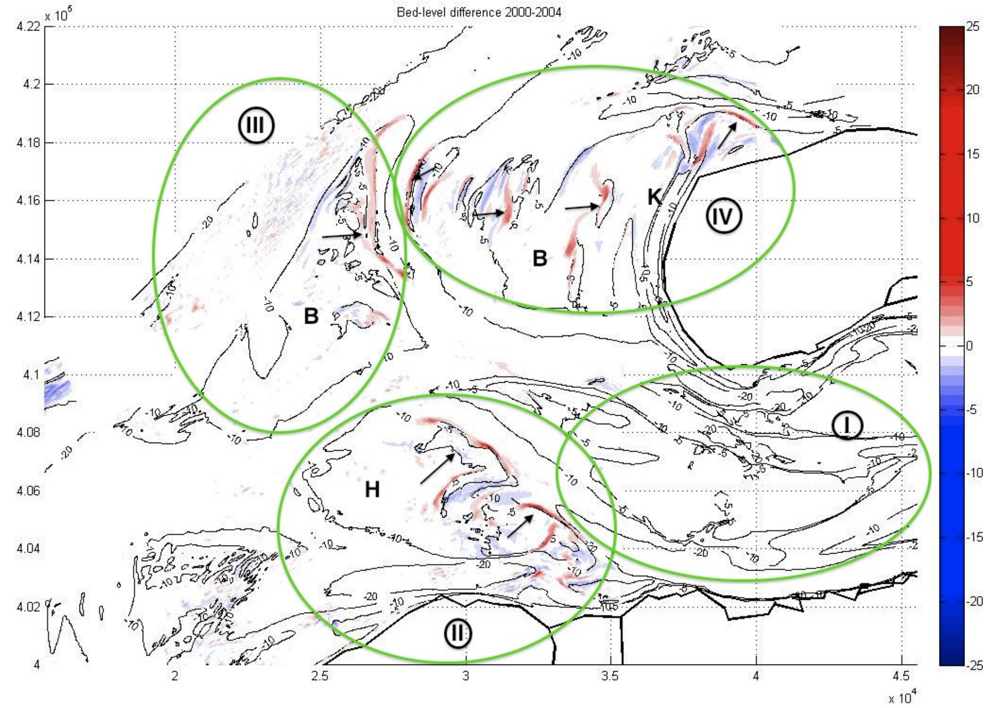


Figure 4.15. Bed level difference in the Eastern Scheldt between 2000 and 2004

Chapter 5. Synthesis

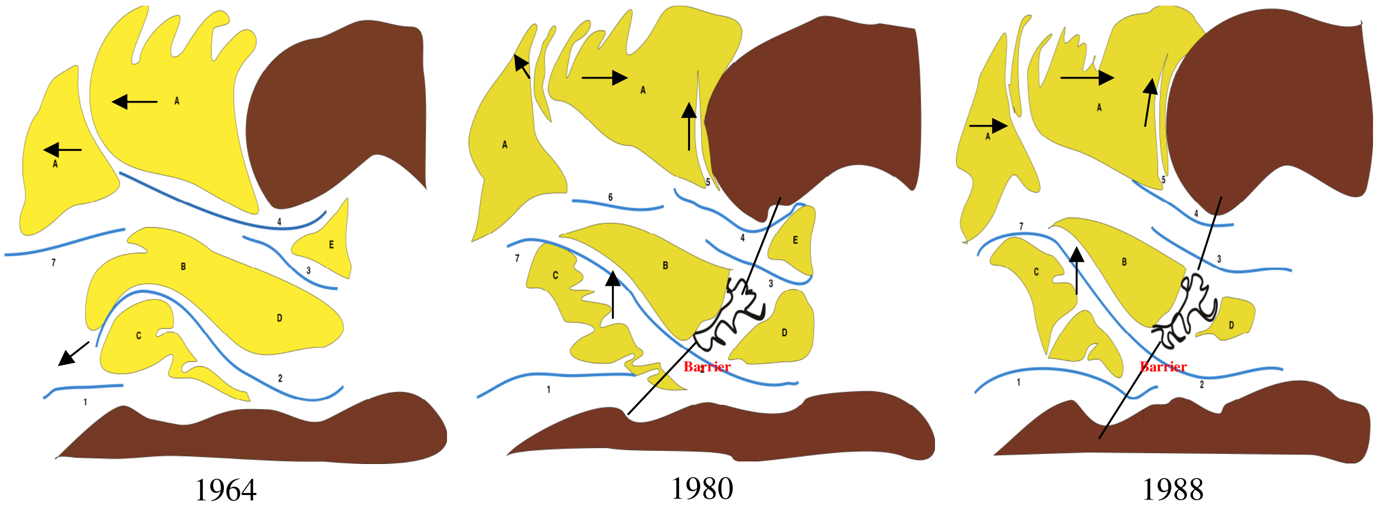


Figure 5.1. Development of the ebb tidal delta in representative year for before, during and after the implementation of the Eastern Scheldt Project

Shoals:

A. Banjaard
B. Hompels
C. Noorland
D. Neetltje Jans
E. Roggenplaat

Channels:

1. Roompot
2. Oude Roompot
3. Schaar van de Roggenplat
4. Hammen
5. Krabbengat
6. Geul van de Banjaard
7. Westgat

Pre- intervention (Prior to 1964) - Natural developments

From 1827 to 1960, the ebb tidal delta shifted from a downdrift- oriented system (Northern side of inlet) to a more centrally oriented system and the cross sectional area tended to increase slightly. Over this period the tidal velocities through the inlet were larger than the equilibrium velocities. It led to the erosion and enlargement of the inlet. The larger velocities could have been caused by an increase in tidal prism which resulted from flooding in the basin. There was a presence of cyclic developments of ebb chutes on the shoal at the updrift (Southern side) of the inlet during the period 1960-1984.

During intervention (1964 -1986) - Increased tidal prism

In this period, the Delta Works in the Eastern Scheldt have been completed comprising Grevelingen Dam (1965), Volkerak Dam (1969), Philips Dam (1986), Oester Dam (1986), and Storm Surge Barrier (1986). These structures have numerous effects to hydraulic conditions and morphology of the Eastern Scheldt ebb tidal delta.

In the 1965-1977 period, the tidal prism and tidal current velocities have increased significantly due to the completion of Grevelingen Dam and Volkerak Dam. It means that there was an increase of sediment transport from the basin to the sea. The sedimentation surplus of the ebb tidal delta resulted in a seaward expansion of the delta front. In addition, there has been a significant deepening of channels and creation of new channels due to the increase of tidal prism. The channels are also oriented toward to the sea and to the north.

From 1977 to 1986, there was a decrease in tidal prism due to completion of the Philips Dam, the Oester dam and the Storm Surge barrier in 1986. These structures resulted in decrease of basin area and of cross section area. However, until 1980 the tidal prism was still larger than the one measured in 1960 when Delta Works in the Eastern Scheldt had not been constructed yet. Consequently, there was continuing erosion in the channels and sedimentation on the shoals but these activities occurred in the smaller rate in comparison with the previous period. The cyclic behaviors of the ebb chutes on the southern shoal of the inlet still remained and kept migrating seaward.

Since 1984 after the placement of the piers and gates in the inlet, the tidal prism has decreased rapidly and these values were much lower compared to ones in 1960. In response to this change, the channels began to demand sediment whilst the shoals were eroded.

Post- intervention (1986 to present) - Decreased tidal prism
After completion of the Storm Surge barrier in 1987, the tidal prism decreases rapidly by 30% and then remains at this stable level. In general, the dynamic conditions decreases. As a result, the shoals are showing distinct vertical erosion while there is no longer sediment supply from the basin to its ebb tidal delta due to the closure of the inlet. Development of scour holes near the entrance of inlet is observed. In contrast, sediment is now tending to be deposited in the channels and the channels tend to seaward migration. The shoal on the northern part of inlet tends to landward migration whereas the cyclic developments of ebb chutes on the southern shoal has been stopped and now starts to migrate to the Northward.

In summary, morphology of the Eastern Scheldt ebb tidal delta had enormous changes due to Delta Project. These changes comprise shoaling and reorientation of channels- from updrift to downdrift (northward) migration of channels (Fig. A.1-A.5-Appendix); landward migration of shoals (Fig.A.7-Appendix); development and diminishing of ebb and flood chutes; and development of scour holes near to the entrance of the storm surge barrier (Fig.A.6-Appendix).

The ebb tidal delta would take a long time (centuries) to establish a new dynamic equilibrium between hydraulic conditions and geomorphology in the Eastern Scheldt inlet because the lack of morphodynamics comes from the decrease in flow and the cutting of the sediment supply from the basin.

Chapter 6. Conclusions and recommendations

The objective of this study is to determine the morphological developments of the ebb tidal delta before, during and after the implementation of the Storm Surge Barrier in the Eastern Scheldt. This research objective is fulfilled by combination of understanding in coastal processes that affect morphological characteristics and using bathymetry maps of the Eastern Scheldt in every four years (from 1960 to 2004).

In order to analyse in detail the consequences of the storm surge barrier and structures within the basin, the development of Eastern Scheldt ebb tidal delta has been divided into 3 periods:

- ✓ *The first period*: Pre- intervention (Prior to 1964) - Natural developments
- ✓ *The second period*: During intervention (1964 -1986) - Increased tidal prism
- ✓ *The third period*: Post- intervention (1986 to present) - Decreased tidal prism

As a result, main conclusions of this research study are presented below.

The construction of the storm-surge barrier diminished the cross sectional area of the channels and caused remarkable reductions of tidal prism by 30%, the average tidal range by 12% and the average tidal current velocities by 33%. Consequently, sediment export from the basin towards its ebb tidal delta has ceased and the scour holes were created near the entrance. It leads to significant changes in morphology of the ebb tidal delta. Meanwhile, the barrier causes a decrease of bed relief inside the basin and also leads to a decrease of marshland and mudflats bordering the basin. The loss of intertidal areas also has negative effects for recreation and shellfish fishers. The siltation of the channels causes less water depth for the navigation.

The morphological development of the Eastern Scheldt tidal system has been influenced dominantly by human interventions. In former times (1960-1976), due to increase in tidal volume, the morphology of system responded by a general erosion of the channels (deepening and widening) and expansion as well as vertical accretion of the ebb tidal delta. However, since 1987 the completion of storm surge barrier has caused a reversed trend to the Eastern Scheldt system due to the decrease of tidal volume by 30%. Thus, there has been sedimentation in channels and degrading of tidal shoals.

The implementation of Delta Project in the Eastern Scheldt has also caused change in relative forces of tide and wave. As the decrease of tidal volume leads a decrease of tidal current force that extended the ebb tidal delta, waves then have more influence. As a consequence, it leads to reorientation of channels (from updrift to downdrift) and erosion on shoals (wave energy dissipation near the edges of the shoals).

Slow morphological activities shown in the recent decades illustrate that the system is now tending to a new equilibrium. However, the Eastern Scheldt system needs by 400

Mm^3 of sediment to meet a requirement of equilibrium state, the tidal currents have decreased and there is no more sediment supply from the basin. Therefore, the Eastern Scheldt ebb tidal delta will take several centuries to reach a new equilibrium.

Recommendations

It is difficult to explain the influences of natural process due to lack of sufficient quantitative measurements in the Eastern Scheldt before 1960. Sea level rise should be considered as a factor that affects morphology of the ebb tidal delta. Further research on the processes controlling the formation of shoals in the Eastern Scheldt is needed.

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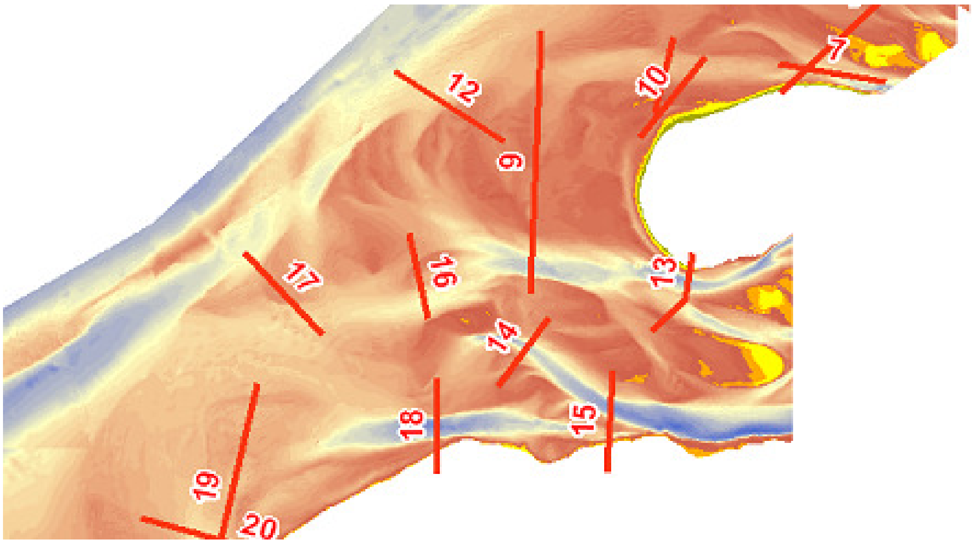
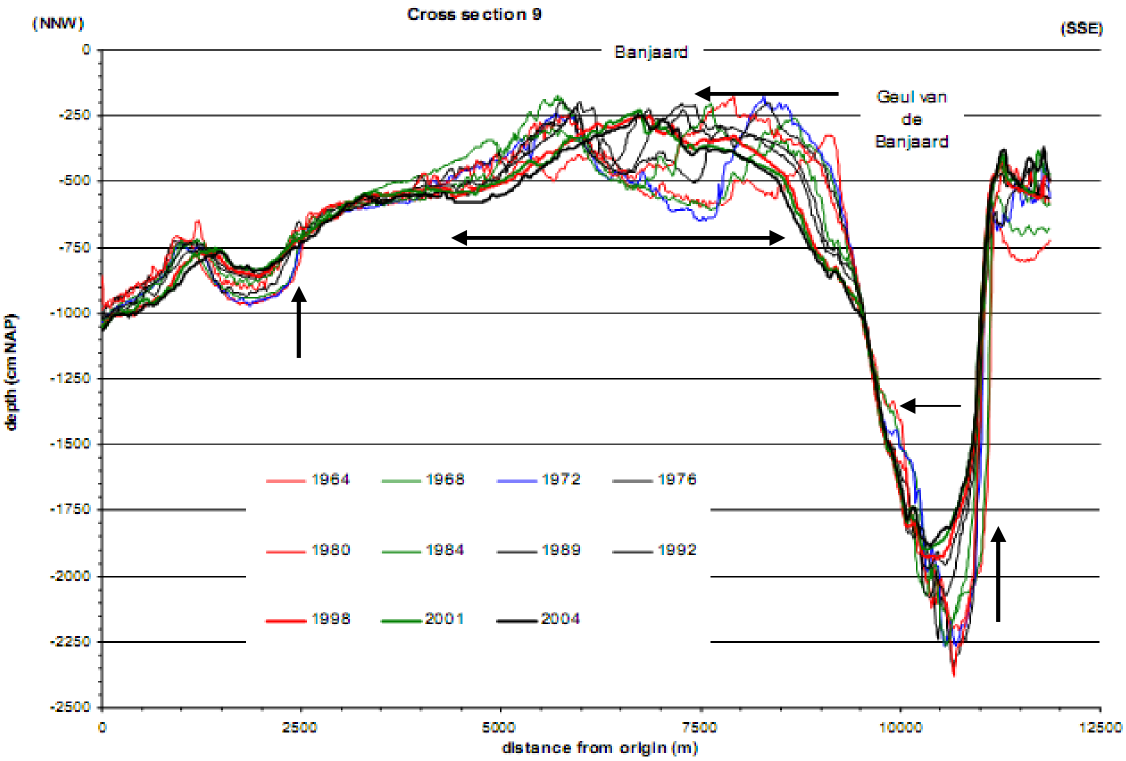
Appendix

This section is based on the research results of (Celveringa, 2008). It is summary of changes in cross section of tidal channels and shoals are defined in the period from 1964 to 2004.



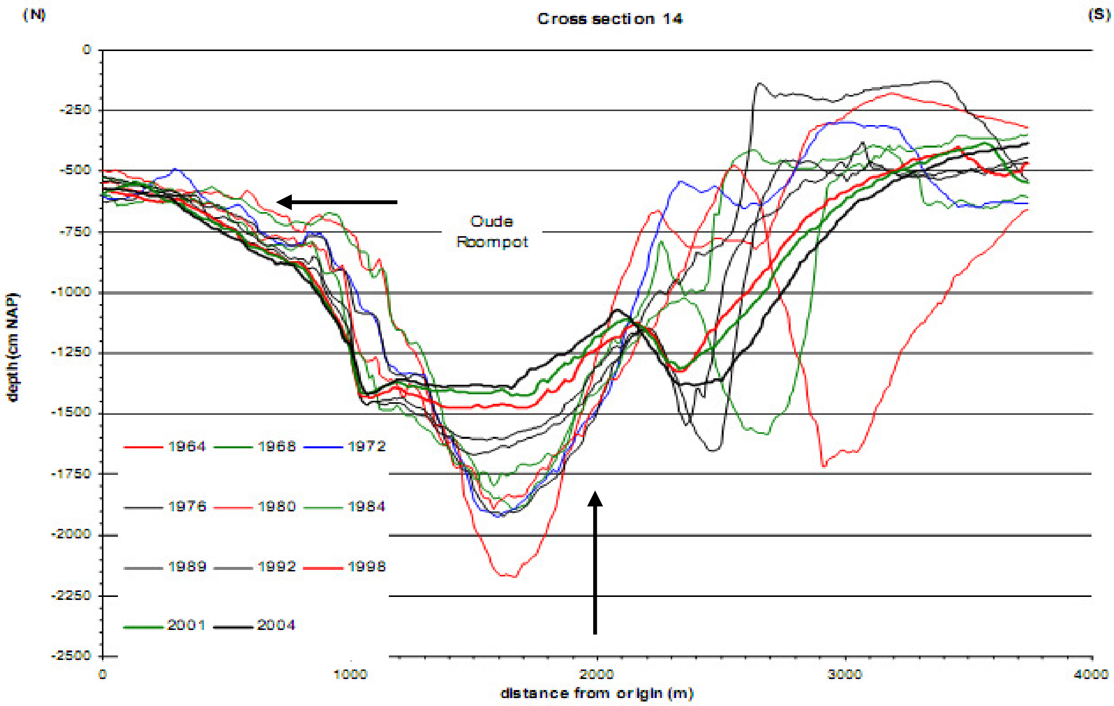
FigureA. 1. Location of observed cross sections

a) Shoaling and northward migration of the tidal channels Geul van de Banjaard, Oude Roompot, Westgat and Roompot.

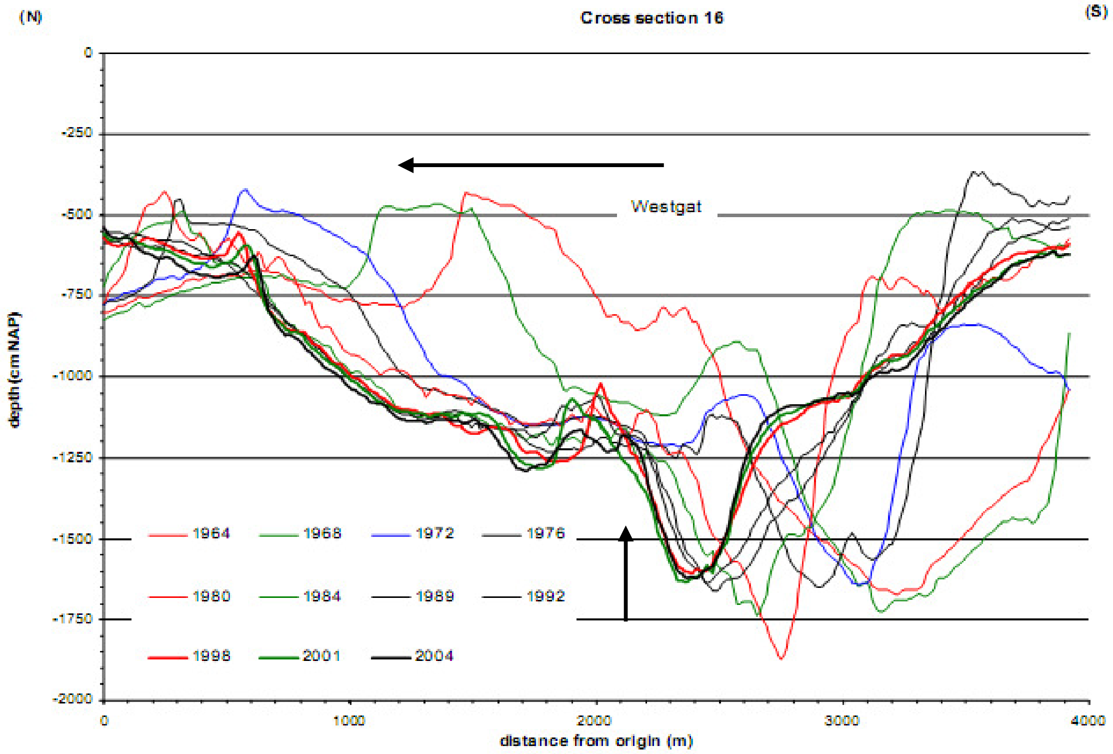


FigureA. 2. In the tidal channel Geul van de Banjaard (Cross section 9)

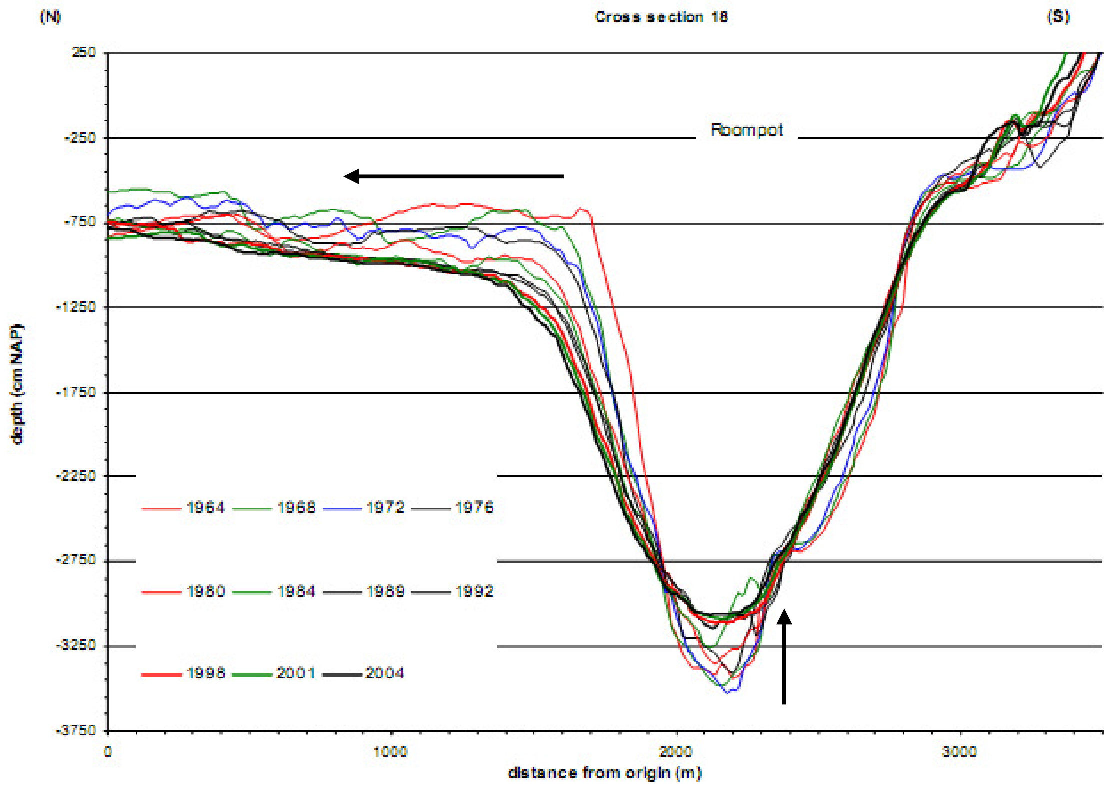
The maximum depth of all and cross sectional area of most tidal channels has decreased from 1964 – 2004. The channels and shoal tend to the North. The shoal area greatly reduces.



FigureA. 3. In the tidal channel Oude Roompot (Cross section 14)

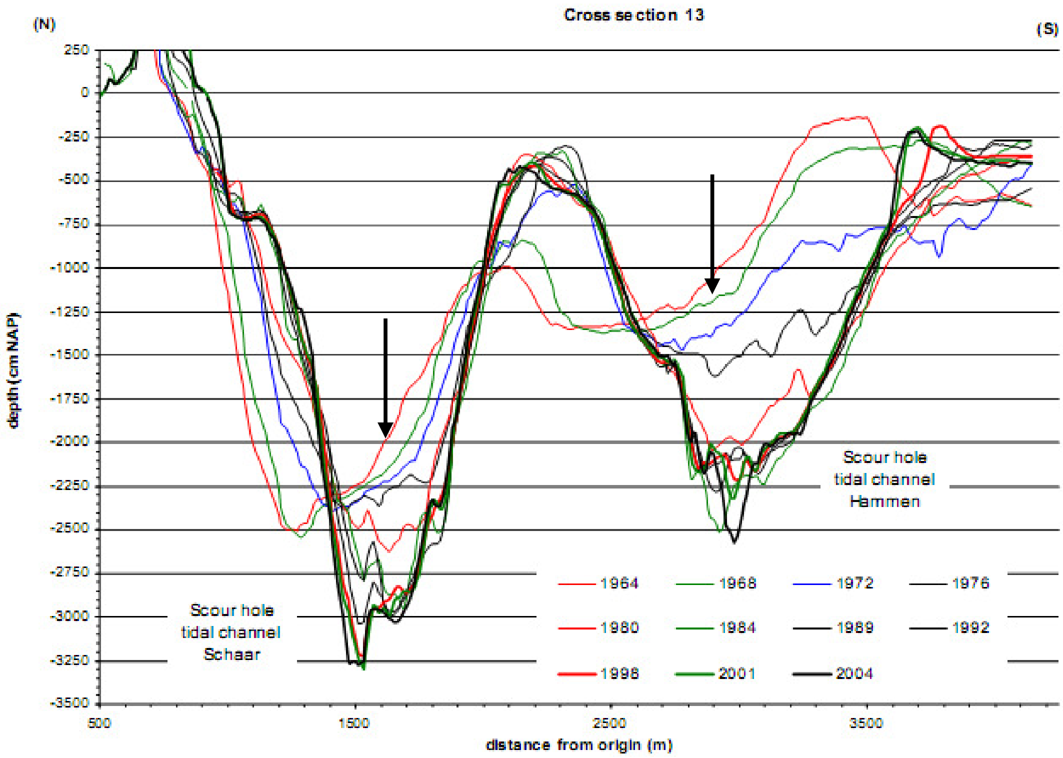


FigureA. 4. In the tidal channel Wesgat (Cross section 16)



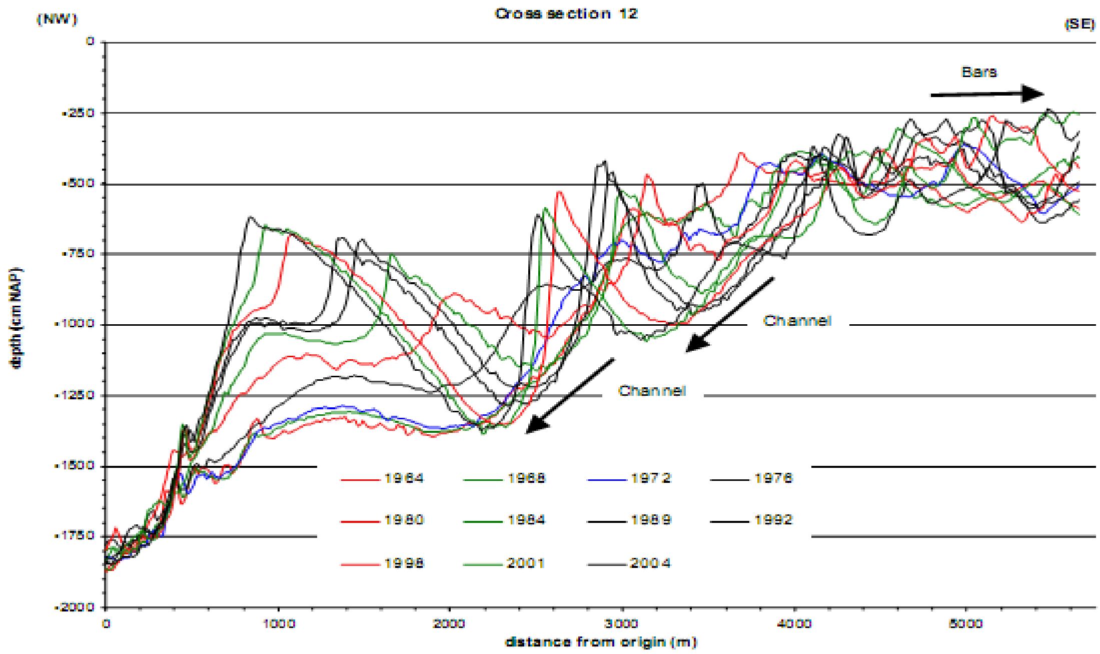
FigureA. 5. In the tidal channel Roompot (Cross section 18)

b) Development of scour hole near the entrance of barrier in the tidal channels Hammen, Schaar.



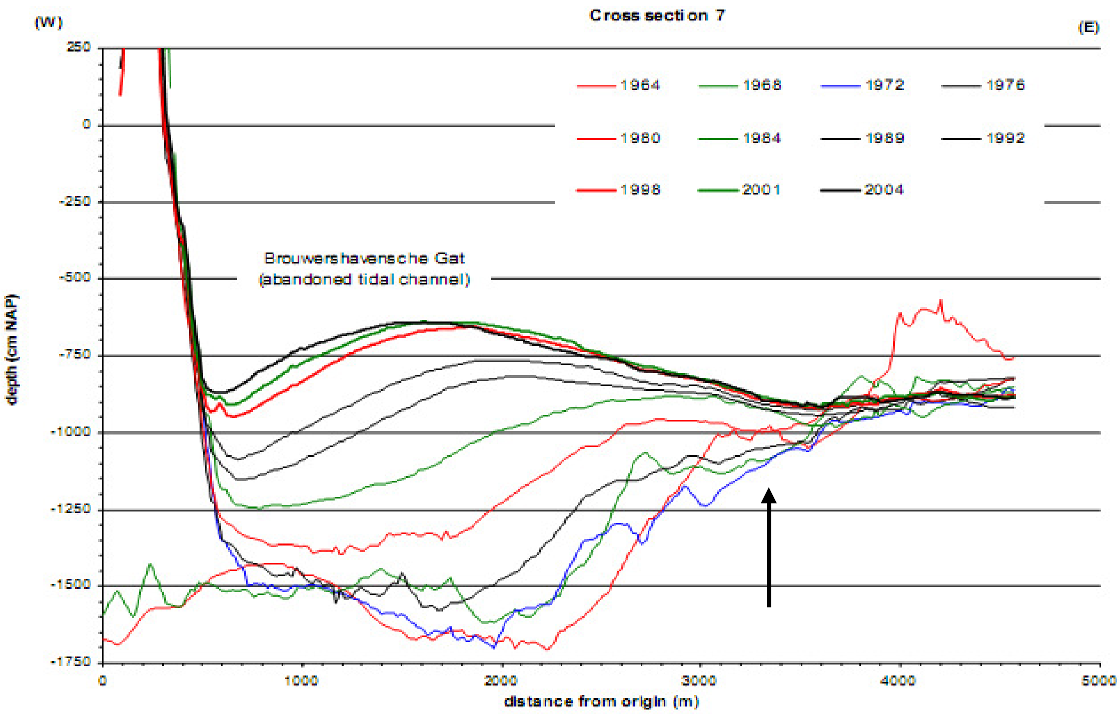
FigureA. 6. Development of scour holes (Cross section 13)

c) Seaward migration of tidal channels and landward migration of the Banjaard shoal (southern part of the inlet)



FigureA. 7. Changes in channels and bars at the Banjaard shoal (southern part) Cross section 12

d) Abandoned tidal channel in the ebb tidal delta of the Grevelingen



FigureA. 8. Changes in channels and bars at the Banjaard shoal (southern part) Cross section 7

The channel is progressive deposited and tends to no longer be a channel.