Tidal River Development

# Morphological management of estuaries

## Case study of the Scheldt estuary

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Port of Antwerp

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This report is limited to a general description of morphological management. The concept is illustrated by some applications of and proposals for morphological management in the Scheldt estuary. However, the report doesn't contain much morphological analysis and is intended for a rather broad public. More technical aspects and a detailed morphological analysis which form the basis of the current proposal can be found in the following report, which is in preparation:

Antwerp Port Authority. *Morphological management of estuaries – Case study of the Scheldt estuary – Base report*

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## Abstract

In the past, the morphology of estuaries has often been managed by taking into account the societal needs of the moment. Such a management approach very often results in human interventions in the estuary with a benefit for the function that was aimed for, but in the same time causing negative effects on some of the other functions. In recent years, the fact that an estuary has multiple functions, which are considered of equal importance, is more and more accepted by estuarine managers. As an example the Long Term Vision for the Scheldt estuary as worked out by the Dutch and the Flemish government in 2001 is mentioned: within this Long Term Vision the accessibility of the ports, the safety against flooding and the naturalness of the estuary are considered as equal important functions. The other functions the Scheldt estuary is offering to mankind (such as fishery, recreation, tourism, …) are also considered, albeit as being secondary.

How should an estuary be managed taking into account all its functions? How can one take into account all different functions an estuary is offering to mankind? Where at first sight it seems that the different functions of an estuary have nothing in common, it must be clear that all of them require a certain state of the morphology. So morphology seems to be the crucial element where the management of an estuary should focus on. Of course the required morphological state is or can be different for each function, and the most suitable morphology of an estuary has to be determined taking into account all different functions.

The concept of morphological management presented in this report offers the possibility to estuarine managers to apply a management that is aiming for a morphological functioning sustaining all functions of an estuary. Such a morphological management will be different for each estuary, however the concept is applicable to all estuaries worldwide. In order to set up a morphological management for an estuary, different steps have to be taken:

- Investigating the morphological behaviour of the estuary, with special attention to the elements that are controlling its morphodynamics.
- Identification of unwanted morphological evolutions, including their cause.
- Defining a long term vision sustaining the different functions of an estuary. This long term vision has to be translated into a morphological state, respecting and conserving the morphological diversity, complexity and mobility of the system. Such a long term vision should be based on the morphological analysis, including the ongoing wanted morphological evolutions, influencing or even trying to curb ongoing unwanted morphological evolutions.
- Investigating the best way to reach the identified morphological state. The engineering measures that can be used include morphological dredging and disposal strategies, modification of existing hard bordering and construction of soft structures. A combination of field measurements, scale and numerical models as well as expert

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judgement should be used to find the most optimal combination of measures.

- Implementing the measures in the field. Monitoring of the effects of these measures should be done in order to assess these effects, and when necessary adapt the strategy.

Since the morphology of an estuary is dynamic, morphological management will be a continuous activity based on observations of ongoing changes and on monitoring of the impacts of actions. Moreover the social and economic requirements change with time. Therefore, it is not realistic to define one single “ideal” shape, pattern and depth of estuary elements and then to “steer” the evolution towards it. However, there is a need to have a long term vision as mentioned before, to define what is desirable and what is unfavourable. Based on this long term vision, it should be possible to define morphological situations which should be achieved through management. Natural changes must be evaluated and checked against the long term vision, some assessed as positive, others as negative or unwanted.

In morphological management, “steering” the morphology should mean working with nature, not against it, except if unwanted evolutions from point of view of the long term vision are to take place, in which case one must attempt to curb this unwanted evolution. This concept of working with nature is not new. As an example the dredging strategy used in the Congo river since the early 1970’s is mentioned here. In the Scheldt estuary morphological disposal along sandbars has been executed in recent years as a first step towards a morphological management. In this report a proposal for morphological management of the region around Hansweert respectively Borssele is given. This proposal should be further investigated in detail, however it demonstrates clearly the concept of morphological management.

## Table of Contents

# 1 Introduction

Since ages estuaries have been densely populated areas. Of the 32 largest cities in the world, 22 of them are located along estuaries [1]. The reason for the attractiveness of estuaries is related to the many functions they offer to mankind: fertile land for agriculture, lots of opportunities for fishery, deployment of ports which maximizes the inland distance seagoing vessels can transport their cargo, extraction of materials for building purposes, recreational value for yachting, nature exploration and swimming, ... As a result most estuaries are experiencing high human pressure.

In the past, the morphology of estuaries has been managed by taking into account the societal needs of the moment, which included among others building levees to protect polders from inundations, dredging to guarantee the accessibility to ports, making engineering structures to protect slikke and schorre from erosion, ... Managing the estuary taking only into account one of its functions, often resulted in human interventions with a benefit for the function that was aimed for, but also with a negative effect for some of the other functions.

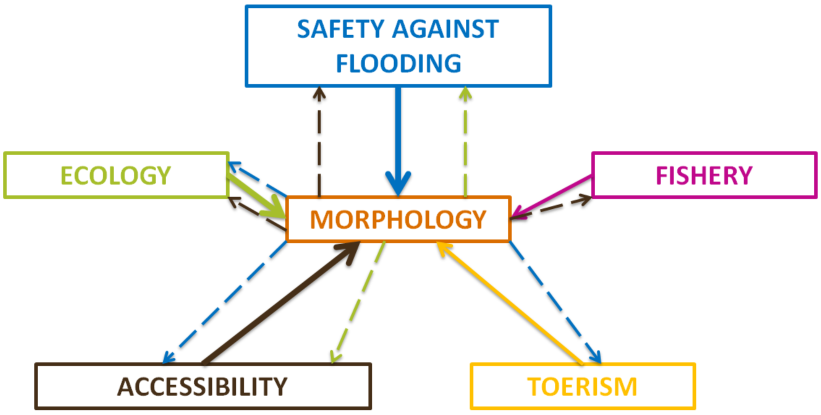


*Figure 1: Schematic visualization of the "one function benefit" approach for an estuary. Measures to improve one function also affects other functions by changes in the morphology.*

In recent years, the perception on some of the estuary's functions has changed. In particular the perceived importance of the natural values of an estuary has increased a lot. Where in the past little to no attention was paid to the naturalness of estuaries, today many laws and directives on different levels have been implemented in order to protect the natural values of estuaries worldwide. This change in perception created a stronger awareness of the multifunctional uses of estuaries. Nowadays, it is agreed on that an estuary housing a port has beside several secondary functions 3 main functions: offering safety against flooding, accessibility of the ports situated along the estuary and the variety in nature values. Where in the past it was considered – from point of view of the "one function benefit" approach – that the development of a port would almost necessarily imply a decline of the nature values and could have a negative impact on tidal propagation, in this report it will be demonstrated that this is not necessarily true. By an integrative holistic management approach of an estuary, taking into account all the functions of an estuary, improving the accessibility of a port can result in a lower risk of flooding and a preservation or even an improvement of the natural values of the estuary.

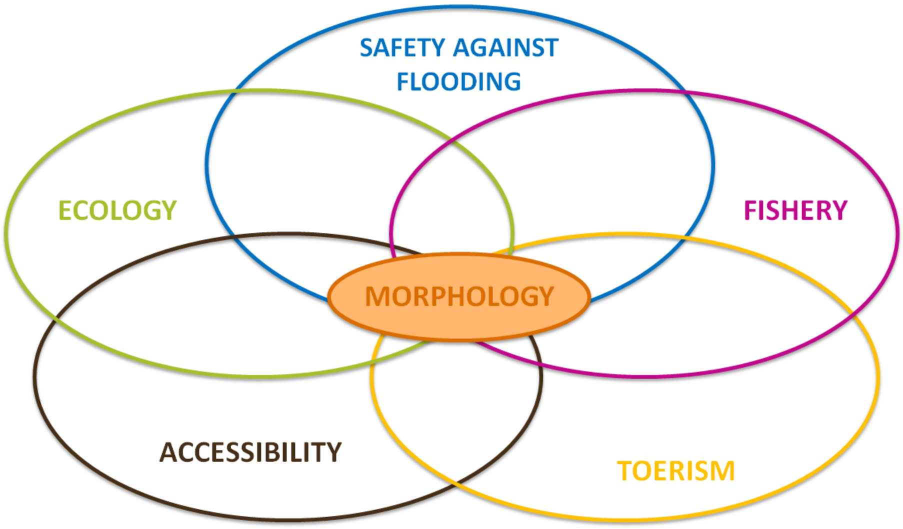


*Figure 2: Schematic visualization of the "morphological management" approach for an estuary. The morphology is supporting all other estuarine functions.*

This report is limited to a general description of morphological management. The concept is illustrated by some applications of and proposals for morphological management in the Scheldt estuary. However, the report doesn't contain much morphological analysis and is intended for a rather broad public. More technical aspects and a detailed morphological analysis which form the basis of the current proposal can be found in report [17].

# 2 Natural estuary system dynamics

## 2.1 Hydrodynamics and geomorphology of estuaries

Looking for a definition of an estuary, one is struck by the different viewpoints, some considering it as a marine environment ("an arm of the sea that extends inland to meet the mouth of a river"), while others find it rather a river system ("the wide part of a river where it nears the sea"). All agree on the importance of the tides and of the mixing of salt seawater with fresh river flow.


*Figure 3: Aereal picture of the Elbe and the Weser estuary*

*Source: Brockmann Consult, Common Wadden Sea Secretariat*

Tides play a crucial role in the hydrodynamic behaviour of estuaries because they provide energy for mixing the river's freshwater with the salty seawater. In the oceans, astronomic forces induce a variation of the vertical water level: the tide. Where the tide is rather small in open seas, the tidal variations in an estuary are often much larger, due to the funnel shaped geometry.

Because of the natural trend in deepening and narrowing of the estuarine geometry, which is enhanced by human activities, tides generally penetrate further inland compared to the past. As a consequence the tidal amplitude increases, creating a stronger influx of seawater and a stronger mixing with the river's freshwater. In the same time this change in tidal penetration impacts the safety against flooding. In these processes, the composition of the river bed determines the rate at which the estuarine geometry will adapt to the increased tidal energy. This is why the geomorphic setting and more particularly the geology and soil mechanical properties in the estuary are so important.

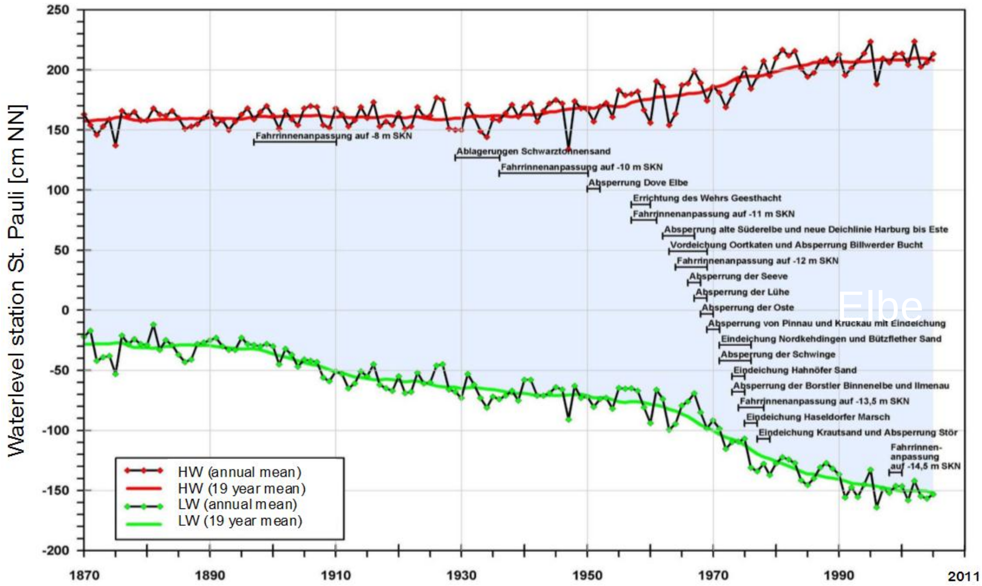


*Figure 4: Evolution of the mean high water (HW) and low water (LW) levels in the Elbe estuary at St. Pauli from 1870 to 2006*

*Source: Hamburg Port Authority*

The mixing processes of the salt seawater with the fresh river water produces a typical circulation of salt in the estuary. Salinity stratification is linked to the development of density currents, which combine with the horizontal tides (flood and ebb). A common feature in all estuaries is therefore the intrusion of the denser seawater along the bottom, the tidal net flow (i.e. the flow averaged over a tidal cycle) at the bottom being directed inland and extending up to a point where it becomes zero. Upstream of this no-net tidal flow point, the net movement is at all levels directed towards the sea.

Another effect of salinity is the flocculation process of fine-grained, colloidal sediment particles, mainly clay and organic material. Flocs (flocculent mass formed by the aggregation of a number of fine suspended particles) have a larger size than the individual suspended particles they are formed from, however their density is smaller resulting in smaller fall velocities. Flocculation occurs mainly in the transition between the freshwater and the brackish water zone, the position of which is mainly determined by the river flow. During episodes of low river flow, flocs settle to the bottom upstream of the zone of no-net tidal movement. During river floods, fine-graded sediment particles may be transported seawards in the upper layers where some of these flocculate and they may settle to the bottom downstream of the zone of no-net tidal movement. Finally, the flocs are for a large part accumulating at the point of no-net tidal movement. They usually create mud layers on the bottom. Because of the intense flow and turbulence in this part of the estuary, they are easily brought into suspension and are responsible for the so-called turbidity maximum. These bottom mud layers occur quite often at places in estuaries where ports have been established. This is in fact not surprising, as these locations were chosen on the basis of geometry, at the transition between the wider sea branches and the tidal river.

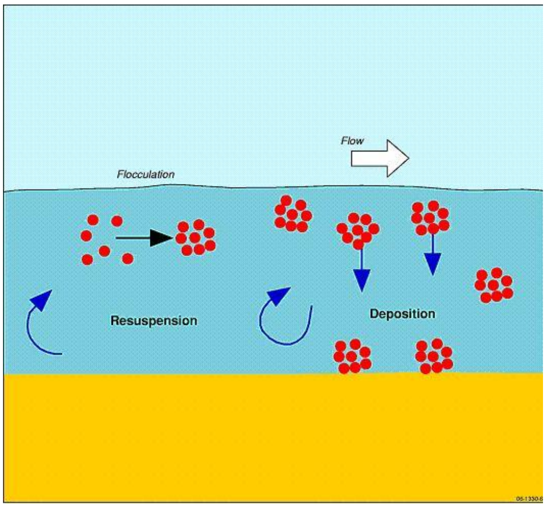


*Figure 5: The flocculation process of cohesive sediments in an estuary*

Given the hydraulic characteristics of an estuary, it becomes obvious that besides the ratio fresh water discharge to tidal volume, geometry is a determining factor for the mixing of seawater with fresh river water in an estuary. As a consequence we may conclude that the geomorphic and/or geologic setting is strongly controlling the functioning and historical evolution of the estuary. Northwestern European estuaries are relatively similar from the point of view of water and salt circulations. However, their geometric features and geological controls differ considerably.

Morphological changes are the consequence of sedimentary processes, driven by the forcing processes of tidal currents, waves, freshwater flows and their interactions. These forcing processes modify the estuarine morphology depending on the availability of sediment entering the estuary (either from marine or riverine origin), the estuarine morphology being 're-worked' due to erosion and accretion within the estuary. The latter (reworking) is controlled by the underlying geology, sediment type and biological processes. The factors of prime importance that affect the morphology of estuaries and their evolution – which are determining the boundary conditions for port accessibility – therefore include: fluxes of fluvial sediment, littoral movement of marine sediment, fluxes of material from scoured geological deposits in the estuary and sediment movements by tidal currents and density circulations within the estuary. These factors combine to make up the estuarine sediment budget [6].

## 2.2 Global ecological dynamics

Animals and plants have adapted to cope with specific environmental conditions. Some species require very specific conditions, others can survive a larger range. In dynamic environments they all are adapted to cope with this environment. Some avoid desiccation and migrate to deeper water at low tide, others close their shell or bury themselves in the sediment. Some can survive low salinities, others are restricted to the more saline parts of the system. The ones which can survive low or variable salinity are protected against predation by the more saline species in regions of the estuary where the marine species can't survive.

Besides the environmental conditions which cause survival or death, it is important that organisms can grow and/or feed. Plants and phytoplankton require nutrients and light. They form the basis of the food chain. Higher plants mainly grow on the saltmarshes (or freshwater tidal regions), and in clear water regions seagrasses may occur in the intertidal. Vegetation in saltmarshes is only grazed by mammals and birds (mainly geese). Phytoplankton (small algae in the water column) and microphytobenthos (small algae mainly on the intertidal sediment) are the main food source for estuarine organisms low in the food chain such as shellfish and worms. These organisms can serve as food for organisms higher in the food chain such as fish, birds and man.

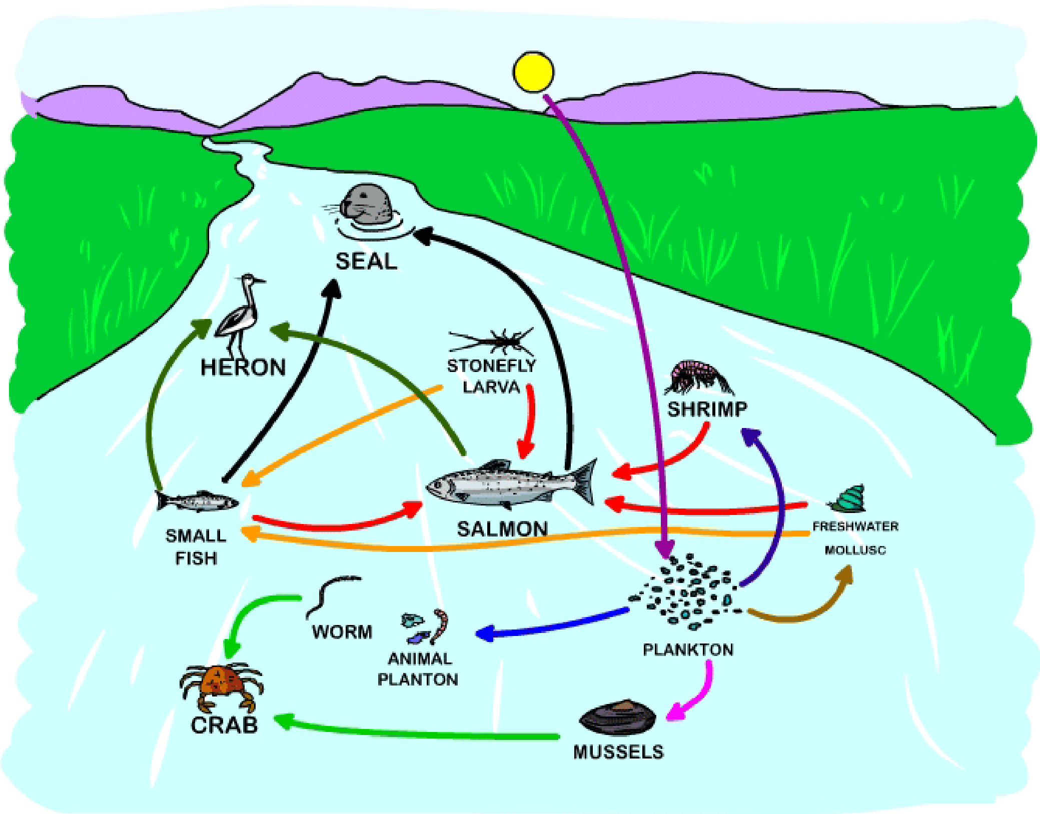


*Figure 6: Schematic presentation of the estuarine food chain*

Because of the large exchange of water with the neighbouring sea, it can be expected that a large proportion of the primary food is imported from the sea. This depends on the mean residence time of the water. However, the ratio between the fresh water flow and the tidal prism will affect the exact residence times in particular locations in the estuary. In the upstream regions the majority of the primary production will be of a local character. In the outer reaches the primary production will mainly be coming from the sea. In other estuaries with a limited residence time, the primary production will be predominantly from a marine origin.

Especially in turbid estuaries a small part of the primary production in the water body is from a local origin, as light is the limiting factor. In these areas, production in the water column will be low and the production will almost be limited to the intertidal flats around low tide. This means that an increase in turbidity will often not be of major influence on the primary production. Around low tide, production can still occur as before. If in the water column it was already low, and if food is imported from the sea, a local increase in turbidity has no impact on production, but may have an effect on organisms feeding by filtration. As flats produce a relatively large amount of algae around low tide, these are the main food source for deposit feeders which graze the area. Deposit feeders can also profit from organic matter which is exported by the rivers and settles in preferential sedimentation areas. Birds mainly feed on fish, shellfish and worms. Fish-feeding birds have preference for clear water; the ones eating other food are mainly depending on the exposed areas of intertidal flats. Some diving ducks can feed on molluscs in deeper water.

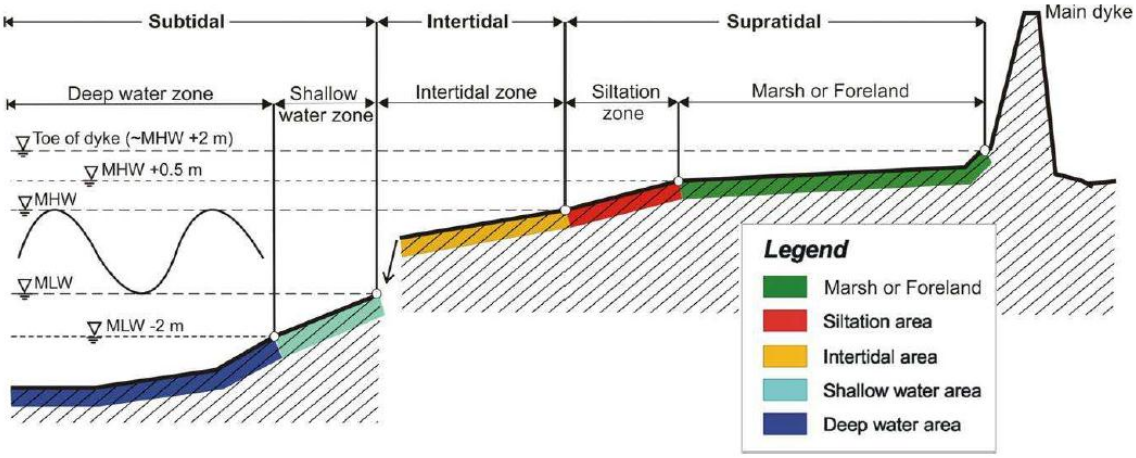


*Figure 7: Different habitat types in an estuary according to their elevation to high and low water level*

Source: NLWKN

From the above it is clear that organisms occur in different densities and in different species assemblages in the various parts of the estuary. On a large spatial scale, estuaries may appear quite stable when considering their freshwater flow, tidal range, aerial extent of channels, gullies, flats and marshes. When viewed on a local scale large however variations may be observed. Channels may move laterally by erosion and sedimentation, intertidal flats may disappear and others re-appear at different locations. As most estuarine organisms are very mobile or can quickly develop new populations, they may well adapt to these changes. On a temporal scale, however, one should realise that we know the estuaries in one point in time in their development over a time scale of millennia. The natural development may lead to a climax situation which is completely different from the system as we presently know it [6].

# 3 Drivers for morphological management

In recent years the anthropogenic pressure on many of the worldwide heavily populated estuaries has increased significantly. Port authorities are asking for larger navigation channels in order to be able to cope with the scaling in the ship construction industry, the sea level rise is triggering flood protection plans and engineering, various directives (on different levels) are implemented worldwide in order to halt the unwanted degradation of estuarine nature values, ... Where at first sight it seems that those different functions of an estuary have nothing in common, it must be clear that all of them require a certain state of the morphology. However the required morphological state is or can be different for each function, and the most suitable morphology of an estuary has to be determined taking into account all different functions.

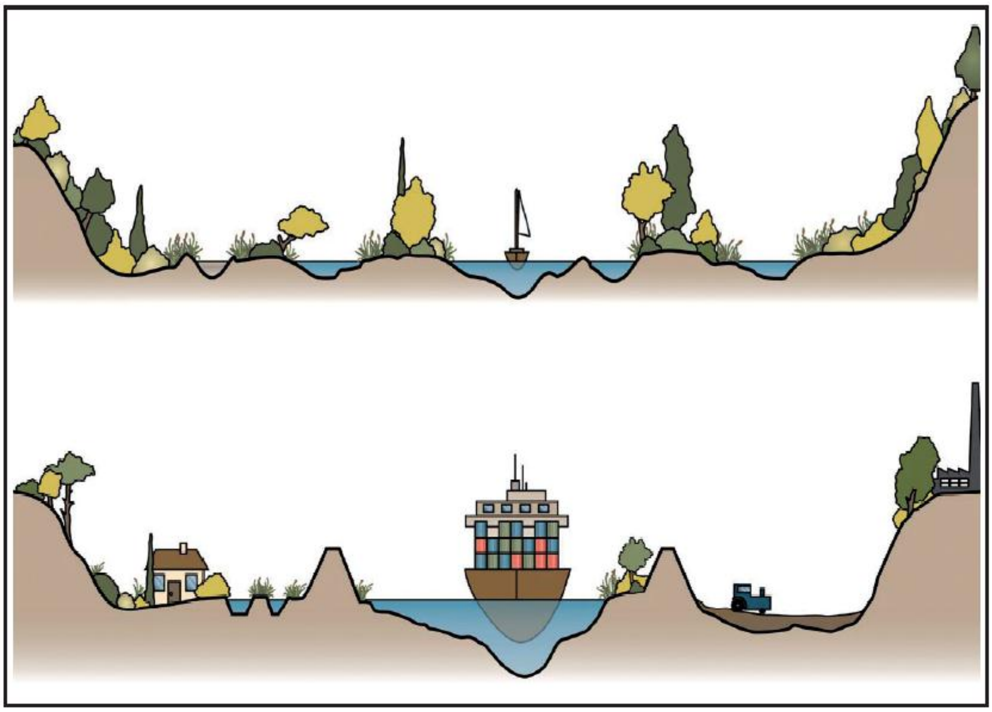

*Figure 8: Schematic evolution of the Elbe estuary over time*
*Source: Hamburg Port Authority*

The drivers for the morphological management are related to the search for a morphological state of an estuary which can "solve" most of the issues which can be found nowadays in many estuaries in developed countries worldwide. How can the large amount of sediments that needs to be dredged to maintain the depth of the navigation channel be reduced? How to remove nautical bottlenecks impeding larger vessels sailing to estuarine ports? How can the energy of the incoming tide be better dissipated, resulting in lower high water levels thus decreasing the chance of flooding? How to stop the degradation of estuarine ecosystems? Is it possible to even improve the status of the estuarine ecosystems? This chapter will deal in more detail with some of these issues hoping to get an answer from morphological management.

## 3.1 Ports accessibility

Shipping companies are nowadays replacing their smaller vessels by larger ones since those are interesting from point of view of economics of transport. Figure 9 shows as an example the evolution of the international container vessel fleet according to the length respectively the draft of the vessels. When considering the capacity instead of the number of ships, the proportion of the large vessels is even more pronounced. The 2015 numbers are a prediction based on the order books of the big shipyards worldwide. A similar evolution can be observed in the conventional cargo and liquid bulk transport segment.

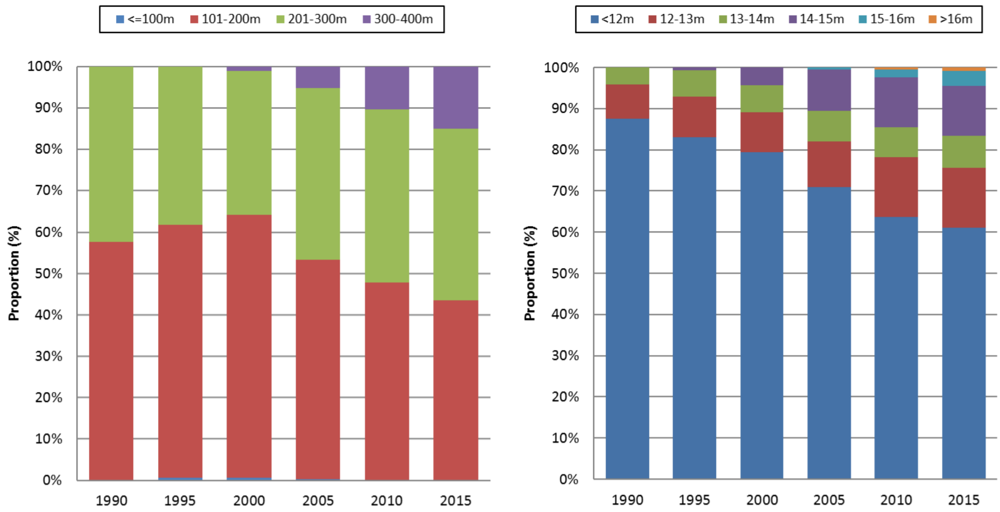


*Figure 9: Relative proportion number of container vessels in the international fleet, according to the length in m (left figure) and draught in m (right figure) of the vessel*
*Source: Antwerp Port Authority*

The advantage of ports situated along an estuary is their inland location, which increases the distance the ships can navigate and decreases the distance the cargo has to be transported with other modi. The disadvantage of such ports on the other hand are the possible nautical bottlenecks (i.e. undeep sills, locations with narrow channel width, …) which occur in the relatively long navigation channel in the estuary. In order to be able to welcome the most modern vessels, ports situated along estuaries need to guarantee a certain width and depth of their navigation channel. While this is no problem in the major part of the navigation channel, measures are required on the sills since the natural depth and/or width of the navigation channel is locally not sufficient. In order to be competitive with deep water ports located close to the sea, estuarine port authorities are asking for an enlargement of the navigation channel. Both constructing engineering works and dredging operations – maintaining the current depth and width of the navigation channel – can guarantee safe navigation of the larger vessels to the ports. It is clear that these measures affect the morphology of the estuary.

As an example the figure below shows the locations in the Scheldt estuary were dredging is needed to maintain the depth of the fairway. In recent years, before the execution of the 3rd deepening campaign in 2010, amounts around 10 Mm³ of sediments were dredged each year on these locations. In order not to disturb the sediment balance of the estuarine system, almost all of the dredged sediments are disposed back in the estuary, mainly in the secondary channels. These disposal locations in the Scheldt estuary are also shown on the figure below.

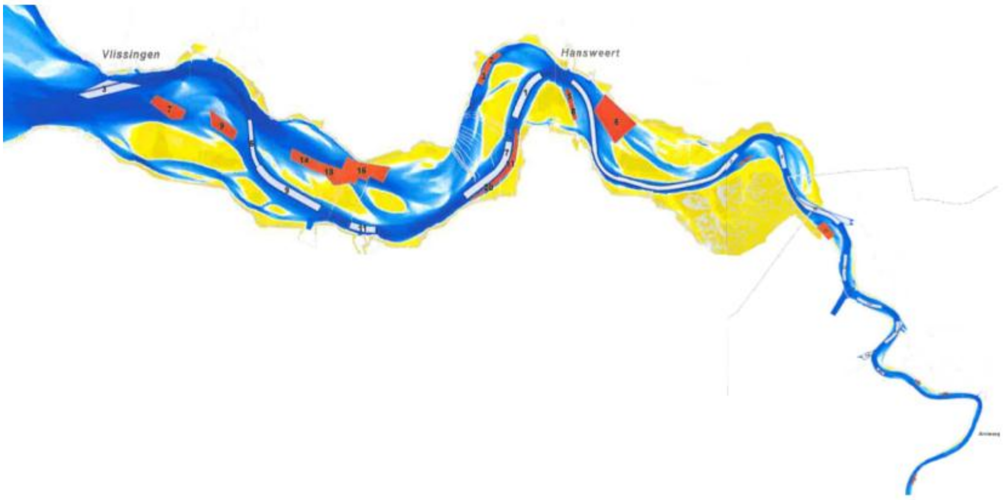


*Figure 10: Overview of dredging locations (white polygons) and disposal locations (orange polygons) in the Scheldt estuary*

*Source: Maritime Access Division*

## 3.2 Safety against flooding

When comparing the current border of an estuary with its border of some centuries ago, it is clear that the area of most European estuaries has decreased significantly, mainly due to land reclamation. Figure 11 shows the poldered areas along the Scheldt estuary (limited to the Dutch territory). To reclaim land from the estuary, levees have been constructed in order to protect the reclaimed land from flooding. Although most of the poldered area had already been silted up significantly before poldering, these polders fulfilled an important role (tidal storage area) during storm events. This trend of narrowing of the estuaries has accelerated the natural trend of increasing tidal penetration in the estuary, resulting in higher high waters, and as a consequence lower safety against flooding. Moreover the water levels in the estuary are rising due to the rise of the sea level. Since heightening of the levees is no longer seen as the only solution to increase safety, nowadays the vision of safety against flooding is partly based on giving back land to the estuary, c.q. depoldering. More efficient with regard to safety against flooding are so called controlled inundation areas which will only be flooded during extreme high waters. An additional benefit of those controlled inundation areas is that part of it can be used as a reduced tidal area, which contributes to the ecological value of the estuary.

Levees contain the flood waters, but they also guide the ebb and flood flow. In this sense, their position and layout influence flow, hence sediment transport and morphology. The current pattern of the levees along an estuary does in most cases not result from a reclamation scheme based on hydraulic considerations. In the past, when a levee failed, closure of the breach was not with a levee at the place of the failure, as the flow through the breach had scoured a deep channel. The new levees went around that newly scoured channel, starting almost perpendicular to the original levee, creating a levee system with some sharp angles. People were concerned about the land, not about what would happen with the morphodynamic behaviour of the estuary. The resulting levee outline is thus rather the consequence of the case-by-case building of structures, which has influenced the large scale morphology of the estuary rather significantly [2]. On the other hand, the large scale morphology of an estuary has an important impact on the tidal propagation trough the estuary, and thus on the safety against flooding. The dissipation of the tidal energy in the estuary will be influenced by the morphology, especially in systems with a multiple channel system such as the Western Scheldt.

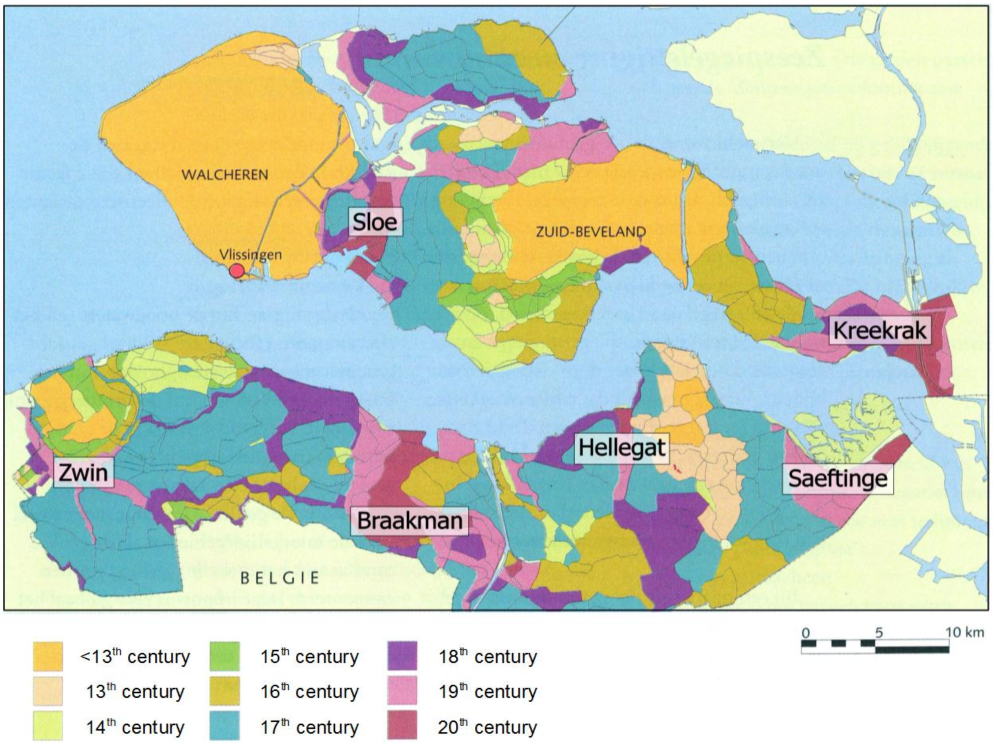


*Figure 11: Overview of historical poldering along the Western Scheldt*
*Source: Vroon, 1997*

## 3.3 European Nature Directives

Estuaries are among the most productive ecosystems in the world. They are of prime importance for wildlife, especially migrating and breeding birds, and of major value in terms of their rich natural resources (e.g. as nursery grounds for commercially important fish). In addition they also offer a wide variety of ecosystem services such as nutrient regulation, detoxification of polluted waters, supply of food and energy resources, ... [4]. In response to the rapid global decline in biodiversity (especially along estuaries and coastal zones) the European Union decided to halt this decline and try to restore the habitats and natural systems by imposing European Directives. Three of the most important directives which form the cornerstone of the EU biodiversity policy are the Birds Directive, the Habitat Directive and the Water Framework Directive.

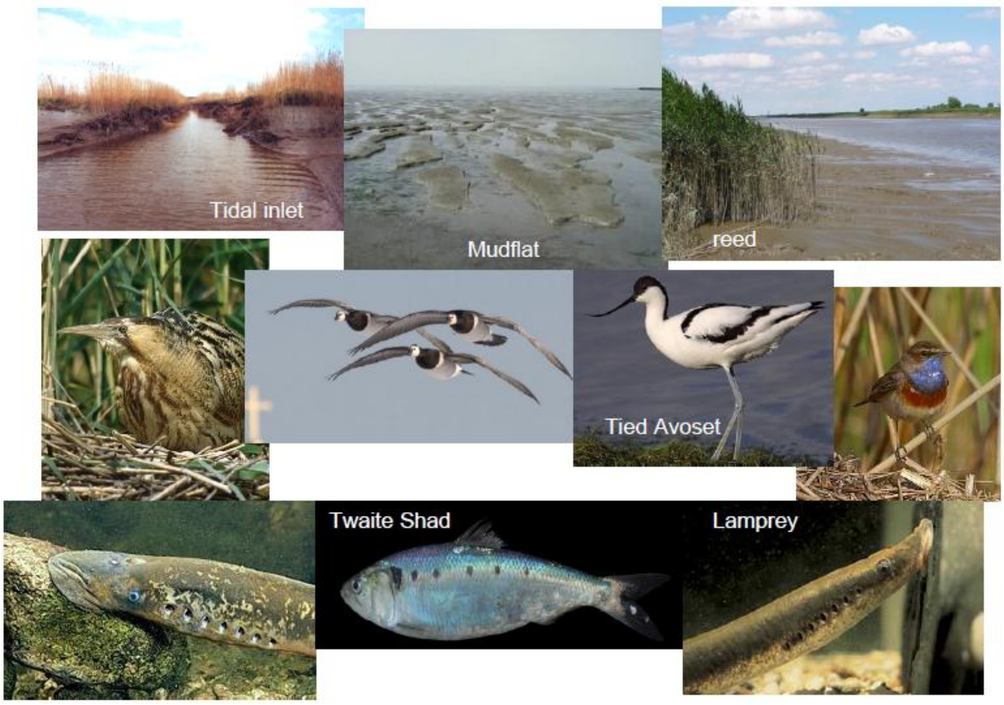


*Figure 12: Examples of protected habitats and species in the Weser estuary*
*Source: NLWKN*

The European *Birds Directive (79/409/EC)* dates from 1979. This directive aims at providing long-term protection and conservation of all bird species naturally living on the territory of the Member States. The impact of the Birds Directive was rather limited until the *Habitats Directive (92/43/EEC)* – which absorbs the Birds Directive to a large extent – was enacted in 1992. The objective of the Habitats Directive is to maintain or restore biodiversity in the Member States by creating a European wide network of protected sites known as Natura2000. The Natura2000 network embraces the Special Protected Areas (SPAs) designated under the Birds Directive as well as the Special Areas of Conservation (SACs) designated under the Habitats Directive.

The *Water Framework Directive (2000/60/EC)* dates from 2000 and establishes a framework for the protection of all bodies of surface water and groundwater on an EU level. Before 2000 some European Directives were already in force tackling some specific aspects related towards the quality of the surface and groundwater. These directives were replaced by the WFD from 2000 on. The purpose of the WFD is to achieve a good ecological status and a good chemical status by 2015. Therefore, river basin management plans have to be set up for each river basin. By neglecting the national and regional boundaries of the Member States, the European Commission has decided to use the most natural boundary of river basins. The river basin management plan has to include a monitoring program, in order to have an overview of the water status in each river basin district.

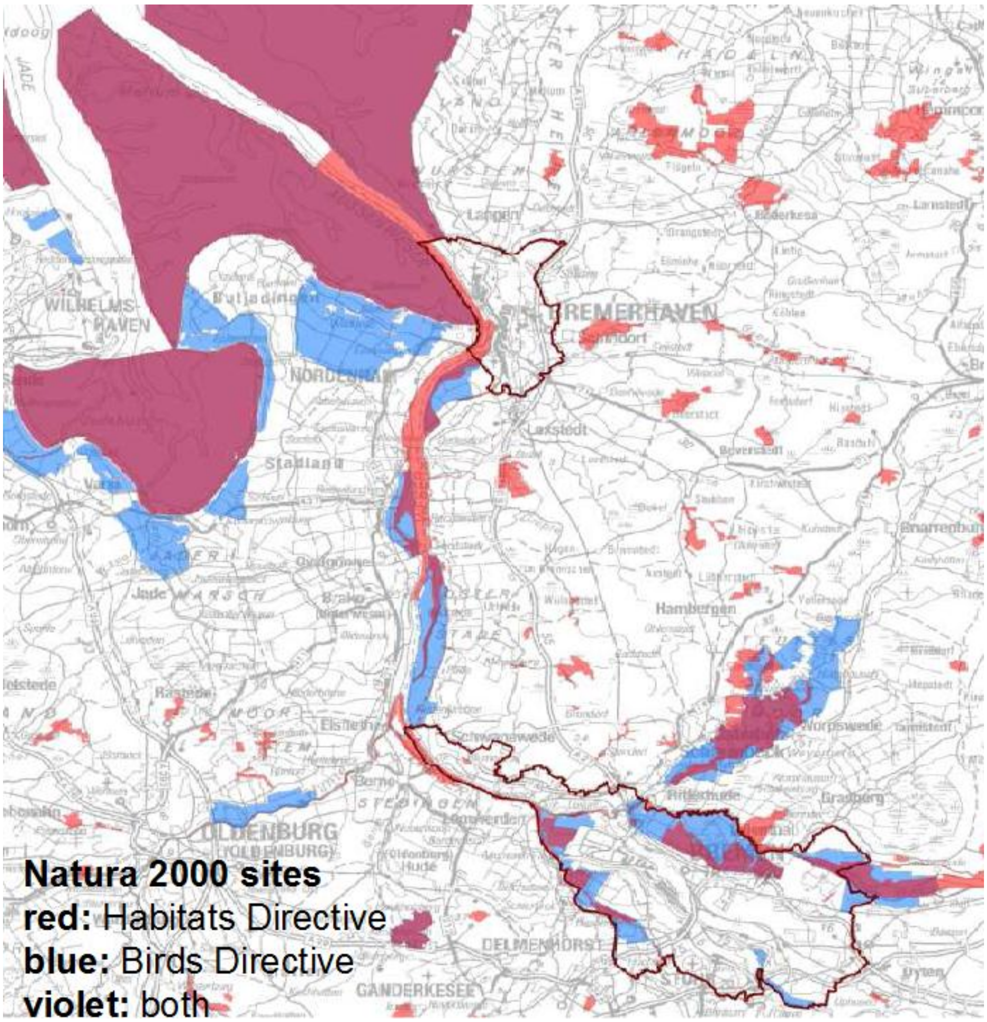


*Figure 13: Overview of protected Habitats and Birds Directive areas along the Weser estuary*

*Source: NLWKN*

Although not explicitly mentioned, the nature directives contain different requirements from viewpoint of the estuary's morphology. However the requirements of the legislation do not always take into account the long term morphological requirements of sustainability of the whole system. Given the high degree of variability inherent in natural estuarine habitats, the plant and animal communities present must have a high capacity to adapt to variations in habitat. The dynamic structure and function of these areas mean that the biological communities must be constantly responding to changes in the environmental variables that determine their existence. It is these dynamics that provide the typical submerged water communities of estuaries in variable salinity conditions that play a key role in biodiversity. Short term and local protection as foreseen in the directives doesn't support the sustainability of the whole system [6]. One should aim for a flexible interpretation of the directives (and its goals) in regard to the natural dynamics of the estuarine system.

## 3.4 Other functions

Where accessibility of the ports, safety against flooding and naturalness of the system are regarded as the 3 main functions, estuaries also offer many secondary functions to society. Recreation and tourism are also an important function of an estuary which includes sailing, yachting, sunbathing on beaches along the estuary as well as walking and cycling on the levees along the estuary. Commercial fishery is another secondary function of estuaries, which has to be regulated in order not to disturb the natural fish stock. Extraction of sediments from the estuary for building purposes is an activity which affects the morphology of an estuary in a direct way. Last but not least farming along the estuary as well as the attractiveness of living next to an estuary are mentioned. Although it seems that both have nothing to do with the estuary, it must be recognized that the ground being used for those activities are often historically reclaimed grounds from the estuary.

*Figure 14: So-called secondary functions an estuary offers to society*

These different functions are seen as being of smaller importance as the 3 main functions accessibility, safety and naturalness. However it must be recognized that these functions also imply a pressure on the estuary, including to a more or less extent a certain state of the morphology.

## 3.5 Conclusion drivers

Estuaries offer different functions to mankind. In this chapter the 3 main functions of estuaries are described in detail. Despite the fact that the driver to develop these functions is totally different (economic, social or legal), it can be stated that there is no priority among these 3 main functions. All of them need to be developed side by side, moreover also considering the many secondary functions of an estuary. Where at first sight one could think that these functions have nothing in common, it is clear that the morphology of an estuary is a key factor for all of them. A holistic morphological management taking into account the different functions of an estuary is thus necessary.

# 4 The concept of morphological management

In the past estuaries have often been managed taking into account the societal needs of the moment. In order to protect reclaimed land from inundations, levees were built or heightened. To increase the economic welfare, port infrastructure was extended and dredging operations were performed to improve the accessibility of the ports. When big infrastructure projects were executed, sand was often withdrawn from the estuary to be used as construction material. In order to protect the slikke and schorre area from erosion, structures such as groynes and jetties were built or riprap was placed at the toe of the eroding slikke area. Little to no attention was paid to the effect of these interventions on the long term morphology of the estuary. However, human activities were not the only factor influencing the morphodynamic behaviour of estuaries. Other natural factors such as sea level rise and geology also influence this morphodynamic behaviour.

The concept of morphological management presented in this report is based on the understanding of the morphological functioning and its past evolution. Knowledge of the behaviour of the morphological system is needed in order to be able to set up a sustainable management strategy for the future. However it is stressed that the morphology of an estuary should not be seen as a goal as such, but rather as a mean for the different functions of an estuary depending on the morphology. In this chapter the concept of morphological management of an estuary will be presented. It will be demonstrated by some good and bad examples of morphological management of the past.

## 4.1 Morphological management

The main goal of morphological management of an estuary is to ensure a morphological functioning sustaining the different functions of the estuary. This management should aim at influencing and even steering when needed the changes in channels and sandbars in order to conserve the morphological diversity, complexity and mobility of the bar and channel system. Besides offering a safe navigation route, the resulting morphology should also have a positive effect on the dissipation of the tidal energy reducing the propagation of the tidal wave, should increase as much as possible the self-erosive action of the currents at crossings and maintain – and when possible even improve – the diversity of the ecosystem. Achieving these goals requires first an identification of unwanted situations and their causes. Morphological analysis must be a continuous activity, based on knowledge of past changes and their causes, on the observations of ongoing changes and on monitoring of the impacts of actions.

The need to preserve the dynamic behaviour of an estuary, including the mobility of its channels and sandbars, must be recognised. The approach to follow should not be a conservative one aiming at “keeping what we have”, but should be more progressive with a calculated risk allowing “giving up something locally, to reach benefits on other locations”. It is not realistic to define one single “ideal” shape, pattern and depth of estuary elements and then to “steer” the evolution towards it. The big challenge is situated in the dynamics of the estuarine environment and how to coop with this. Moreover the social and economic requirements change with time, while the nature does its own work. However, there is a need to have a long term vision, to define what is desirable. Based on this long term vision, it should be possible to define situations which should be achieved through management. Natural changes must be evaluated and checked against the long term vision, some assessed as positive, others as negative or unwanted.

In order to favour natural positive changes and to reduce or halt unwanted changes, one must understand the morphological functioning of the estuary, especially which elements are controlling it. As such special attention should be given to the effect of the hard bordering (including erosion-resistant geological layers, bank protection works, groynes and levees) on the morphology, more specifically on the location of channels, sandbars, slikke and schorre. In-depth studies are needed to achieve such morphological understanding. The causes must be understood, so that appropriate actions can be designed to modify them if needed.

In morphological management, "steering" the morphology should mean working with nature, not against it, except if unwanted evolutions are to take place, in which case one must attempt to curb this unwanted evolution. Although the concept of working with nature is not new, only in recent years the idea has received more attention (e.g. PIANC working group Working with Nature) and has been used in several projects. When one wants to start to manage the morphology of an estuary in an appropriate way, the goal must be to improve the morphology in the present channel layout with the measures mentioned in the paragraph 4.3. But before implementing measures, extensive research on which measures are most appropriate should be performed. The tools available to do such research are described in the next paragraph.

## 4.2 The research tools

River and coastal morphology remains an experimental science, in which theories are not yet well established and bring little help for solving engineering problems. If flow and sediment movements are key elements to the morphological behaviour of an estuary, they are certainly not the only ones. The way the flow and sediment transport patterns are influenced by controls like harder river bed material and by hydraulic structures is also essential.

A sound morphological management of an estuary starts in understanding its past morphology. This morphological analysis must be a continuous activity, based on analysis of topo-bathymetric maps from the past and the present situation. As mentioned before, information about hard geological controls is essential for understanding these processes. Monitoring of different parameters such as flow velocities, discharges, sediment transport, … is necessary to increase the knowledge about the local hydrodynamic and sediment transport processes. Analysis of such monitoring data will help in interpreting the observed evolutions on topo-bathymetric surveys.

Where monitoring data reveals information about local processes, models – numerical as well as physical – can be used to understand the processes on a larger scale. It is important that such models are accurately calibrated and validated using the monitoring data in order to be sure that the model is reproducing well the real physical processes. Where it is generally accepted that the physics of hydraulic models is very well understood, this is not the case for morphological models. Therefore hydraulic models are to be preferred, where the morphological predictions should be made based on expert judgement. From point of view of sediment transport, physical scale models can be used. However, full morphological modeling still has its limitations: where a lot of improvement has been made in recent years, the lack of knowledge on sediment transport processes causes rather poor results for this kind of models, both on short as well as on the longer term [18].

Where one is confronted with the fact that all research tools have disadvantages, it is believed that a multi-tool approach as suggested here (combining analysis of historical topo-bathymetric maps, field measurements, numerical and/or physical models and last but not least expert judgement) combines the advantages of all research tools, minimizing the uncertainties of the final result. Besides the research tools mentioned above, an in situ test – including an extensive monitoring program to detect all possible effects – can be used to give absolute certainty. Especially for projects with a possible large negative effect this option can be preferred: where such a test will give 100% certainty about the results, the negative effects that might occur will be small and most of the time reversible due the scale of the in situ test.

## 4.3 The engineering measures

Engineering works in estuaries are traditionally structural (such as groynes and spur dykes, jetties, bank revetments, guiding banks or guiding levees) and/or dredging. Obviously, engineers consider their works as influencing the morphology. However, this is more in the sense of controlling, sometimes even “taming” nature. For example the common technique of disposal of dredged material in the side channels of a multiple channel system – aimed at getting rid for some time of the sediment before it comes back to the navigation channel – is obviously affecting morphology but this is not what we understand by morphological disposal. Morphological management must be flexible, responsive and holistic. Local interventions or too rigid approaches have failed. The possible measures for managing the morphology of an estuary include [2]:

1. *Modification of hard bordering*

In the past hard bordering along estuaries (including hard structures such as groynes, spur dykes, …) was often built without taking into account the morphology of the estuary. And if this was taken into account at the time of construction, the hard bordering might not have remained appropriate anymore in the present situation since the morphology – and as a consequence also the hydrodynamics – is changing all the time. Therefore, the hard bordering of estuaries may influence its current morphology negatively, for example by orientating water flow in an unfavourable direction. A clear example of how hard bordering influences the morphology in a negative way can be found around the bend of Hansweert in the Western Scheldt (see paragraph 4.4.1).

2. *Construction of new (soft) structures*

In order to guide the flow or to affect the erosion-transport-deposition process, one could build flow guiding structures. Since the morphology of estuaries is changing all the time, the efficiency of a structure may decrease over time, possibly even causing negative effects after a while. Therefore preference should be given to soft structures, which can be removed or adapted easily if necessary. Structures built with concrete or riprap should be avoided if possible (see negative review of scenarios including such measures in chapter 5).

3. *Morphological dredging*

Dredging is used to create new channels of deepen and/or widen existing channels (capital dredging) or to maintain existing navigation channels (maintenance dredging). However, dredging can also be used as a tool to influence the morphological behaviour in the estuary. Morphological dredging is meant to trigger evolutions, so that the channels and sandbars become more adapted to the needs of navigation and ecology. This may include dredging to rectify channel borders or to initiate new channels, either a main channel or a secondary channel.

4. *Morphological disposal of dredged material*

Morphological disposal is not just getting rid of the dredged material. In the vision of morphological management, the disposal of the dredged material is seen as an opportunity to initiate certain desired evolutions. As an example disposal can be used to provoke wanted evolutions of sandbars, or to influence the lateral movement of channels.

5. *Combination of the above works*

In order to implement morphological management of an estuary, one will most likely need a combination of all engineering measures mentioned above. However, the goal of these works is not to work against the natural evolution, but rather with the natural evolution. Extensive research is necessary in order to determine the most optimal morphology of the estuary, sustaining and if possible even improving all the functions of the estuary.

## 4.4 Some examples of morphological management

### *4.4.1 The Scheldt estuary*

A first example of morphological management of an estuary concerns the new disposal strategy used during the capital dredging works in 2010 in the Scheldt estuary. Before this project, the disposal of dredged material was rather seen as an inevitable consequence of dredging of the navigation channel. The disposal strategy was one oriented on getting rid of the dredged sediments, disposing sediments mainly in the secondary channels. Where one was happy that this strategy did not have negative effects on the system, there was a possibility that the multiple channel system could be jeopardized if the disposed quantities would be too high. Therefore, the Port of Antwerp Expert Team – a team of 5 international experts appointed by the Antwerp Port Authority to investigate the feasibility of a 3rd deepening campaign of the navigation channel in the Western Scheldt – proposed a new strategy to dispose dredged material in the estuary [7]. By disposing the dredged sediments on strategically chosen sites, one could try to curb in a positive way unwanted morphological evolutions in the estuary such as, for example, a reduced self-scouring of a crossing, the dying out of important secondary channels, the increase of flow velocities in ecological valuable habitats, ...

Based on an analysis of topo-bathymetric maps of the Western Scheldt, the PAET concluded that one of the most suitable locations for this morphological disposal strategy is the Walsoorden sandbar. The seaward tip of this sandbar had been eroding since more than 50 years, resulting in a relatively wide cross-section locally causing high amounts of sediments to be dredged in the navigation channel. The PAET proposed to extent and reshape the seaward tip of the shoal of Walsoorden by disposing dredged sediments. This would result in a better distribution of the flood flow over the ebb and flood channel, improving the sustainability of the multiple channel system at this location. Since the width of the local cross-section would decrease due to the extended shoal of Walsoorden, the self-erosive capacity of the flow at the sill of Hansweert would increase resulting in less dredging activities needed. And last but not least this disposal would better concentrate the flow in the main channels, decreasing the flow velocities on the shoal of Walsoorden. This flow reduction together with the extension of the ecological valuable shallow water and intertidal area would create benefits for the ecology of the estuary [8].

After an extensive multi-tool feasibility study in 2002-2003 [9] it was concluded that none of the results opposed the feasibility. However it was judged that final prove had to be given by an in situ disposal test. A small amount of sediments (circa 500 000m³) would be disposed in order to investigate the stability of the disposed sediments. A first disposal test was executed by the end of 2004, followed by an extensive morphological [10] and ecological [11] monitoring program. The test was a success from morphological viewpoint, while no significant negative effects on ecology were observed. In 2006 a second disposal test was executed, this time using another disposal technique (the so-called clapping technique). Again the results of the morphological monitoring [12] were positive, while the ecological monitoring [13] revealed no significant negative effects.

In the framework of the 3rd deepening campaign of the fairway in the Scheldt estuary, an environmental impact assessment [14] and appropriate assessment [15] were carried out studying different scenarios. Based on the success of the disposal tests at the shoal of Walsoorden, one scenario was defined where the dredged material was disposed along sandbars, using the dredged material to induce morphological positive evolutions. Besides the Walsoorden sandbar (0 on Figure 15), 3 other locations in the Western Scheldt were appointed to be reshaped and extended by disposing dredge material: Rug van Baarland (1), Hooge Platen Noord (2) and Hooge Platen West (3). From the assessment studies it was concluded that the scenario including the disposal along these 4 sandbars is the most valuable alternative, since this scenario could create benefits for nature.

For every disposal location, a site specific strategy was worked out. The objective of this research was to maximize the ecological benefits from the disposal, by increasing the low dynamic shallow water and intertidal areas. Besides this ecological objective, improving the sustainability of the multiple channel system was another aim. The experience gained near the Walsoorden sandbar was used to investigate the optimal disposal strategy at the 4 different locations. An extensive research program was carried out, including field measurements and numerical model studies [14,15&16].

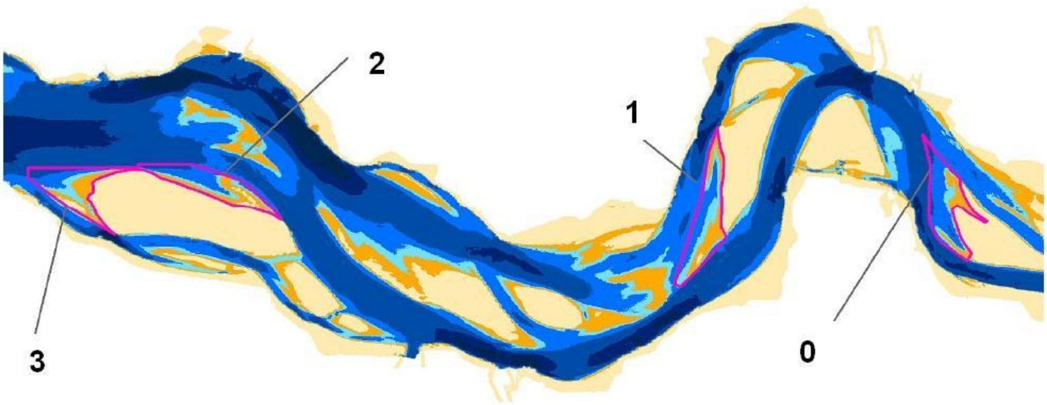


*Figure 15: Overview of the 4 disposal locations along sandbars used during the 3rd deepening campaign of the navigation channel in the Western Scheldt*
*Source Flanders Hydraulics Research, 2008*

In 2010 the enlargement of the navigation channel was carried out, including the disposal along the 4 sandbars. A combination of the traditional clapping technique and a pontoon with diffuser has been used to execute the disposal along the sandbars. A total amount of 7,7 Mm³ sediments from the capital dredging works plus 2,2 Mm³ sediments form maintenance dredging works has been disposed along the sandbars in 2010. In total an amount of 12,0 Mm³ of sediments from maintenance dredging works will be disposed at these locations during a period of 5 years. An extensive monitoring is going on to monitor all effects – expected positive effects as well as possible unexpected negative effects – of this disposal strategy. A certain flexibility to adapt the disposal strategy in space and in time is foreseen in the permit depending on the results of the monitoring program, guaranteeing the most optimal results of this strategy.

#### *4.4.2 The Congo river*

Another example of good morphological management can be found in the Congo river, in the region between the port of Boma and the mouth of the river in the Atlantic Ocean. The discharge in this river is so large that the tidal penetration is limited. On the other hand, the large discharge causes a lot of sediment transport in the river, making it a multiple channel system with channels and sandbars which are very mobile. The management of the navigation channel in this reach is done in a dynamic way, taking into account the natural dynamics of the system. Morphological evolutions are observed and if necessary (e.g. the navigation channel is located in a channel which is degenerating) the navigation channel is moved to another channel. The figure below shows the topo-bathymetry of 1932 and 1968: where in 1932 the channel is located south of the large supratidal sandbar “Ile des oiseaux”, it is clear that in 1968 the channel north of this sandbar is used for navigation. The dredging works throughout the years have been minimized, trying to work with the natural evolution as much as possible. In this way the natural dynamics of the system are preserved, reducing the impact of human interference in the estuary from point of view of port accessibility.

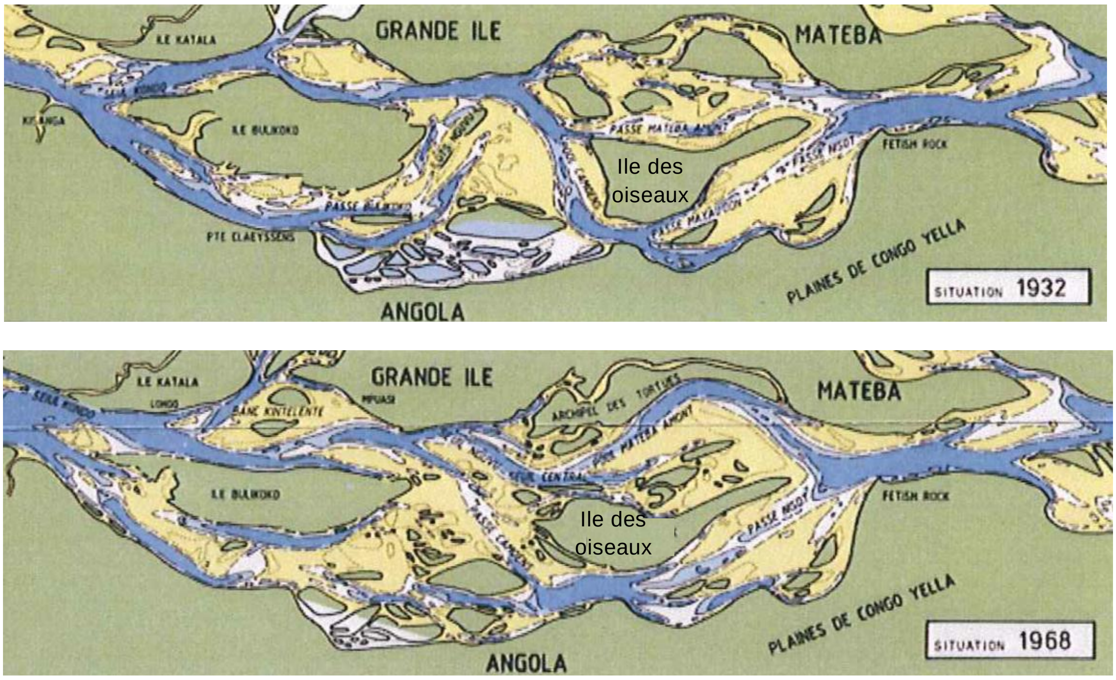


*Figure 16: Topo-bathymetric map of the multiple channel Congo river between the port of Boma and the mouth*

*Source: Peters, 2006*

As a case study, the recent evolution of the channel Canard – situated between the sandbar Kindu and Bunia – is mentioned (see Figure 17). Due to sediment transport the Kindu sandbar had been shifting in western direction, the sandbar in fact moving into the Canard channel. Since the fairway was situated in this channel, high volumes of maintenance dredging works were required here in order to keep the necessary depth. Moreover measurements with GPS floats indicated that the discharge through the Canard channel had decreased over time, the flow preferring to go over the Bunia sandbar instead. Since the amount of discharge determines the flow velocities, and sediment transport is dependent on flow velocities, it was obvious that the Canard channel was naturally degenerating. On the other hand it was to be expected that a new channel would develop through the Bunia sandbar.

Where one could keep the navigation channel in the Canard channel by intense dredging activities, in fact stopping the shift of the sandbar Kindu and thus the local morphodynamics, it was chosen not to do so. Instead the natural morphological evolution was fastened by dredging a channel through the Bunia sandbar, taking into account the local flow direction. Figure 17 clearly shows the position of the newly dredged channel, which coincides with the measured flow patterns. Due to a profound hydrodynamic and morphodynamic analysis, this new navigation channel didn't experience sedimentation over time. The flow velocities in this newly dredged channel were high enough to keep the initial dredged channel depth, even causing gradual widening and deepening of the channel over time. As a consequence the maintenance dredging works in this part of the channel were very low.

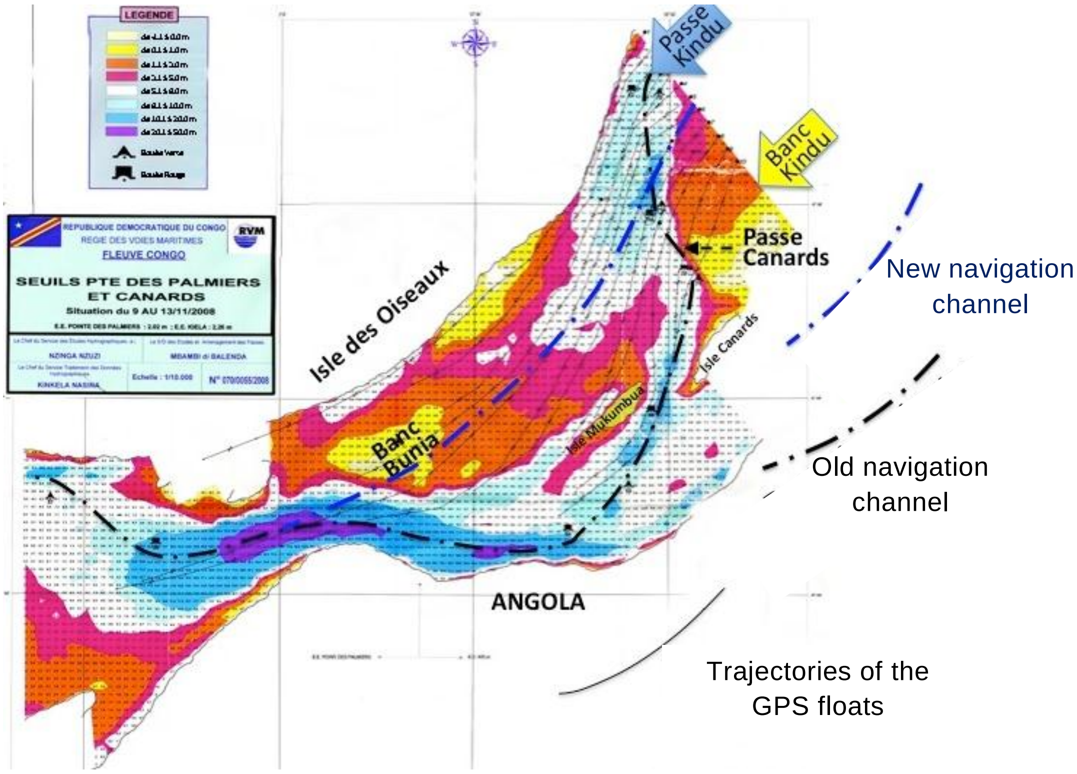


*Figure 17: Topo-bathymetric map of the region around the Canard channel with indication of the old position and the new position of the navigation channel. The trajectories of GPS float measurement just before opening of the new navigation channel are also visualized*

*Source: Peters, 2010*

Where this morphological management of the Congo river requires regular measurements to observe and analyse the natural morphological evolution, the advantages of such management are not small at all. Firstly, the dredging works to maintain the depth of the navigation channel are minimal. Secondly, the natural morphological dynamics of the system still remain resulting in a system where the human impact on morphodynamics is very limited.

### *4.4.3 The Weser estuary*

A typical example of the one function benefit approach can be found in the Weser estuary. A distinction can be made between the inner and the outer section of the Weser estuary, which have a different morphology. The channel-like inner estuary has a length of 65km and is nowadays aligned by continuous dikes next to the channel to protect the hinterland from flooding. The outer Weser estuary has a longitudinal extension of 60km. Inshore it is lined by extensive tidal flats of the German Wadden Sea, followed seawards by shallow subtidal shoals [21]. Where the port of Bremerhaven can be found at the transition from the inner estuary to the funnel-shaped outer estuary, 3 smaller ports exists more upstream: Nordenham, Brake and Bremen.

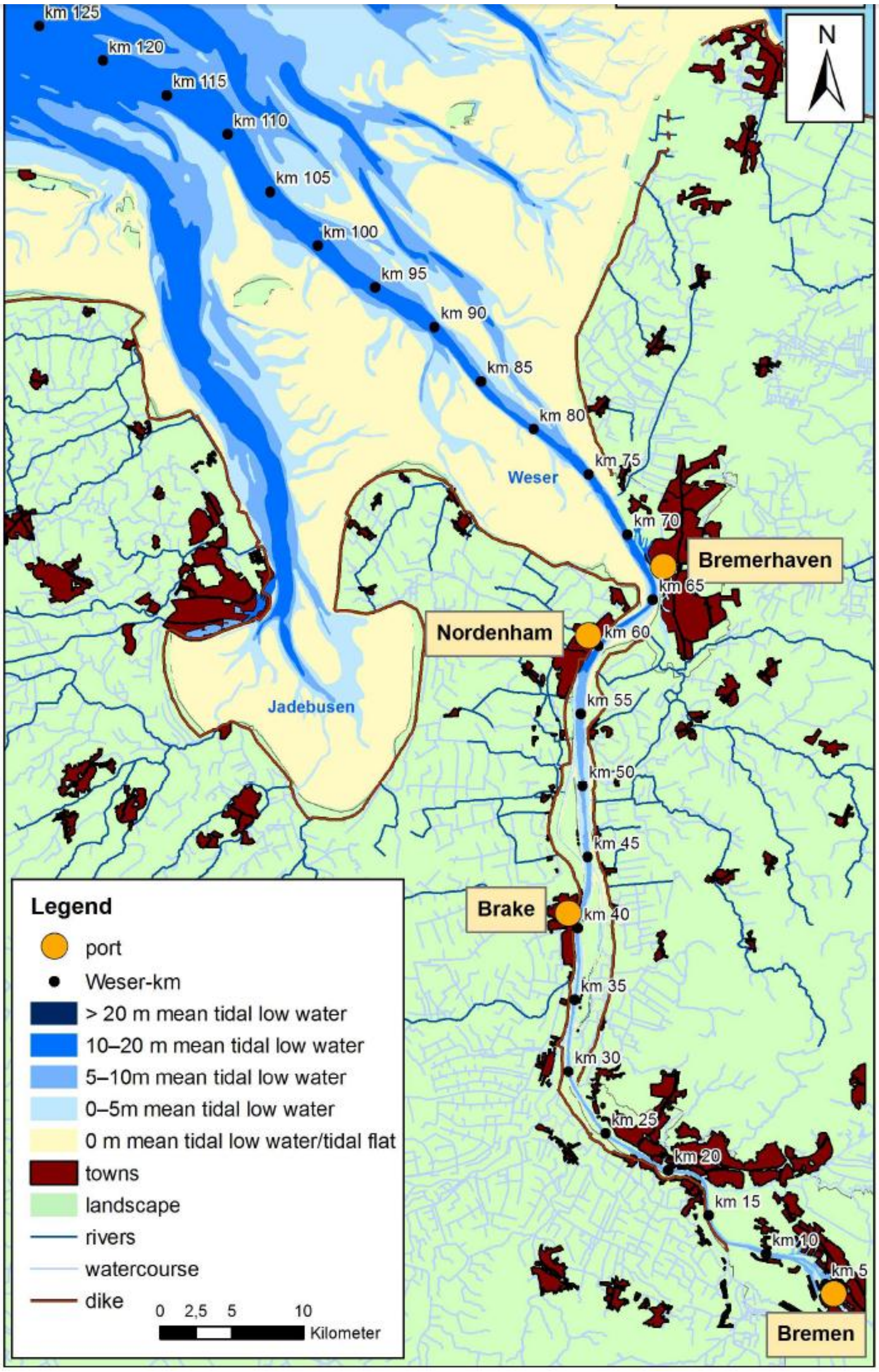


*Figure 18: The Weser estuary*

*Source: BioConsult, 2012*

In order to guarantee the accessibility to the ports, a first substantial deepening campaign in the inner estuary was executed between 1887 and 1893. This deepening campaign allowed vessels with a draft of 5,0m to reach the port of Bremen. Besides the dredging works, profound river engineering works were executed as well, trying to have the current concentrated in the main channel. During the 20th century, 4 further periods of capital dredging works took place in the inner estuary: in 1913-1916 to 7,0m draft, in 1925-1930 to 8,0m draft, in 1953-1959 to 8,7m draft and in 1973-1977 to 9,0m (below low water spring tide, BLWS). Additionally in the 1980’s an extensive groyne construction program has been executed in order to improve the flow concentration in the main channel, reducing the necessary dredging works [21]. Currently an application has been submitted for a new deepening campaign to be able to welcome ships with a draft of 12,8m independent of the tide in the port of Brake and a draft of 11,1m independent of the tide in the port of Bremen [22].

The morphological situation in the outer Weser estuary sufficed the navigation requirements until the end of the 19th century. In 1891 first local dredging activities were initiated here and during the following 20 years the channel was successively deepened over its entire length: to 8,0m below low water tide (BLW) in 1896-1899 and to 10,0m BLW in 1906-1913. In 1922 the fairway was relocated to the western tidal channel in the outer estuary and deepened to a water depth of 10,3m BLW. It was not until 1968 that a new deepening campaign was executed: to 12,0m BLWS in 1968-1971, to 14,0m BLWS in 1998-1999 [21]. The large dredging campaigns were accompanied by extensive river engineering measures such as the construction of groynes to further strengthen the main channel. Currently an application has been submitted for a new deepening campaign to be able to welcome ships with a draft of 13,5m independent of the tide in the port of Bremerhaven [22].

A consequence of this management strongly focused on the accessibility of the ports is the fact that the environmental conditions of the Weser estuary have changed drastically during the last 100 years. A good example to illustrate this is the strong increase of the tidal range. Around Bremen, the tidal range increased from around 0,13m in 1882 to over 4m nowadays. The continuous deepening campaigns eased the tidal penetration in the estuary, causing much higher flow velocities. Upstream Bremen a weir has been constructed to prevent further penetration of the tide. It is clear that this management strongly focused on accessibility created a morphology which is favourable from port accessibility point of view, but rather unfavourable from the point of view of many of the other estuarine functions (e.g. nature, safety against flooding, recreation).

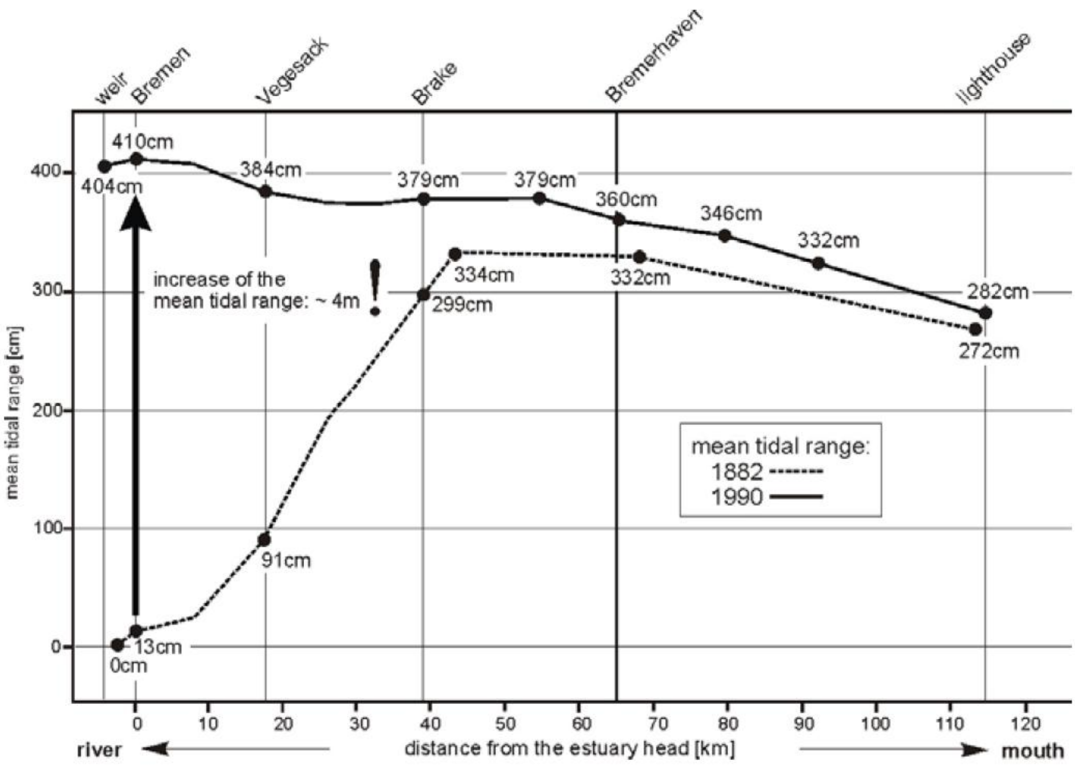


*Figure 19: Evolution of the tidal range in the Weser estuary*

Source: Wienbert, 2003

# 5 A proposal for morphological management in the Scheldt estuary

In this chapter the concept of morphological management will be demonstrated in the Scheldt estuary. Where this proposal is the result of extensive morphological analysis of the Scheldt estuary, this chapter will be rather synoptic not dealing with all the details. For more technical aspects and a substantial analysis, the reader is referred to [17]. This proposal of morphological management can not simply be copied to be applied to other estuaries since it is estuary specific. However the concept of morphological management is applicable to all estuaries. The proposals for the Scheldt estuary in this report are used to illustrate the concept and to demonstrate how a thoughtful management of the morphology can give benefits for all functions of an estuary. First a short introduction to the Scheldt estuary will be given.

## 5.1 The Scheldt estuary

The Scheldt estuary starts at Gentbrugge and has its mouth in the North Sea. The estuary can be divided into 3 morphological different systems: (1) the Sea Scheldt, a natural meandering single channel system between Gentbrugge and the Dutch-Belgian border; (2) the Western Scheldt, a typical multiple channel system between the Dutch-Belgian border and the bottleneck at Vlissingen-Breskens; (3) the Vlakte van de Raan, the open mouth of the estuary in the North Sea.

The tide from the North Sea is penetrating into the estuary. At Gentbrugge, approximately 160km from the mouth, the tidal penetration is stopped by a weir. Where the tidal wave is amplified between the mouth and Temse – some 100km from the mouth – due to the funnel shape of the estuary, friction is becoming more important between Temse and Gentbrugge resulting in a decrease of the tidal amplitude. At the mouth of the estuary the tidal amplitude is on average 4,0m, around Temse it reaches its maximum up to 5,5m on average, whereas at Gentbrugge the mean tidal range still exceeds 2,0m. Between Antwerp and Gentbrugge the different tributaries are also (partially) under tidal influence.

The Scheldt estuary flows through various geological formations in which it has cut its channels. Some of these geological layers are erosion-resistant clay layers, controlling the riverbed in many places in the Western Scheldt. The mean sediment size d50 of the bed material in the Western Scheldt ranges from 50 to 400 µm. These are mainly fine sands and thus quite mobile and easily transported by the tidal flow. In the channels, the size ranges rather from 150 to more than 400 µm, while on sandbars and tidal flats sediment sizes usually range from less than 50 to 150 µm. In the Sea Scheldt the mean size d50 of the bed material is smaller than 150µm, consisting of mainly silt and fine sand [6].

Different ports are located in and around the Scheldt estuary: the port of Zeebrugge in the mouth area, the port of Vlissingen, Terneuzen and Antwerp in the estuary and the port of Gent along the canal Gent-Terneuzen. The port of Antwerp, located more than 60km from the mouth of the estuary, is the largest of these ports. Figure 20 shows a map of the Scheldt estuary where the location of all ports mentioned can be seen.

For a more detailed description of the Scheldt estuary the reader is referred to literature or other TIDE reports.


*Figure 20: Overview of the Scheldt estuary, including all tide dependent tributaries*

## 5.2 A proposal for morphological management

In this paragraph a proposal for the morphological management of the Scheldt estuary is given. Where [17] deals with such a proposal for the entire Scheldt estuary, this report will be limited to 2 regions where a clear need for morphological management exists. After a short description of the local morphology and the current morphological bottlenecks, a proposal to manage the region in a morphological sound way, taking into account all functions of the estuary, is given. Multiple options are suggested without conclusion on which option has to be preferred. It must be clear that the feasibility of these different options and the preferred scenario for each location still has to be investigated in detail. Last but not least it is mentioned that these proposals are optimal with regard to the current morphology of the estuary. Morphological changes will require over time an adaptation of the management strategy as proposed here. Indeed, the morphological management of an estuary is based on a dynamic strategy, anticipating on the morphological evolutions which are inherent to an estuarine environment.

### *5.2.1 The reach Vlissingen-Terneuzen*

The reach between Vlissingen and Terneuzen is a typical flood-ebb channel system with deep channels separated from each other by large intertidal sandbars. Around Borssele a transition is found between the upstream channel system Everingen-Pas van Terneuzen and the downstream channel system Honte-Schaar van Spijkerplaat-Vaarwater langs Hoofdplaat. The fairway in this reach is located in the Honte, going via the sill of Borssele to the Pas van Terneuzen. For the convenience of the reader, the location of the main channels and sandbars in this region are shown in Figure 21.

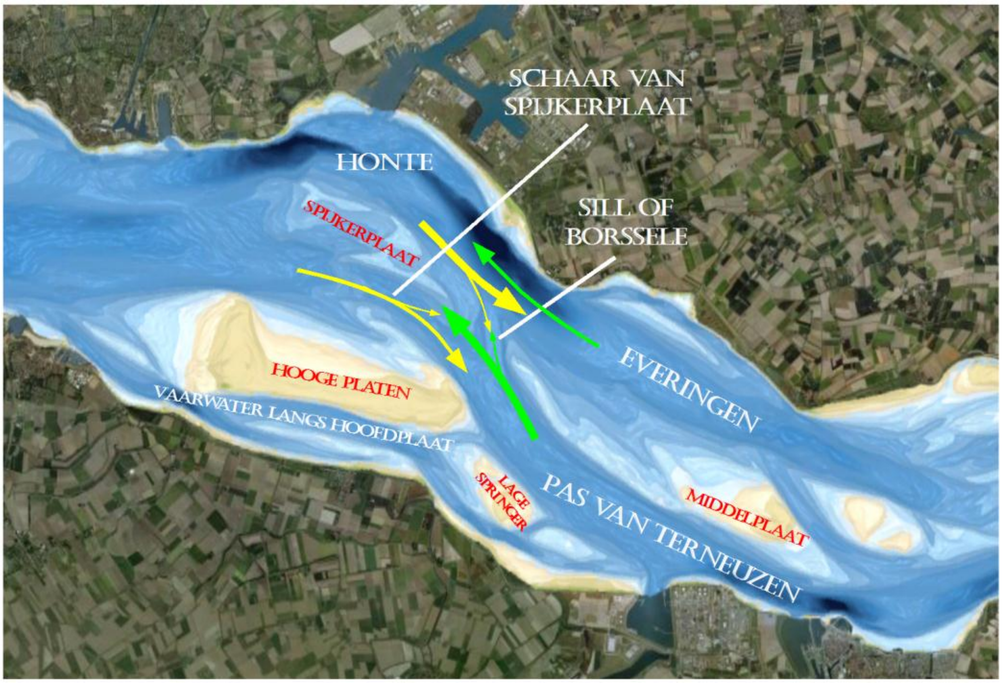


*Figure 21: Overview of the region Vlissingen-Terneuzen in the Western Scheldt. Schematic distribution of ebb flow (green) and flood flow (yellow) around the sill of Borssele is given.*

*Source aerial picture: Google Maps*

The connection between the Honte and the Pas van Terneuzen is not favourable from morphological point of view. During flood only a small amount of the flow from the Honte is crossing the sill of Borssele to go to the Pas van Terneuzen, whereas the flow leaving the Schaar van Spijkerplaat is mainly going to the Pas van Terneuzen. During ebb the flow of the Pas van Terneuzen is heading towards the Spijkerplaat, attacking this sandbar complex. Only a small amount of the ebb flow will go over the sill of Borssele. This morphological unfavourable situation is mainly due to the morphological evolution of the channel Schaar van Spijkerplaat. Maintenance dredging works on the sill of Borssele are necessary to keep the fairway in this channel. These maintenance dredging works are in fact working against the natural morphological evolution.

In order to improve the morphological situation at this location, 2 different alternatives for morphological management are proposed. Both alternatives take into account the natural morphological evolution of this region.

**Alternative 1: Improve connection Honte-Pas van Terneuzen**

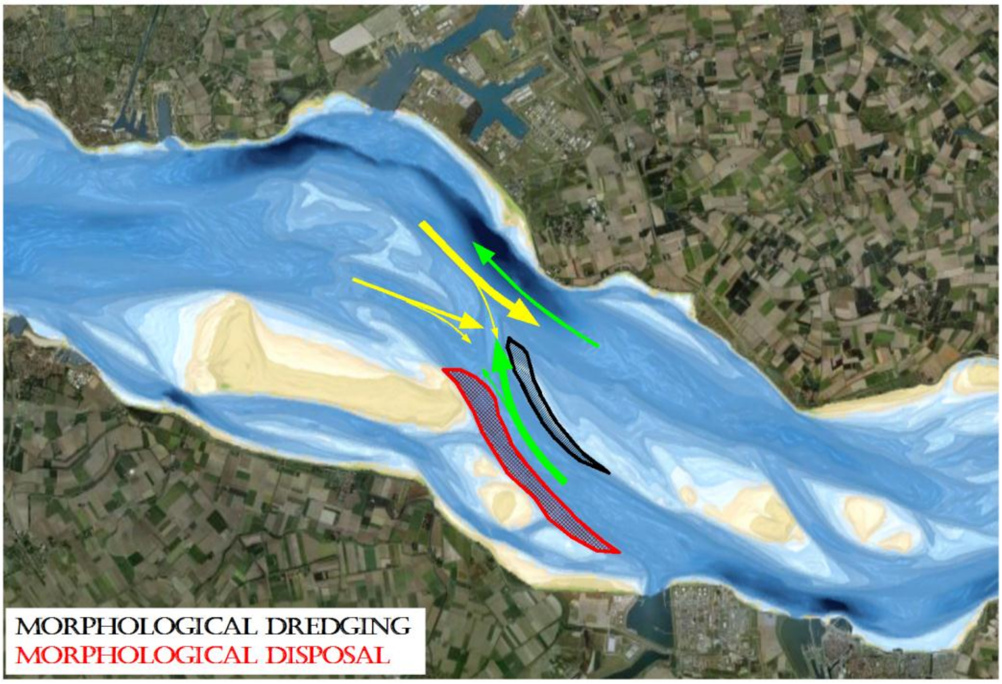


*Figure 22: Reach Vlissingen-Terneuzen: proposal improving connection Honte-Pas van Terneuzen. Schematic distribution of ebb flow (green) and flood flow (yellow).*
*Source aerial picture: Google Maps*

| | |
|---|---|
| **Goal** | To guide the ebb flow from Pas van Terneuzen towards Honte over sill of Borssele |
| **Strategy** | Shift of the seaward end of Pas van Terneuzen in north-eastern direction (possibly combined with shift in western direction of sill of Borssele) by:<br>- morphological dredging of the seaward tip of the Middelplaat (black)<br>- continuous morphological disposal along the south-western bank of the Pas van Terneuzen (red) |
| **Strengths** | - restore morphological connection between Pas van Terneuzen and Honte<br>- stop attack of ebb flow on Spijkerplaat sandbar<br>- increase discharge over sill of Borssele (less maintenance dredging works required)<br>- improve the local multiple channel system |
| **Weaknesses** | - working against the natural evolution (i.e. shift of the seaward end of Pas van Terneuzen in south-western direction)<br>- use of continuous morphological disposal is required (where will disposed material settle, need for extra dredging works?)<br>- possible sedimentation along the inner bend of Pas van Terneuzen, which will require maintenance dredging works |

*Table 1: Summary of proposal alternative 1 in the reach Vlissingen-Terneuzen*

**Alternative 2: Improve connection Schaar van Spijkerplaat-Pas van Terneuzen**

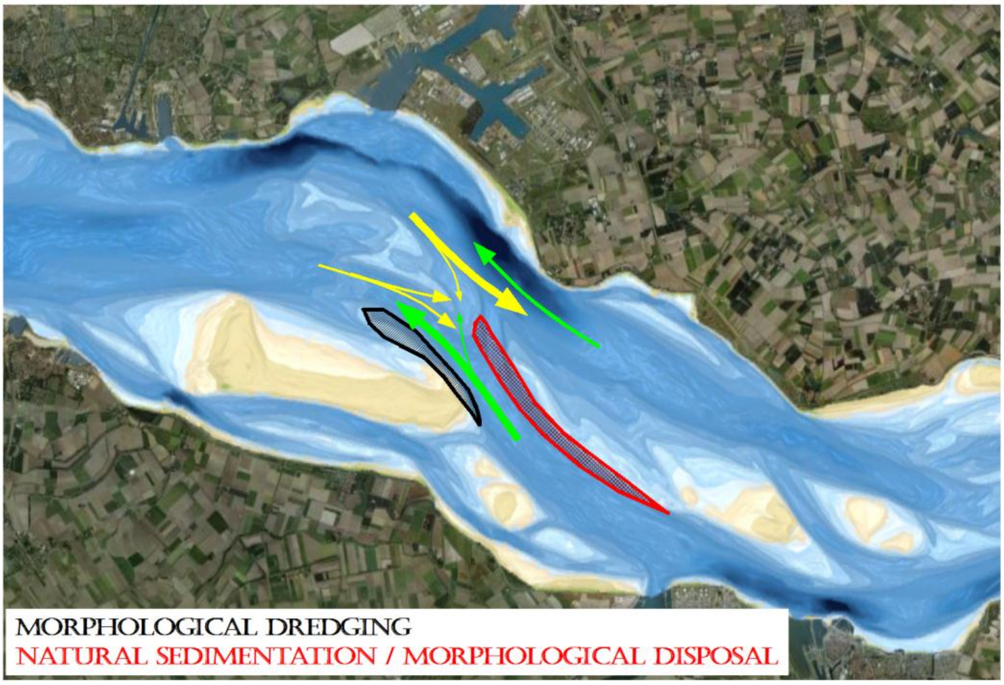


*Figure 23: Reach Vlissingen-Terneuzen: proposal improving connection Schaar van Spijkerplaat-Pas van Terneuzen. Schematic distribution of ebb flow (green) and flood flow (yellow).*

*Source aerial picture: Google Maps*

| | |
|---|---|
| **Goal** | To guide the ebb flow from the Pas van Terneuzen towards the Schaar van Spijkerplaat |
| **Strategy** | Shift of the seaward end of Pas van Terneuzen in south-western direction by:<br>- natural sedimentation and/or morphological disposal along the north-eastern bank of the channel (red)<br>- capital dredging works in the Schaar van Spijkerplaat<br>- (possibly) morphological dredging of the landward tip of Hooge Platen (black) |
| **Strengths** | - working with the ongoing natural evolution (i.e. connection between Pas van Terneuzen and Schaar van Spijkerplaat)<br>- stop attack of ebb flow on Spijkerplaat sandbar<br>- extension of ecological valuable undeep water and intertidal area along the Middelplaat<br>- creation of nautical benefits (fairway in Schaar van Spijkerplaat instead of Honte)<br>- avoiding cross currents at the sill of Borssele<br>- shortening of the fairway to the more upstream ports |

| | |
|---|---|
| **Weaknesses** | - natural morphological processes will shift the Schaar van Spijkerplaat in northern direction over time, possibly creating temporary unfavourable nautical conditions<br>- (possibly) maintenance dredging works in the Schaar van Spijkerplaat |

*Table 2: Summary of proposal alternative 2 in the reach Vlissingen-Terneuzen*

### *5.2.2 The reach Baarland-Baalhoek*

In the reach from Baarland to Baalhoek, one can distinguish 3 different flood-ebb channel systems. Around Baarland the ebb channel Middelgat is separated from the flood channel Gat van Ossenisse-Overloop van Hansweert by a large sandbar complex: Rug van Baarland. Around Hansweert, the intertidal sandbar Platen van Ossenisse Oost is separating the large ebb channel Overloop van Hansweert from the flood channel Schaar van Ossenisse. The Overloop van Hansweert changes name to Zuidergat channel around the jetties of the Hansweert lock. At this location the river has a very wide section resulting in high amounts of maintenance dredging works [17]. The sill of Hansweert – name of the sill at this location – is the sill with the highest amounts of yearly maintenance dredging works. Up-estuary of the sill of Hansweert another flood-ebb channel system can be found: the ebb channel Zuidergat and the flood channel Schaar van Waarde. In between both channels the large intertidal sandbar of Walsoorden-Platen van Valkenisse West can be found. The fairway in this reach is going form the Gat van Ossenisse in the Overloop van Hansweert, through the sill of Hansweert into the Zuidergat channel. The reader can find the location of the different main channels and sandbars in this region in Figure 24.

The morphological situation in this area is not favourable. Hard bordering along the estuary has oriented the flood flow coming from the Overloop van Hansweert towards the seaward tip of the shoal of Walsoorden. As a consequence this sandbar has been eroding in the past, creating the wide cross-section of the channel at the sill of Hansweert. Similar the orientation of the ebb flow has changed over time: where the ebb flow used to go through the Middelgat channel, nowadays the ebb flow is oriented towards the Geul van de Molenplaat. As a consequence the discharges through the Middelgat have reduced considerably, causing sedimentation in this channel. If no measures are taken to improve the morphological situation, there is a danger for the Middelgat to disappear, changing the Western Scheldt locally into a single-channel system.

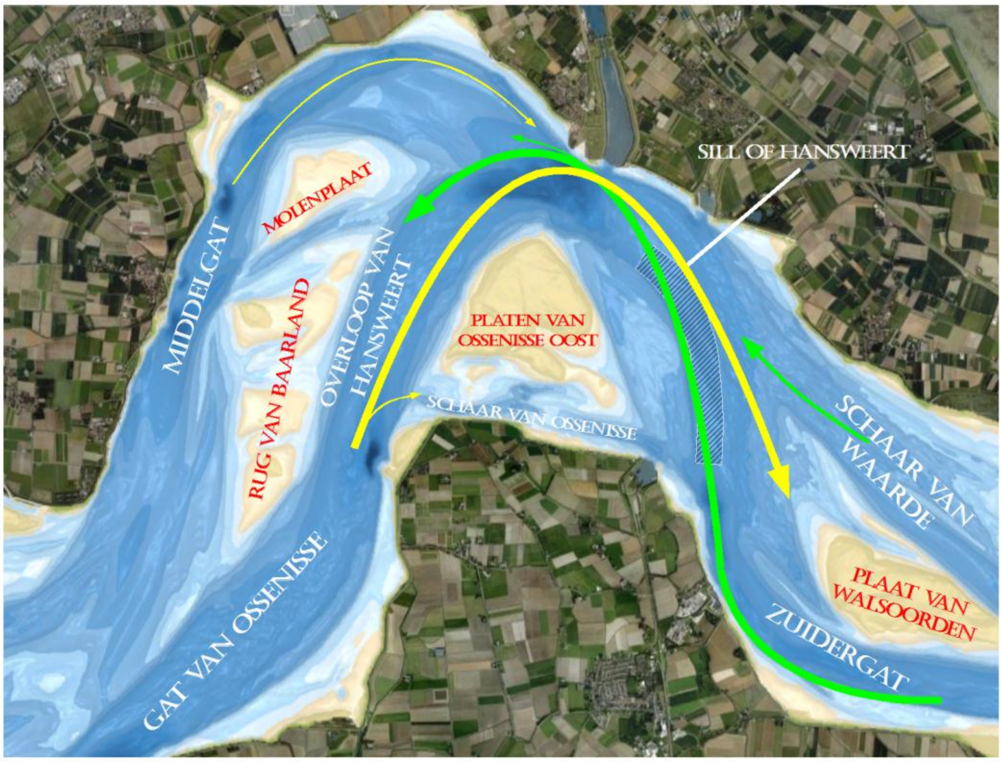


*Figure 24: Overview of the region Baarland-Baalhoek in the Western Scheldt. Schematic distribution of ebb flow (green) and flood flow (yellow) around the bend of Hansweert is given.*

*Source aerial picture: Google Maps*

In order to improve the morphological situation at this location, 2 different alternatives for morphological management are proposed. Both alternatives take into account the natural morphological evolution of this region.

### Alternative 1: Restoring the original Middelgat connection

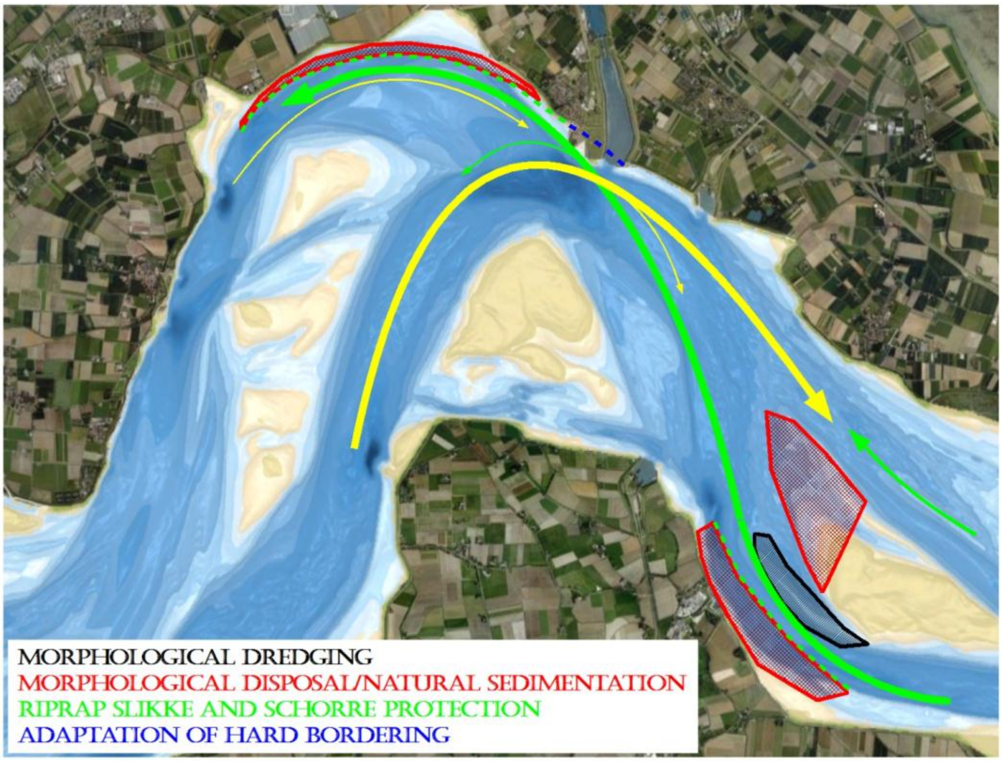


*Figure 25: Reach Baarland-Baalhoek: proposal restoring Middelgat connection. Schematic distribution of ebb flow (green) and flood flow (yellow).*
*Source aerial picture: Google Maps*

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|---|---|
| **Goal** | Restoring the Zuidergat-Middelgat connection for the ebb flow and the Overloop van Hansweert-Schaar van Waarde connection for the flood flow |
| **Strategy** | Improving the ebb flow through the Middelgat channel by:<br>- realignment of the bend of Zuidergat channel by morphological dredging, riprap slikke and schorre protection and morphological disposal<br>- narrowing the cross-section of the sill of Hansweert by morphological disposal (i.e. restoring the shoal of Walsoorden) to increase the self-eroding capacity of the flow<br>- adapting the hard bordering at the Hansweert lock<br>- concentrating the flow in the Middelgat channel by riprap slikke and schorre protection and morphological disposal |
| **Strengths** | - maintaining the multiple channel system<br>- stop attack of flood flow on Walsoorden sandbar<br>- restore morphological connection Zuidergat-Middelgat and Overloop van Hansweert-Schaar van Waarde |

| | |
|---|---|
| | - ecological potential of the three intervention zones<br>- reduction of dredging effort on sill of Hansweert |
| **Weaknesses** | - working against the natural evolution in the Zuidergat channel (i.e. erosion at outer channel bend) although in present situation already fixated by hard bordering<br>- application of rip rap protection is required (i.e. preventing erosion in the outer bend)<br>- adaptation of hard bordering is required<br>- use of continuous morphological disposal is required<br>- effect of proposal on dredging works in Overloop van Hansweert (= fairway) not clear |

*Table 6: Summary of morphological proposal alternative 1 in the reach Baarland-Baalhoek*

### Alternative 2: Improving the Geul van de Molenplaat connection

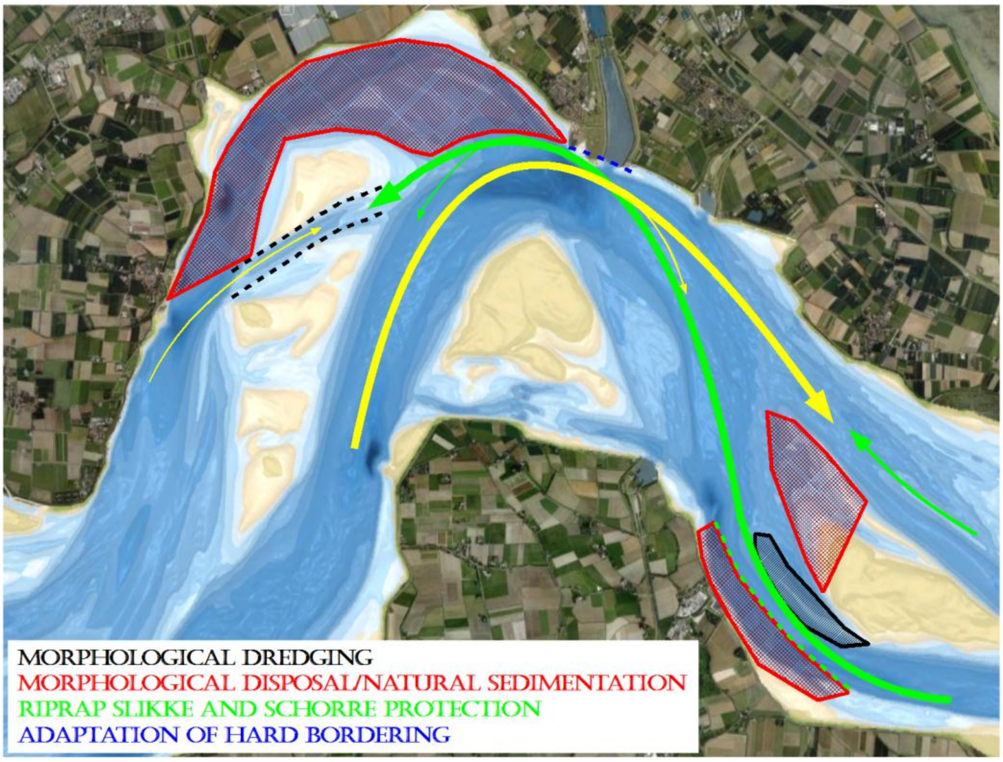


*Figure 26: Reach Baarland-Baalhoek: proposal improving Geul van de Molenplaat connection. Schematic distribution of ebb flow (green) and flood flow (yellow).*
*Source aerial picture: Google Maps*

| | |
|---|---|
| **Goal** | Improving the connection Zuidergat-Middelgat through the Geul van de Molenplaat for the ebb flow and the Overloop van Hansweert-Schaar van Waarde connection for the flood flow |
| **Strategy** | Improving the ebb flow though the Geul van de Molenplaat by:<br>- enlargement of the cross section of the Geul van Molenplaat by capital dredging<br>- adapting hard bordering at the Hansweert lock to better guide flow to Schaar van Spijkerplaat<br>- developing a large undeep water and intertidal area zone in the bend of Hansweert by morphological disposal/natural sedimentation |
| **Strengths** | - maintaining the multiple channel system locally<br>- stopping attack of flood flow on Walsoorden sandbar<br>- creating zone in outer bend of Middelgat channel with large ecological potential<br>- restore morphological connection Zuidergat-Middelgat and Overloop van Hansweert-Schaar van Waarde<br>- working with natural evolution (i.e. shift of ebb flow direction towards Geul van Molenplaat) |
| **Weaknesses** | - effect of proposal on dredging works in Overloop van Hansweert (= fairway) not clear<br>- uncertainties about the morphological evolution of the Geul van de Molenplaat<br>- adaptation of hard bordering required<br>- application of rip rap protection in Zuidergat is required (i.e. preventing the natural erosion in the outer bend) |

*Table 7: Summary of morphological proposal alternative 2 in the reach Baarland-Baalhoek*

## 5.3 Conclusion morphological management in the Scheldt estuary

When investigating the morphodynamics of the Scheldt estuary, one can see that the large scale dynamics are nowadays hindered at many locations by the hard bordering of the system [17]. Depoldering of large areas located along the estuary would be necessary in order to restore these large scale morphodynamics. Where such measures would be beneficial from morphological point of view, they are at this moment not acceptable from societal point of view. The morphological management for the Scheldt estuary as presented in this chapter takes into account this societal aspect as well: it is aiming to keep the morphodynamics on meso scale and small scale, minimizing the area that needs to be depoldered. As a consequence, some measures have to be taken to stop the estuary from trying to have its large scale morphodynamic behaviour (i.e. morphological disposal and/or rip rap protection along the outer bend of natural eroding channels), since this leads to unfavourable morphological situations.

For both the reach Vlissingen-Terneuzen and the reach Baarland-Baalhoek the proposal for morphological management aims at concentrating the flow in the channels, in mean time stopping erosion of sandbars due to an unfavourable direction of the flow. This strategy improves the multiple channel system of the estuary, which is considered as being essential in the Long Term Vision of the Scheldt estuary since it is offering benefits to the different functions oft he estuary. For both regions, 2 alternatives are worked out with indication oft he advantages and disadvantages of each alternative. Further research has to be done in order to determine which alternative is to be preferred from morphological point of view, and how exactly this has to be done in the field.

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