WESTERSCHELDE

Draft
Baseline Report

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PREAMBLE

In 1999, the Antwerp Port Authorities requested a team of 3 international experts to give independent advice on the technical feasibility of a further deepening of the maritime access to the Antwerp harbour. The team started the activities on 6 December 1999.

This interim document reports on the findings of the first phase of the assignment. The study is sub-divided in three phases; phase one provides an analysis of the basic information on the long-term trend in the estuary's behaviour; it is presented in this report, called the base-line report. In a second phase a more detailed impact analysis of deepening the navigation channels by dredging will be examined. In the third and final report, the feasibility of a further deepening for navigation will be analysed on the basis of all the data and ongoing studies and suggestions given for a sustainable management of the Westerschelde.

This report for phase 1 starts with a first chapter on the genesis of the Western Scheldt estuary during the last Holocene transgression period, from about BP 12.000 till today. This period is subdivided in three parts, the first going till year 1.800, the second from 1.800 till 1.960 and the third from 1.960 till 2.000. They are characterised by a varying the human impact on the natural changes, ranging from none at the start of the Holocene to significant today. The following indicators are therefore utilised:

- tides and their propagation through the estuary (hydraulic parameters, from qualitative since 1550 to quantitative for the last century)
- salinity and its intrusion in the river system
- morphology (geometric parameters, mainly qualitative)

The study remains obviously general as it is based on the available information; the experts were not requested to conduct any special research or modelling, only the processing of information that exists already. The sources of information are many, diverse, but not always easily accessible, most of them in Dutch.

The authors acknowledge the risks and problems of writing a report on such a complex issue and they do not have the intention to present an exhaustive work that compiles all the knowledge gathered on the estuaries in general and on the Western Scheldt estuary in particular. The reports are not set up as a monograph, rather as a review of parts of existing knowledge that may be useful for answering basic questions:

> *What could be the future evolution of the estuary under influence of natural factors and human impact, and what are the possibilities to further improve the navigation conditions without damaging the estuarine environment?*
>
> *On the longer term, what kind of management is needed to have the estuary evolving towards an even more healthy morphology as the one that existed some fifty or sixty years ago?*

This fits in the Long Term Vision (LTV) project, set up jointly by the Dutch Rijkswaterstaat and the Flemish Government. The Team was therefore fortunate to be accepted in the LTV Cluster Morphology that responds to requests from the LTV Working Groups Accessibility, Safety and Naturalness. Because the LTV partners expressed the need to receive as quickly as possible the ideas of the expert team, this report is issued in a preliminary draft version. The team leader apologises for the errors and shortcomings of this version, but believes it is more appropriate to distribute it now so that it can be used as a piece of information for the LTV meetings to be held in June 2000.

INTRODUCTION

Estuaries exist since freshwater discharges through rivers into seas and the ocean. The definition of an estuary given in 1955 by Pritchard says:

> *Estuaries are semi-enclosed coastal bodies in which tides propagate freely and in which freshwater drained from land mixes in a measurable way with the seawater*

It does not refer to the transit of solid materials through the estuarial systems, now recognised as a key factor for their evolution.

Estuaries have been studied intensively because of their importance as areas of economic development and their high ecological value. However, the natural changes as influenced by the varying climatological conditions only recently received due attention. The impact of "global warming" is presently a hot topic. However, it should be remembered that dramatic changes occurred from the end of the Pleistocene into the first phase of the Holocene period - from year BP 18.000 till year BP 5.000 - with a sea level rise of over hundred meters. In comparison, the magnitude of present sea level changes are extremely mild, although the rate of change may be(come) significant, even endangering those living in lowland areas.

As a consequence of this sea level rise, the shoreline has been changing all that time since the start of the Holocene and sediment, both marine and continental, have been filling up the inundated river courses. In every particular case, the sediment processes create a whole array of coastal environments, from estuary to delta or lagoon, depending on the relative magnitude of sediment supply originating from land or sea:

the estuary, in which sediment supplied by the river is not sufficient to fill the river course down to the coastline; it has a typical dominant sea influence characterised by the tides

the (river) delta, in which sediment supplied by the river was sufficient to fill the downstream river course up to and beyond the coastline, extending the alluvial fan in the sea; it has a typical dominant river influence characterised by the inflow of sediment of continental origin

the lagoon, in which marine sediment moving along the coast under influence of tidal currents and waves creates a barrier that retains the fresh river water in a lake along the coast, while the barrier can be breached during river floods; the lagoon lake may be progressively filled with continental sediment supplied by the rivers

Because of the significant climatic changes in the Holocene period, the morphology of most estuaries, and in particular the coastal plain estuaries, has been continuously adapting to the variations in sea levels and in hydrological conditions in the river catchments. Estuaries became deltas or lagoons, depending on the relative magnitude of sediment transported by the riverflow or sea currents. The boundaries of estuaries are sometimes hard to identify and a distinction has to be made between the estuary defined by the length of intrusion of the salinity and the one defined by the limit of the tidal wave propagation, sometimes referred to as the maritime reach of a river.

The ideas developed in this report focus on coastal plain estuaries, for which the Western Scheldt estuary is somehow an example, not a typical one, though. Many natural factors control the physical existence of estuaries and their evolution, among others geology, tectonics, soil mechanics, biology, physico-chemistry, hydraulics (flow and sediment). Mechanisms related to the sediment supply, transport and deposition induce irreversible changes in the estuarine environment. These changes are unavoidable, natural and they control the long-term trend in the morphology of the estuary. They require appropriate management and conservation measures to keep the best possible estuarine environment, from the point of view of its ecology, instead of a policy of preservation of a prevalent situation that anyhow can not remain unchanged. The challenge is to ensure a healthy evolution of a coastal plain estuary to benefit mankind, respecting its valuable ecology.

A. GENERALITIES AND BACKGROUND INFORMATION

NATURAL MECHANISMS OF COASTAL PLAIN ESTUARIES

The mechanisms and forces controlling the behaviour of a coastal plain estuary are many and not all well known or understood. Attempts to predict the morphological behaviour of these complex systems with models have not yet been very successful. Only simplified models allow simulations of distinctive mechanisms, one example being the mixing of the fresh river water with seawater, that can be predicted in some way but without understanding thoroughly the intimate mixing mechanisms that are therefore rather poorly reproduced in the models. The estuarine environment at seas with significant tides combines the characteristics of the river, in which flow is driven by earth's gravity with those of the sea along the coast, mainly driven by the tides having their origin in the astronomical forces. Density flows having their origin in differences in temperature, salinity or turbidity may also intervene in the sea, but in the Southern Bay of the North Sea, the tidal forces are by far the most important source of energy for the estuaries like the Scheldt. Wind and waves may also impact the estuarial processes.

The oceanic tide produces a the tidal wave that propagates inland towards the head of the estuaries. Its energy combines in each section with the energy of the river flow to mix the fresh river water with the salt seawater. A comprehensive description of the physical properties of estuaries can be found in the literature. It will not be repeated here and only the basic mechanisms and forces relevant for the Scheldt, a well-mixed coastal plain estuary, will be summarised hereafter. They are limited to what is relevant for the purpose of this report, which is to assess the past long-term changes in the Scheldt estuary's morphology needed to appraise the present and future changes, as influenced by the natural processes and by human interventions.

Hydrodynamics

The flow in every position of the estuary is the result of the combined power of the tidal wave with that of the river flow.

The tidal action

The tidal power available at the open sea boundary varies cyclically. The process is well known and only the main characteristics shall be repeated here:

- the periodicity is controlled mainly by the moon cycle which produces a tidal wave in the ocean, deformed in its progression by the geometry of the seas
- the changes in relative position of the celestial bodies controlling most the tides - which are the earth, the moon and the sun - induce periodical variations in the tidal wave at the time scale of the rotation the earth in its relative orientation to the moon (the semi-diurnal period of 12.4 hours), of the rotation of the moon around the earth (the spring-neap tidal cycle of 28 days), of the rotation of the earth-moon system around the sun (the annual cycle of 365 days)
- long-term celestial movements produce an 18.6 year cycle in tide generating forces (the nodal cycle)

The characteristics of the tides are changing with the variations in sea level, especially in the shallow seas that were progressively submerged during the Holocene. At the mouth of a coastal plain estuary discharging in such a sea, as for the Scheldt, variations in tidal energy are partly due to the changes in coastal morphology. These are usually slow and result from the hydrodynamic processes, but also from geophysical processes such as tectonics.

In this baseline report, the Scheldt tidal data will be analysed for assessing the trends at the various time-scales. An attempt is made to distinguish between the medium- to long-term trend in the Holocene period, mainly due to the ocean level rise, and the more recent trend resulting mainly from morphological changes in the North Sea.

Before analysing the tidal data and processes, the boundaries of the system need to be defined. There is often confusion about the location of the mouth of a coastal plain estuary, the boundary between the sea and the estuary. Sometimes, the limit is clearly the point of encounter of the river with the coastline. In a case like the Scheldt, the choice of the boundary is taken on the basis of the plan form geometry, like the bottleneck-type end, just before reaching the "open" sea.

For the Scheldt, the bottleneck at Breskens-Vlissingen has traditionally been taken as the seaward boundary of the estuary, whereas the boundary would rather be some 25 to 35 km further seawards[1]. The upstream boundary is the place where the propagation of the tidal wave ends, or by exhausting its energy through friction, or by reflecting on a barrage. For the Scheldt, this place is Gent, where a barrage halts the tidal wave in its propagation. The Scheldt estuary is about 190 km long.

The volume of water entering an estuary during the flood phase of the tide is determined by the propagation and deformation of the tide during its movement towards the head of the tidal reach and by the geometry of this tidal reach. The tidal prism volume may change with natural processes and works, such as the erosion and siltation processes. Also land reclamation or barrage building on the

[1] This is measured along the Scheur-Wielingen channel, down to the open sea, at the end of the Vlakte van de Raan

river or on its tributaries affect the volume. Furthermore, changes in sea level and tidal wave amplitude modify the tidal prism volume.

Storms

In absence of man-made coastal protections, storms affect the shoreline and the coastal plain estuaries discussed here. During storms in shallow seas, sedimentary processes along the seacoast are temporarily changing the shoreline, but it recovers its shape quite rapidly. Storms therefore do not induce long-term changes in the morphology of the coastal plain estuaries when the shorelines are not affected significantly, also because the usually short duration of a storm. However, exceptional storms such as the one in February 1953, affect significantly the morphology of an estuary because of the breaches in the shoreline protections that modifies the flow and sediment transport patterns.

Besides the wave action, storms produce sea level changes. A significant sea level rise during a storm may provoke breaches in the natural coastline defences and these incidents are more likely to occur when they coincide with extreme spring tides. Storms may cause inundation of lowlands when the dunes or levees along a coastline or an estuary are breached. If the area of inundated polders is large, a cyclic filling and emptying of the polder creates strong currents through the breaches that erode a system of channels and creeks.

In the early stages of the Rhine-Maas-Scheldt delta formation, storms have created numerous of these creeks that became as many branches of the estuarial system within the lagoon formed during the Holocene sea level rise. The shape of these channels and creeks has changed progressively under influence of the tidal action: scouring of channels and siltation of sediments on shoals and tidal flats.

The freshwater river flow

Among the characteristics of the freshwater flows draining the catchment of a coastal plain estuary, two are controlling most the longer-term morphological trends:

- the total yearly freshwater volume inflowing the head of the estuary
- the intensity of the river floods

They are determined by the transformation of rainfall into runoff in the river system, for which the spatial and temporal distribution of the rainfall and the catchment topography are most relevant.

Another key factor is the river slope and its variation in the tidal reach. The river slope may remain significant till the coastline or end before it, as for rivers discharging in lagoons. In the Scheldt, this point is inland of the Westerschelde, at some 90 km from Vlissingen. The impact of the freshwater flow on an estuary depends on the shape of the flood hydrograph, controlled by the rainfall-runoff processes and by the river flood wave propagation.

The freshwater-seawater mixing processes

The mixing intensity of the fresh river water with the salt seawater depends on the one hand on the relative magnitude of the available energy originating from the sea - mainly the tidal - and the energy originating from the river flow, and on the other hand on the geometric characteristics of the estuary. When the mixing intensity is small, the fresh river water will flow on top of the salt seawater, making a "salt-wedge" type system with two layers, the upper being occupied by the river flow moving seaward. The lower layer is the seawater that intrudes into the river near the bottom, undergoing a piston-like up movement with the tides. When the mixing is more intense, the two-layer system changes in a partially mixed estuary having a gradual variation in salinity from bottom to surface and from land to sea. The further sequences when mixing becomes stronger are the well-mixed estuary, followed by the homogeneous estuary. The degree of mixing and stratification changes along the estuary, and in any place with the river discharge.

The residence time - sometimes also called the flushing time - of the freshwater in the estuary depends on the degree of mixing with the seawater. In a salt-wedge estuary, the residence time is quite short, from hours to days depending on the case. In well-mixed estuaries, the residence time may become very high, from weeks to months, like in the Scheldt.

Sedimentary processes

The river sediment transport

The processes of erosion, transport and deposition of the sediment carried by the river affects obviously the long-term trend in river morphology. In aggrading rivers, the sediment load is higher than what the flow is able to carry by its transport capacity and the riverbed will rise. When such a river discharges in an estuary, this will fill up progressively and become finally a delta. The Ebro in Spain is an example of a river which mouth changed in a short time - about some hundreds years - from an estuary cutting into the coastline and where the saline sea water intruded into the river, towards an extended delta protruding on the coastline. The cause of this rapid change has been identified as the increase of sediment load carried by the river, a consequence of deforestation around 1500.

The littoral sediment transport

Tides and waves induce sediment movement along the shoreline. The sediment source may be the material eroded from the coast itself or the alluvium discharged in the sea by rivers. The Holocene sea level rise produced in some places intense reworking of the coastline and resulted in the creation of lagoons and deltas. The coastal morphology may further change with the construction of coastal structures such as harbours or shoreline protections or with the depletion of the river's sediment load because of barrage construction. The modifications in the littoral sediment transit may have significant impact on the morphological development of the coast, and consequently on the coastal plain estuaries.

The in-system estuarine sedimentary processes

In a coastal plain estuary, processes of sediment erosion, transportation and deposition are complex and many. The sediment in one section may have various origins: from the sea (marine), from the upper river catchment (fluvial), from the erosion of the estuarial bottom itself (mixed, can be both marine and continental) and authogenic (crystallisation). In this report, the discussion of the sedimentary processes is limited to the well-mixed estuary like the Scheldt, with predominant tidal influence.

The tidal currents produce a cyclic circulation of the sediment, an up- and downstream movement with flood and ebb, along different paths. In some channels, upstream movement is predominant, in other channels the seaward movement is predominant. The average movement is typically upstream for flood channels and seaward for ebb channels. A common opinion is that, because main flood and main ebb channels join and split again, there is a sort of circulation of sediment around the shoals and bars. This concept is too simplistic and may lead to wrong conclusions about the flow and sediment movement.

The process of sediment transport in an estuary is extremely complex. Particles staying on the bottom during the slack of the tide may be eroded with upcoming flood or ebb currents, then transported along the bottom and possibly re-suspended in the water column. The bed movement results in different kind of bedforms, common ones being ripples and dunes. Particles transported in suspension may settle again or remain in suspension, depending on their size and the local flow conditions. Finer particles eroded from the deeper portions of the estuary - from the channel - may end up deposited on sandbars, slikke or schorre. Material eroded from the higher grounds may end up in the deeper parts. The complexity of the sedimentary processes results in a blurry picture of the distribution of solid materials, which complicates the analysis of field data. It is hazardous to deduce sediment transport patterns from the spatial distribution of sediment sizes for example. Also bedform shapes and dimensions are the result of various transformations, the observed shape being the result of the last movement, a remnant picture.

The sediment load carried by a river like the Scheldt is mainly composed of very fine, colloidal particles. As explained earlier, the freshwater-seawater mixing creates longitudinal, vertical and transverse salinity gradients. The light colloidal particles such as clay or some organic materials are prone to flocculation, creating mud flocs that settle more easily. In a well-mixed estuary, the colloidal particles carried by the river flow encounter in their way to the sea a progressively increasing salinity. In between values of 1 and 5 ‰, flocculation makes the colloidal part of the suspended load - the wash load - moving as mud flocs closer to the riverbed. Because of the density currents, the tidal-averaged flow close to the bed is entering the estuary at both boundaries: at the mouth, bottom currents carry marine sediments upstream while in the river the bottom currents carry fluvial sediments towards the sea. There is a place, determined by the freshwater-seawater mixing, where the bottom flow has a zero residual movement, this means that the water undergoes in average only a flood and ebb displacement having the same excursion. At that place, called the no-net transport zone, the mud produced by the flocculation of the colloidal fraction of the river sediment and that moves close to the river bed, will create the typical estuarial mud deposits. In these areas, mud can be found in the deeper channel and on the mud flats, while coarser material such as sand may be present along the side of the channel.

Estuarial morphological processes

To begin with, it has to be mentioned that sediment transport is only part of the processes responsible for the morphological changes, besides many others. The morphological processes are controlled by the geomorphic setting, in which the sedimentary processes have to act. The large variety of estuarial settings does not allow giving an overview of all morphological processes encountered in estuaries. Therefore, the discussion will focus on the typical - and may be unique - example of the Scheldt.

In the Westerschelde, the geology of the bottom is quaternary and tertiary. The flow reworks the older sea or river silt or sand deposits. It also scours consolidated clay such as the Boomse Clay, which is well apparent in Hemiksem, some 10 km upstream of Antwerp, but is also found more downstream. The past and future morphological evolutions must therefore be analysed within the geological context.

The active channels in the former lagoon have undergone a process of deepening and widening, while the shoals became shallower and rising above low tide. This accretion process - called "verlanding" in Dutch - is going on since the start of the Holocene sea level rise, still continuing today. The tides have been progressing further upstream and continue eroding progressively the cross-sections more upstream, up to the point when the flow currents reach a kind of an equilibrium stage. The presence of clay makes the erosion more difficult.

Initially, the channel and creek network in the lagoon was very complex. Tidal waves are deformed during their propagation, the flood becoming shorter and the ebb longer. Many secondary creeks connecting the main creeks silted up progressively and were reclaimed to make polders or, more recently, harbours.

Being the combination of a channel network in a lagoon with a river, the morphological processes in the Scheldt estuary are neither simple nor easy to analyse. Because of the continuing deepening of the channel, both by natural scouring and by dredging, more erosion resistant layers appear at the bottom and control the further morphological evolutions. This has to be taken into account in the assessment of the management of the Westerschelde.

Conclusions

The present knowledge about estuarial processes is rather limited in general. Therefore, management tools must rely on a large range of assumptions and simplifications. Models must be based on the best possible understanding of the natural processes.

THE LONG TERM CHANGES IN THE SCHELDT ESTUARY

Creation of the estuary and overall description

The Western Scheldt estuary is located in a coastal plain, along a shallow sea, the Southern Bay of the North Sea. This bay area was once land, before it was invaded by the sea level rise during the last Holocene Transgression (Fig. 1). Before that, it had experienced other transgressions that created the lowland area extending along the present seacoast from the North of France to Denmark. The area was shaped and reshaped many times, in periods with very different climatological conditions.

The geomorphologic changes of the Southern Bay of the North Sea and the Rhine-Meuse-Scheldt delta during the early Holocene are only roughly known. At the end of the Pleistocene, the rivers Rhine, Meuse, Scheldt and Thames discharged in the Atlantic Ocean in the middle of what is now the North Sea, near Doggersbank (Fig. 2). Some 7,000 years ago, the sea invaded the Strait of Dover (strait of Kales) between England and France. From then on, tidal currents eroded the cliffs along the French coast and this erosion increased with a further sea level rise. The sediment produced from the eroding coast moved in Northeast direction, creating sandbanks in the sea in front of what is now the Belgian and Dutch coast. Where these banks emerged, the wind and associated waves formed the dunes. When high enough, they formed an almost continuous chain and created so a lagoon occasionally breached by storms and river floods. In Roman times, an almost continuous barrier of sand-dune islands - the "Wadden" islands - extended from Cape Blanc Nez in France to the Weser river in Germany (Fig. 3). In the past 5,000 year, the rate of sea level rise was small. In the past 1000 years, the sea level fluctuated about the present altitude. It is now recognised that in the Southern Bay of the North Sea, sea level is rising at a rate between 0.15 and 2 m per 100 years (see Appendix 2 on tides)

From the rivers discharging in the lagoon, the Rhine and the Meuse carry a significant sand load that started to fill the lagoon, much more than by the import of marine sediment. Instead, the Yser and the Scheldt rivers carrying little sand load saw their lower course receiving mainly marine sediments. The tidal currents imported sediment in the lagoon, silting up the shallow areas bordering these tidal channels. The channels through the coastal sand barrier were maintained because of the tidal currents as long as the inundation area they were feeding remained sufficiently large. This is illustrated by the case of the Zwin, the access channel to the harbour of Bruges, that silted up more rapidly when a gate structure was build in Damme to protect Bruges from flooding. Progressively, extended areas became shallow in this very large lagoon, which is called now the Rhine-Meuse-Scheldt delta, though it is not a typical delta formation (Fig. 4).

The entire coastline from Cap Blanc Nez in France to the Weser River in Germany has been many times breached and reshaped by storms. The need for agriculture land and the fear for inundation during catastrophic floods motivated the progressive land reclamation behind man-made levees or embankments - the poldering - and riverbank protection schemes. Along the Southern Bay of the North Sea and along the Scheldt Estuary, the last severe flooding of polders occurred in February 1953, when a North-western storm combined with spring tide made the high water levels exceed the normal ones by about 3 meters. The Delta Plan originated from this catastrophic event and the Westerschelde is now bordered by a complete scheme of high levees, which complex shape is the result of the long history of building of levees or embankments, breaching by storms or wars, then rebuilding levees.

The seaward boundary of the Scheldt estuary was usually taken at the bottleneck between Breskens and Vlissingen, but there is in fact a progressive transition from the estuary to the sea through a morphologically complicated delta-shaped area. This kind of mouth of an estuary is sometimes called an "ebb-tidal-delta" as the sediment flushed out of the estuary by the tides creates this sort of feature. As explained earlier, marine sediment of the littoral transport from France to Netherlands created and still shapes the mouth area of the Westerschelde[2]. The need to include this mouth area in the studies of the Scheldt was mentioned in the seventies (Peters, 1975) but has only recently be accepted. The importance of this is that the evolutions of the part seaward from Breskens - Vlissingen in response to works along the coast - like the Delta Project - can be expected to have a significant effect on tidal propagation and on the sediment transport in the Western Scheldt.

The present Scheldt catchment has an area of 21,860 km^2 and has a quite mild topography. The river Scheldt has its source at an altitude of only about 100 metres above the present sea level. Gates in Gentbrugge, at some 160 km upstream of Vlissingen halt the propagation of the tide. The freshwater drained from the catchment is only partly entering the tidal reach, the rest being diverted through canals directly to the sea and to Terneuzen, situated close to the mouth. River slopes reflecting the effect of gravity on the flow in the river is significant only down to the confluence of the Rupel, at about 90Km from Vlissingen, where the river meets the Honte, a major channel created in the lagoon by the action of the sea. In the early stages of the lagoon, the Schelde river flow was mainly drained by the Eastern Scheldt (Oosterschelde). The connection between the Westerschelde and the Oosterschelde was closed in 1867. The reason for this change of course is unclear, but may reside in the overall tidal circulation in the originally coupled Oosterschelde and Westerschelde channel network as its

[2] It could be called a "flood tidal delta"

morphology was altered by natural processes and human interference[3]. No documented conclusive explanation of this process of capture has been discovered yet[4] but it is such a fundamental change that it needs to be understood, particularly in the light of the proposal to reconnect the two systems[5]. It is amenable to historical documentary analysis and should form part of any continuing programme.

Tidal phenomena

The tidal wave movement from the Atlantic Ocean through the Strait of Kales is associated with an increase in tidal amplitude in the converging part, followed by a decrease caused by the frictional dissipation of the tidal energy and the diverging coastlines of UK and France-Belgium-Netherlands (Fig. 5). The tidal amplitude at the mouth of the Westerschelde amounts to about 4 m.

The progressive shoaling over the past millenaries and the poldering in the past thousand years limits the area into which the tide can propagate. Embankments have reduced the space where the channels can migrate. The anticipated consequence of these actions is mainly an increase in tidal propagation, documented in tidal summary records supplied by the Flemish Ministry. An analysis is given in the Appendix on tides but the main conclusions, which are consistent with other recently completed researches, are as follows:

Assessments of available data indicate that the basic tidal driving process is not constant. The well-known 14-day lunar cycles are superimposed on:

- the long term rise in seal levels following the last glacial period

[3] poldering, embankments, cut off secondary channels
[4] the difference in amplitude and phase of the tidal wave at each Schelde mouth
[5] As was understood by the Team, the proposal is to reconnect the Westerschelde to the Oosterschelde with a canal operating only at extreme water levels, i.e. during storm events

- cycles in the celestial tide generating forces of approximately 18.6 years, the so called nodal cycles
- long term climatic cycles or changes in water levels and rainfall

Assessment of tidal data from sites around the Southern North Sea Basin should be performed on a data set that is long enough to allow averaging out of the nodal and shorter term cycles. The analysis made shows that the rates of change of tidal characteristics (mean high water, mean low water, mean sea level and mean tidal range) at Vlissingen are two to three times the rates of change at Oostende in the period 1880 to 1990.

The increase in High Water at Vlissingen from 4.1m in the period 1888/ 1895 to 4.35 in the period 1981/1990, an increase of 0.25m, contrasts with the change in high water at Oostende of + 0.18m in the period 1820 to 1999. Changes in mean sea level at Oostende are similar to changes at British Ports in the Southern North Sea. This suggests that tides at Vlissingen are influenced by the factors affecting the tidal propagation in the estuary and as such Vlissingen should not be considered as the boundary of the Scheldt estuary, either outside the estuary or as a long term tidal reference station.

From the data reviewed it is evident that tidal characteristics and propagation in the Schelde have changed markedly in the 102 years up to 1990. The tide propagates more rapidly than it did in 1888, the high water levels are higher and the range is greater. In the period 1888 to 1990, within the Scheldt upstream of Vlissingen, the height of the maximum high water level in the Westerschelde has increased by approximately 0.7m and its position moved upstream by 33Km. Tidal range has increased by almost one metre and the position of maximum range has moved upstream by 44Km The speed of propagation of the tide has increased by 18% from 6.55m per second to 8 metres per second. The observed position of the range maximum has moved up-estuary and so a change in the circulation dynamics of water and sediment is to be expected.

If the volume of the estuary was the same then more water would be entering the estuary more quickly than in 1888. The inevitable consequences of this would be more energy in the system and greater morphological activity.

These observed changes in tidal characteristics are entirely consistent with what is expected when the morphological development of the system is constrained and the intertidal volume reduced by poldering.

The processes of poldering have resulted in changes in the intertidal volume of the estuary though at present it is unclear what the changes in tidal characteristics represent in terms of the actual volumes and rates of water being transported and the relative energies involved. In figure 6 are shown the areas made polder during the period from 1300 to the present. The majority of the poldering appears to have taken place in the 17th and 18th centuries but key events, including the closure of connections between the Oosterschelde and Westerschelde occurred in the 19th and 20th centuries.

In the context of the period for which good tidal data is available, data reviewed reveals that areas of the estuary may be designated as follows:

Interdidal Areas in 1997 and poldered Areas, 1800 to 1980			
1997		Poldering	
Areas	Ha	Period	Ha
Supra tidal	2.958	1800 to 1860	7.112
Intertidal	11.029	1861 to 1905	2.843
Sub-tidal	19.634	1906 to 1931	1.642
Harbours	760	1932 to 1960	2.400
		1961 to 1980	1.241
		Total:	15.238

From these data it appears that in 1800 the intertidal area of the Schelde occupied of the order of 26.267 Ha. By 1980 of the order of 15.238 Ha of intertidal area had been poldered, a loss of intertidal area of 58%. In that it is the intertidal area into which the tide propagates, the loss of 58% of the intertidal area will inevitably affect the tidal regime. From data examined it is evident that the tidal ranges and mean water levels outside the Schelde estuary have increased only slightly over this period, whereas within the estuary the tidal range and other tidal characteristics have changed greatly. In particular the location of height and range of maxima have moved up estuary although peaks in the amplification profiles have moved seaward. It is conclude that on the basis of the analysis so far that the observed changes in the tidal regime of the Schelde Estuary are related to changes in the morphology of the estuary.

At present the documented changes show a reduction in the intertidal area of the estuary. The observed changes in tidal regime are wholly consistent with the noted reduction in intertidal area.

A separate but equally important issue for the analysis of tides is the changing morphology of the tidal delta seaward of Vlissingen. In figure 10, the ongoing growth in the area of the Vlakte van de Raan since 1800 and the widening of the Scheur and Wielingen. The influence of the Delta Project, involving the closure of the Haringvliet and Grevelingen and the control of tidal flows in the Oosterschelde, on the evolution of the Vlakte van de Raan, has not been evaluated in this study but is felt to be important for the following reasons.

- The external delta is a principal route through which sediment is exchanged between the "inner estuary" and the North Sea. If this area has changed from a source area to a sink area, this would have important implications for the future development of the Scheldt morphology.
- Changes in this large area immediately in front of the narrow section of the estuary have important implications for the propagation of tidal energy into the estuary, also for the transport of sediment and the consequent evolution of the morphology.

Impact of dredging on morphology

The more detailed assessment of dredging and mining operations on the morphology of the Westerschelde will be presented in the second report. Nevertheless, a first evaluation of the possible overall impact of dredging and mining on the long-term evolution is presented in this baseline report.

Dredging, which includes the maintenance of navigation channels as well as sand mining, is a direct intervention in sediment transport mechanisms, which result in a morphological change. The significance of dredging needs to be assessed in the context of sediment transport mechanisms into or out of the estuary and the movement of sediment within the estuary.

There are no reliable data about the exchange of sediments between the sea and the estuary. Estimates vary from zero to of the order of 1.2 to 1.6 million cubic metres per year. However, this figure may show considerable variability (Fig. 7). There is a need to examine the methods used and assumptions made in deriving any estimates of sediment transport in such a geometrically complex area. This is a very important, a critical issue in relation with a long-term vision and for the future management of the estuary. Furthermore, realistic or reliable estimates of tidal or seasonal sediment transport within the estuary have not been identified so far and the Team hopes to receive more whatever information is available.

The patterns and pathways of sediment movement and the residuals of these patterns have been derived from a variety of studies using techniques such as the interpretation of particle size distributions, interpretation of sonar records and air photographs, direct field observations and computational modelling. The results of these studies are not internally consistent. The particle size based methods and the methods based on morphological interpretation do not yield quantitative estimates of flux. Direct field observations are spatially and temporally limited. Numerical simulations involve important assumptions. It is thought that studies may have been undertaken which can give long term and relatively reliable results for changes in the quantity of sediment in the estuary. These studies have yet to be identified. It is concluded that there is considerable uncertainty regarding the patterns and intensities of sediment transport within the estuary.

Dredging Quantities.

The impact of two types of dredging is to be considered separately.

- Redistributive dredging in which sediment is dredged from crossings and from some reaches in the navigation channel - places where there is insufficient draft or width for vessels - and deposited in selected dumping sites, preferably in nearby flood channels, and

- Sand mining where sand is dredged and landed on-shore, or marketed, thereby being removed permanently from the estuarial sediment budget.

The quantities involved in recent activities in the Westerschelde are of the order of 5 to 15 million cubic metres of redistributive dredging and dumping, while about 2 million cubic metres of material originating in these operations is removed from the system by sand mining, landed or marketed.

Studies have been made of the depths at crossings as they are affected by dredging. Studies have also been made of the local effects of redistributive dumping. However, though these studies claim to show that dumping produces accretion both sub-tidally and inter-tidally, there does not appear to be a quantitative evaluation of the amounts involved and how these compare with other processes. Studies made elsewhere show that the efficiency of dredging on crossings may be strongly linked to the natural morphological evolutions, especially to the self-scouring (self-dredging) of the flow in the critical spots, this being determined by the layout of the channel pattern. These studies have also showed the important role played by sediment sources and sinks in the distribution of sediment fluxes between channels.

Salinity

The Westerschelde part of the Scheldt estuary can be classified as well mixed, with mild vertical salinity gradients. These gradients are however sufficient to produce a residual inland movement of suspended sediment. This phenomenon was confirmed with the analysis of the riverbed sediment composition. It complicates the sediment budget, because the difference between the vertical velocity gradients during the flood and the ebb phase must influence the bed material transport capacity.

The salinity distribution in the Scheldt estuary was well documented since the fifties. Studies of the longitudinal salinity distribution showed that in the mouth area seaward from Breskens Vlissingen, mixing is intense due to the tide and flow circulation around the Vlakte van de Raan. Because of the strong tides in the Southern Bay of the North Sea and the quite small residual flow through it, freshwater masses inflowing from rivers have a long residence time in the area. Therefore, the salinity at the seaward edge of the "fore-delta" of the Scheldt is less than the salinity of the Atlantic Ocean.

The longitudinal salinity gradient in a reach just upriver the bottleneck Breskens-Vlissingen (approximately till between Terneuzen) is quite mild. Mixing coefficients computed with one-dimensional advection-dispersion models are abnormally high. Water exchange processes between the mouth area (the fore-delta") and the initial reach, a kind of "pumping" effect, can explain this. The brackish water is flushed out of the estuary by the ebb flow through part of the channels while saltier seawater enters preferentially the estuary through other channels. In reality, the mixing processes are obviously extremely complex.

Observations show a significant shift in position of the longitudinal salinity profiles, with both discharges and tides: respectively of the order of 40 km and 10 km (Fig. 8). As tidal flow during one tidal cycle may be affected by many factors, such as wind stress, conclusions from direct measurements of salinity can only be useful when well documented. The team has analysed data collected between 1960 and 1998 and was not able to see a trend that would illustrate a further inland penetration of salinity. This can be explained by the strong mixing in the Westerschelde, especially with the flow through many main and secondary channels, and over the sandbars and tidal flats at higher water elevations.

A report by RIKZ[6] compares tidal-averaged chlorinity values observed in the period 1950-1970 with model calculations for 1989 (Fig. 9). In the

[6] Holland A.B.M. & H. Smit, 1994 - Zoet water in het Schelde-estuarium, verandering in de salinitiet

Westerschelde, there would be no changes, except in the vicinity of Hansweert where a shift in seaward direction by a few kilometres is predicted by the model. The authors explain the changes by a stronger penetration of seawater in de Westerschelde because of morphological changes together with the dredging activities, creating a more flood dominant character especially in the reach Terneuzen - Bath. The stability of the salinity at Bath is explained by a larger supply of freshwater from the Antwerp Harbour and from the flush-canal in Bath.

As will be described in next section, the morphological changes in the Westerschelde are mainly due to a continuation of the long-term trend. With the available field data, there is no clear indication of a possible significant impact of dredging on the salinity pattern in the Westerschelde. This can be explained by the complexity of the morphology which natural evolution continued over the pas 40 years. However, this aspect needs to be further investigated in order to distinguish between both natural and man-made impact, mainly by analysis of field data. Model simulations used in some recent reports to assess the changes in salinity distribution have shown how sensitive they are to the mixing coefficients. High values found for these coefficients are explained by the many processes that they have to integrate. Not surprisingly, they are often referred to as "garbage coefficients" and their prediction is really hazardous. Their calibration is evenly hazardous, as the long residence time of the freshwater makes the salinity distribution adapting slowly to flow and tide.

Morphology

A discussion of the morphological evolution of the Scheldt estuary is given with more details in Appendix 2. It is based on the available information and does not pretend to be complete. The main goal is to indicate an alternative way to analyse the past morphological changes by taking into account all natural and anthropogenic processes. A quick overview is given in the condensed analysis below.

Useful qualitative information about the morphology of the Westerschelde is available since the 17^{th} century, reliable charts since 1800 (Fig. 10). On the maps produced in the "Mercator-Hondius-Janssonius-Atlas" of 1636 (Fig. 11), the remains of the lagoon are well visible. Large portions are reclaimed for making polders and traces of flooding creeks appear with the marshland they drain. Interesting is to observe the layout of the elongated sandbanks along the coast, almost parallel to it and entering into the mouth area close to Breskens (Fig. 12).

For unclear reasons, the morphology of the sandbars in the mouth area changed, so that it became progressively an integral part of the estuary. In the 17^{th} and 18^{th} century, there were still four main channels, distributed over the triangle-shaped mouth. In the 19^{th} century they became three and today only two remain (Fig. 10). The one along the Belgian coast is the most active, directing large percentage of flood and ebb flow through the bottleneck Breskens-Vlissingen. This natural morphological evolution results from the adaptation to sea level rise. It must have changed the penetration of the tidal energy into the estuary, so also the flow and sediment movements through the bottleneck Breskens-Vlissingen. This bottleneck must be controlled by geology, probably clay layers (Fig. 13).

Since the Middle Ages, poldering had progressively created large islands separated by creeks. In the 17th century (Fig. 11), many of these creeks were still active, with tides propagating through them, sometimes between main channels (e.g. the Sloe), sometimes from and to the same main channel (e.g. the Braeckman - Hellegat) or to a tidal flat area without other outlet (e.g. t'Saeftinger Gat).

The land reclamation in the Sloe and Braeckman reduced the tidal flows in and out of these creeks. The channels of the Westerschelde leading to these became progressively less active, as can be seen from the morphology in 1800 and 1865. Especially the southern channel along Breskens (now "Vaarwater langs de Paulinapolder") reduced in size and its flood flow was progressively diverted towards the main channel along Terneuzen (Fig. 10[7]).

In the first half of the 19th century, the reduced flow in and out the Sloe and Braeckman creeks, combined with the above mentioned changes in the mouth area, made the main channel in the Westerschelde to develop a more pronounced meandering course. In this evolution, the point of attack of the ebb flow in the meander was initially directed towards the embankment at Borssele, but it moved then to the West so that it started eroding the entrance of the Sloe leaving space for the Spijkerplaat to develop in Northern direction.

The Everingen was meanwhile developing, reworking the kind of delta at its inland extremity. The sediment of this area started to develop an elongated sand ridge, which moved inland. This created a dual channel system: the Middelgat to the West as an ebb channel and the Gat van Ossenisse to the East as a typical flood channel, with at the end an inland delta. In 1865 the Everingen was remarkably developing as a predominantly flood channel, however oriented to and aligned on the Middelgat, that was developing as a predominantly ebb

[7] From here on, please follow the changes on figure 10

channel. The flood and ebb channels between Vlissingen and Hansweert did not have the layout that today is said to be typical for the estuary.

In 1800, the region around of Hansweert, East of the Middelgat, was still adapting to the reworking of the landscape by flooding and poldering. In 1865, the sandbank seaward of Hansweert was progressively eaten away by the migration of the channel towards the North. This movement was likely influenced by the Gat van Ossenisse flood channel delta. By this, the Schaar van Waarde had developed further as the flood channel, also terminated at the inland end by a delta. About that time, the connection between the Westerschelde and the Oosterschelde was cut off.

To summarise the Westerschelde lay out of 1865, it can be said that it was adapting to natural changes in the North Sea (layout sandbanks in mouth area) and to the poldering all along its course, those in the Braeckman and Sloe having the strongest impact.

From 1865 to 1938, the morphology of the Westerschelde and its mouth area became simpler, more typical, with in general a better-defined ebb and flood channel system. All flood channels ended by a kind of a delta over which the sediment was spread by the flood flow, while the ebb flow concentrated in an almost continuous meandering channel. The morphology was approaching an idealised layout, like the one that now is said to be the most valuable. Though the Middelgat had cut at its seaward end through the elongated sandbar that existed in 1865, there were still one or two well developed "fingers" that were oriented towards the flood channel Everingen.

In the mouth area, the Scheur-Wielingen was further developing around 1938 as the main channel, orienting the flood flow more to the Northeast. This movement, together with the Westward shift of the ebb channel (see above description) favoured the formation of the flood-ebb channel system Schaar van de Spijkerplaat - Honte. This flood channel was oriented towards the Everingen.

From 1938 on, the development of the channel system became progressively more controlled by the layout of the embankments, but also influenced by the continuing reclamation of polders and the closure of remaining creeks. The Westward movement of the Pas van Terneuzen for example makes a long stretch with little curvature, "hanging" at the embankments in the vicinity of Terneuzen. The Gat van Ossenisse had continued its Eastward shift and touched the embankment at Ossenisse, producing a tortuous channel shape, not a smooth curve as before. As this channel received more flood flow from both Pas van Terneuzen and Everingen, the Gat van Ossenisse could cut finally through its delta and became from 1969 on the main navigation route. The evolution of the Middelgat and Gat van Ossenisse is also influenced by the construction of the jetties for the harbour of Hansweert, protruding on the bank-line. Due to these changes in morphology, the Gat van Ossenisse flood channel formed a smooth transition with the ebb channel Zuidergat and with the flood channel Schaar van Waarde, while the Middelgat presented in its plan form a discontinuity with both. The Zuidergat became also more attached to the embankment.

The flood flows passing Hansweert are distributed between both flood and ebb channels Schaar van Waarde and Zuidergat, but the rotation of the channel alignment from a Northwest-Southeast to almost North-South direction made the Schaar van Waarde loosing strength.

Looking at the maps in the nineties, a further natural evolution is observed, though influenced by more dredging. The shape of the flood and ebb channel system is clearly not optimal, certainly not in front of the Sloe and at the connection between the Everingen and the Middelgat. Also the layout of the embankments and of other fixed points - such as jetties and groynes or dykes - is creating undesirable morphological evolutions.

From the analysis of the maps, it can not be concluded that dredging had till now an impact that is comparable to the one by poldering, embanking, closing of creeks, constructing structures protruding on the bank-line etc.

CONCLUSIONS OF THE BASELINE REPORT

The Expert Team appointed by the Port of Antwerp has analysed as much as possible the basic information available to them. The fact that most documents are in Dutch made their work not easy. Nevertheless, it was possible to make a first assessment, thanks to the collaboration of many partners in LTV.

The experts came to the following main results:

- The Scheldt estuary as a whole and particularly the Westerschelde downstream of the Dutch-Belgian border is a very young and dynamic coastal area
- Today, the Westerschelde undergoes still significant morphological changes as a consequence of the process of adaptation to the sea level rise, also under the increasing impact of human activities
- The morphological changes in the Westerschelde are leading to a more simple geometry, with deeper channels, more stable and higher sandbars and tidal flats (process of accretion, "verlanding" in Dutch)
- Because of the simplification in the morphology, the tidal energy is less dissipated in the Westerschelde than before; the tides penetrate more and quicker inland with, as a consequence, an increasing risk for flooding, mainly upstream the Dutch-Belgian border
- Reclamation of land for poldering, building of embankments, groynes, jetties and other hard points along the Westerschelde had and still have today a significant impact on the morphological changes in the Westerschelde

- Compared to the other human impacts, dredging as such does not seem to have influenced yet strongly the morphology of the Westerschelde; however dumping of dredge material may likely have a marked effect on the further changes
- The layout of the embankments, groynes, jetties and other fixed structures, also the natural fixed points such as clay layers, should be studied in view of achieving a new, more healthy - because more dynamic - morphology.
- A more appropriate layout can not be designed with models only, rather by combining several tools. This all requires a thorough analysis of existing data and the collection of more field information
- Though the detailed work on the dredging (second report) and on alternative management scenarios for the estuary is still going on, the preliminary results show that a further deepening of the Scheldt is possible without jeopardising the safety and naturalness of the Westerschelde, in a perspective of sustainable development
- Deepening of crossings for better navigation channels might be easier by reworking the morphology of the Westerschelde, especially the plan form, so that self scouring would be more efficient
- It is important to slow down as much as possible the process of land accretion in the Westerschelde and this should be achieved by an array of measures, in which dredging is part but should not be the only one
- Alternative strategies for managing the dredge material will be studied by the expert team in view of using the redistribution of the sediment to steer and trigger morphological changes
- A long term vision for the management of the Scheldt estuary requires the best possible understanding of past evolutions, a thorough

monitoring programme, analysis and studies of all the information with several tools

- Studies of the morphology and of the circulation of water, sediment and salt have to rely on good data and the modelling must rely on good concepts, to be derived from the studies on the data

During the work on this baseline report, the experts came to the conclusion that the LTV needs a more integrated effort with closer collaboration between the Dutch and Flemish partners, also between the partners in Belgium where human and financial resources seem to be scarce in proportion with the challenges.

EDITORIAL COMMENT

The following is missing in the preliminary draft baseline report:

- Executive summary
- List of figures and tables
- Bibliographical list
- Acknowledgements

Brussels, June 2000

Appendix 1

APPENDIX 1:

ASSESSMENT OF THE MORPHOLOGICAL CHANGES IN THE SCHELDT ESTUARY

The future management strategy of the Westerschelde needed for reconciling its different functions - accessibility, safety and naturalness - must be based on a thorough assessment of past evolutions, both natural and anthropogenic. Therefore, a first attempt will be made in this chapter to make such an assessment, aiming at identifying the key factors. Among these, following are being assessed as far as information is available:

- changes in flow and sediment patters in the mouth area
- poldering
- cutting off secondary branches
- flood embankments, bank protections and other hydraulic structures
- deepening of channels, natural and by dredging
- siltation on shoals, bars and tidal flats
- dredging, mining and dumping of dredge products in the estuary
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The need for further investigations is indicated.

This Appendix is supplementary to the chapter on morphology of the baseline report.

The changes in the mouth area downstream of the bottleneck Breskens-Vlissingen were significant over the last centuries and are still ongoing. Hydrographic material is available but has not been investigated thoroughly. Centuries ago, this area was a part of the Flemish Banks that had been formed during the Holocene by sedimentation, but also by scouring through older geological formations. Two main flood channels, the Wielingen and the Spleet, were almost parallel to the Belgian coast and gave access to the Scheldt. The ridge in between contained clay outcrops, like the Bol van Heist, the Bol van Knokke. Within the scope of this assessment, it was not possible to analyse the available information on the geology of the sub-bottom, but it seems that clay layers are denuded in many more places, undergoing slow scour by the tidal currents. With the charts available over more than 400 years, there is evidence that these processes explain how the many geological controls have determined, together with the sediment transport, the morphological evolution of the coastal area in front of the lagoon and more particularly the Scheldt mouth area.

In the last two centuries, the shallow area in the triangle Oostende - Westkapelle - Vlissingen has undergone a process of grouping and accretion of the sandbars, as well as a reduction in number and simplification of the channels. This must have affected significantly the tidal flow pattern and wave propagation through the area, thus also the sediment transport processes. The construction in phases of the Zeebrugge harbour has obviously contributed to the morphological evolution. A last significant natural change was the accretion of the Spleet flood channel around 1860, probably due to the littoral sediment transit. Meanwhile, the ebb flow started to scour a channel North of the Bol van Heist towards the remains of the Spleet flood channel, so that the Wielingen connected to it through a new channel called the Scheur[8] (Fig. 14).

The Deurlo channel exists since centuries (Figure 10) and is still clearly visible in the 19th century, when it was still cutting through the Vlakte van de Raan. Together with the Oostgat channel, they form a fan, a kind of a webfoot, the channels being the fingers, relatively well distributed over the fan. With time, the two left fingers - the Spleet and Wielingen - changed in a single channel Scheur-Wielingen, while the middle finger, the Deurlo lost its importance and only the Oostgat remains as the active Eastern channel. The Vlakte van de Raan has unified the different high grounds to form the large delta[9] shaped bar which separates the Scheur-Wielingen Western channel from the Oostgat Western one. In this evolution, the Delta Works[10] must have affected the flow and sediment transport patterns, thus the sediment budget in the coastal area, now called the "fore-delta" by the Dutch Rijkswaterstaat.

From the old maps (Fig. 15) it can be deduced that the bottleneck at Breskens - Vlissingen must be controlled by geology. The other creeks - Zwin, Sloe, Braeckman - of the Rhine-Meuse-Schelde lagoon are well visible on the 1636 Mercator - Hondius - Janssonius map, which shows that the Honte[11] is narrowing to the East of Terneuzen, after turning from NW-SE direction into SW-NE direction. The village of Axel stood in a marsh area, at the end of the Braeckman creek.

The series of maps between 1800 and 1972 show how both the schorre along the Sloe and the Braeckman branches were progressively reclaimed. The upper parts of these creeks where cut off when they had silted up to about low water, though they still represented a large area, for a significant floodwater storage.

In the 19th century, the creek leading to the village and harbour Sas van Gent at the end of the Braeckman was still active. Since the reclamation works of the

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[8] The Dutch word "scheur" means the "tear", the fissure created between the channels Spleet and the Wielingen

[9] delta refers here to the shape, not to the river delta, because the Vlakte van de Raan was created by marine sediments, not by river sediments

[10] Closure of the Haringvliet and Grevelingen branches of the lagoon and partial closure of the Oosterschelde

[11] The name of the Westerschelde before it captured most of the riverflow

Braeckman it has degraded, though still existing today[12]. Interesting to note is the progressive shift to the West of the main channel downstream of Terneuzen, shift that might be associated with the closure of the Braeckman.[13]

The land reclamation and shortening of the Sloe had less impact on the morphology of the area than the works in the Braeckman. However, the main channel moved steadily to the North, eating away the deposits in the mouth of the Sloe. This can be associated to the Westward shift of that part of the main channel between Terneuzen and the Sloe. It would be interesting to analyse these movements also in relation to the geology of the bottom, especially the reason for the higher grounds in front of the present Sloe Harbour.

The role played by the bank protections on the development of the morphology of a river is still poorly understood. As an example, the levee along the right bank of the Scheldt protrudes into the river at Borssele, East of the Sloe. In the 19th century, the ebb channel coming from Terneuzen was oriented towards this protruding point and an extended salt marsh area existed in the entrance of the Sloe creek. During its shift in Westward direction, that ebb channel became finally oriented towards a stretch of the right bank situated to the West of the Borssele protrusion. The channel started to outflank into the Sloe mouth area, allowing the Spijkerplaat shoal to move to the North[14]. At the same time, the changes in the mouth area, namely the Scheur - Wielingen channel gaining in importance, made the flood channel "Schaar van de Spijkerplaat develop. At present, the morphological configuration is however not favourable because none of the Schaar van de Spijkerplaat or the Honte have a clear ebb or flood dominant character. The morphology is still evolving quite a lot under the influence of the morphological development in the mouth area and controlled at fixed points, such as at Vlissingen, Breskens, Borssele and Terneuzen. Despite all these changes, the Pas van Terneuzen and the Everingen kept respectively their predominant ebb and flood channel function.

In the 17th century, the Schelde was in contact with extended marshland on the left bank east of Terneuzen, with the village Axel in the middle. This intertidal flood storage area was in contact with the Braeckman at Sluiskil[15]. Most of this marshland was reclaimed in the second half of the 17th century, leaving to the east a major creek, the Hellegat. The polders and their flood embankments along the right bank were built since the 16th century

The 1800 chart shows that the configuration of shoals and channels was still adapting to the poldering and construction of the levees which were completed

[12] "Vaarwater langs Hoofdplaat" and "Vaarwater langs Paulinapolder"

[13] Too often, the decision is taken to cut of a side branch of an estuary that still acts as an active channel feeding floodwater into intertidal storage areas. This reflects a lack of understanding of the estuarine flow and sediment processes.

[14] See figure 10, evolution 1865-1938

[15] through a channel still visible on the pr maps as Axelsekreek

centuries before on the right bank between Hoek van Baarland and Hansweert and even further. At that time, channels and creeks in the lagoon, formed historically with the storm floods and inundation, were progressively adapting to an estuarine multiple-channel pattern. There was only one main channel between Hoek van Baarland and Hoedekenskerke, attached to the right embankment. Close to Hansweert, it split in two distinct channels, the Southern one being the Middelgat (the "gate in the middle").

The impact of the poldering in the Hellegat is not so important as the one in the Braeckman, certainly since the connection between the two was closed off, at the end of the 17th century. A secondary channel seen on the chart of 1800 close to Ossenisse is likely the remains of a creek feeding the marshland area on the left bank during the ebb phase of the tide. It lost its importance in the second half of the 19th century.

On the map of 1865, a dual channel system was forming: the Middelgat ebb channel connecting to the Everingen flood channel, while the flood flow from the Pas van Terneuzen scoured through the Platen van Ossenisse. In this process, the meander bend at Hansweert shifted to the North, eroding the sandbar along the right bank. The connection of the flood channel with the ebb channel is the result of the morphological evolution triggered by the poldering, more particularly by the flow guiding effect of the flood embankments.

From 1865 to 1938, the Gat van Ossenisse worked progressively more and more as a flood channel and was separated from the Middelgat by a longitudinal ridge. Its upstream end shifted to the East. The 1938 map shows that ebb flow from the Middelgat channel is still diverted to the Everingen flood channel. This confirms that the morphology of the reach between the bottleneck Vlissingen - Breskens at the mouth up to Hansweert has not a typical estuarine morphology. In this part of the lagoon, several creeks and channels were created when storms breached the levees and they have united later to make what resembles an estuarial channel pattern.

The trend was sustained till the moment when, at the end of the nineteen-sixties, the Gat van Ossenisse flood channel pushed through its delta, making the Overloop van Hansweert deep enough to act as a navigation channel. The delta at the downstream end of the Middelgat ebb channel had than become too difficult to dredge. At this moment, there is a conflicting situation where the Middelgat ebb channel meets the Everingen flood channel.

Besides the morphological impact of poldering - especially in the Braeckman - and of building the embankments, one of the likely causes of the complex morphological situation in the area is the construction of the jetties for the locks of Hansweert. Combined with the shift of the meander apex to the North, these hard points have created and maintained a shape discontinuity in the transition between the Middelgat channel and the meander belt Overloop van Hansweert - Zuidergat.

The 1636 map shows that the Western part - the left bank from Perkpolder to Baalhoek and the right bank from Hansweert to Waarde - had been reclaimed before the 17th century, but that the Eastern part has experienced flooding. On the left bank, a large creek called t'Saeftinger Gat entered a wide flood area limited in the South by a borderline running between Hulst and Kallo. To the North, a series of creeks between Valkenisse and Zandvliet - among which the Zuidkreek, Mosselkreek, Kromvliet and Pietermanskreek - connected to the Oosterschelde (Eastern Scheldt), parting from the Westerschelde near Zandvliet.

The extended area between Zandvliet and Valkenisse to the North and between Saeftinge and Kallo represented a huge intertidal storage zone. Between 1800 and 2000, poldering reclaimed large areas and in 1867, the connection between the Eastern and Western Scheldt was cut off. On the 1800 map, the flood channel coming from the Middelgat interrupted before reaching the ebb channel coming from Bath and halting close to Walsoorden. This part of the Westerschelde has in fact undergone the most significant change over the last two centuries. The map of 1865 shows how the ebb channel - now Overloop van Valkenisse - cut through the sandbars and making the Zuidergat while the flood channel Schaar van Waarde developed further. The channel situation on the map of 1938 has smooth channel shapes. The Middelgat connects without discontinuity to the Schaar van Waarde flood channel and its channel probably carried a large portion of the flood flow.

The morphological changes described in the previous section, with the discontinuity at the Hansweert Harbour, has reoriented the flood flow more to the South, so that the Schaar van Waarde, as a flood channel, had lost quite some sediment carrying capacity. A more detailed analysis of this reach of the Western Scheldt will be given in the report on the dredging activities. However, already on the basis from the above description appears that the change from a multi-channel to a single channel situation can be at least partly explained by a natural evolution, triggered by poldering, cutting of branches, building embankments and fixed points such as harbour jetties.

Preliminary conclusions about the long-term evolution of the Scheldt Estuary

From the preliminary analysis made, the following elements can be identified for further investigation, so that the hypothesis put forward could be corroborated or refuted:

- The Westerschelde is located in what has been a lagoon in which series of flooding during sea storms created a complex system of channels and creeks

- Higher grounds were built up by siltation on which poldering created vast islands since the Middle Ages, behind embankments (levees)
- Tidal flows concentrated in the many creeks in between these islands; these silted up progressively
- The Honte - the early stage of the Westerschelde - is one of these channels, which captured the flow of the Schelde River and became its estuary
- The width of Honte was progressively reduced by natural siltation, accelerated by human intervention and main channels developed because the tidal wave penetrated more inland as its energy was not dissipated anymore in the shallow lagoon.
- Cutting of creeks - side branches - of the Honte triggered a further evolution of the channels, becoming more streamlined
- The mouth area underwent in the last centuries remarkable changes, with the shoals along the Belgian coast modifying from the marine Flemish Banks system to part of the estuarine bars; the boundary of the Scheldt estuary moved seaward
- Due to both the changes in the mouth area and in the Westerschelde itself, channels acquired a more pronounced flood or ebb character, though today the situation remains complex and under further evolution
- The bank protection works, groynes, jetties and other fixed points interfere significantly with the long-term evolution, together with the harder geological sub-bottom when this appears in the riverbed
- Based on the analysis of the morphology of the Scheldt, dredging does not seem to have a significant impact on the long-term evolution, so that the strategy for managing the estuary needs other measures like adaptations in lay-out of embankments, groynes and other structures.
- Besides these structural interventions, dredging and especially the disposal of the dredged material can probably be used as a tool for steering the morphological evolutions.

Appendix 2

Appendix 2

Evaluation of changes in Tidal Propagation in Schelde Estuary during the period 1880 to 2000

INTRODUCTION

Propagation of tidal energy provides the fundamental driving force for a wide range of estuarial physical processes. Through the derivative agencies of sediment erosion, transport, and deposition, the propagation of tidal energy powers the morphological evolution of an estuary. In the absence of eustatic or isostatic changes in relative sea level, long period cyclicity in celestial tide generating forces, such as the 18.6 year nodal cycle, produce fluctuations in tidal propagation and energy dissipation. It is widely recognised that estuarial morphology evolves over long time scales and it is evident to students of estuarial geomorphology that an estuary exists in a dynamic state of morphological evolution. This evolution may be balanced about some mean parameter values related to intertidal volume, freshwater inflow and tidal energy, producing a dynamic morphological equilibrium. Alternatively the estuarial morphology may evolve progressively, in a particular direction, for example towards the estuary being filled with sediment or towards a simplification of the channel patterns.

Contemporary theories of estuarine geomorphology also encompass the physical translation of morphological zones and processes up or down the estuary in response to changing sea levels, tidal dynamics and climate. The contributing morphological components, the populations of sand and mud, react to changes in the energy inputs or energy dissipation at different rates. The changes in energy may be brought about by such agents as global sea level rise or fall, local regional changes in eustatic balance or engineering works. Additional complicating factors are the effects of either climatic changes or water management policy on the freshwater inputs which provide additional driving forces in terms of residual thermo-haline circulations. These factors also directly affect the locus of development of the fine sediment population (the turbidity maximum) which of itself influences the patterns of sediment circulation and morphological development.

This section of the report considers the historical documentation of the changes in the tidal regime in the Schelde in the context of changes in the Southern North Sea immediately outside the entrance to the estuary. This is felt necessary because the basic tidal forcing function for the Schelde originates in the North Sea. It is therefore a requirement to identify , by comparison, those components of change which are possibly due to external factors and those which are due to factors within the Schelde estuary. In order to assess the degree to which observed changes are typical of estuaries in the region, a comparison is made with an analysis of the tidal regime of a similar United Kingdom Estuary, the Humber Estuary.

A: Water Level Variations in the Southern North Sea

In order to place consideration of the tidal regime of the Schelde in context, the long term trends in water levels along the Belgian, Dutch and English coasts are considered using data from references 7,8 and 10.

From an analysis of tidal data from Oostende , Zeebrugge and Nieuwpoort by Van Cauwenberghe (Ref 7) it can be concluded that the period 1820 to 2000 is characterised by small increases in tidal levels, mean sea level and tidal range, as shown in Table 1.

Table A1. Tidal Characteristics for Coastal Sites and Vlissingen
Levels are in Metres relative to National Datum

Site	Date	M. H. W.	M. L. W.	M. S. L.	M. T. R.
Oostende	1820	4.1	0.23	2.165	3.77
	1999	4.28	0.41	2.345	3.87
	Change	+0.18m	+0.22m	+0.18m	+0.10m
Zeebrugge	1960	4.17	0.49	2.33	3.68
	1999	4.23	0.56	2.395	3.67
	Change	+0.06m	+0.07m	+0.65m	+0.01m
Nieuwpoort	1960	4.29	0.25	2.27	4.04
	1999	4.46	0.33	2.395	4.13
	Change	+0.17m	+0.08m	+0.125m	+0.09m
Vlissingen	1880	3.99	0.33	2.16	3.66
	1999	4.37	0.53	2.45	3.84
	Change	+0.38m.	+0.20m	+0.29m	+0.18m

M.H.W.= Mean High Water. M.L.W.= Mean Low Water. M.S.L.= Mean Sea Level.
M.T.R.= Mean Tidal Range.
Only the data from Oostende provides a sufficiently long record to allow filtering the secular changes in tide generating forces. However, from these data it is evident that changes in the various tidal parameters at the sites outside the

Schelde Estuary are small. It is also evident that changes at Vlissingen are significantly different from changes at sites clearly outside the estuary.

In reviewing water levels along the Dutch coast, van Malde (Ref 8) presents data on mean sea level for a number of ports along the Dutch coast. He observes that the mean sea level has a well established trend over the past 100 years of showing a rise of the order of 0.15 to 0.20m per 100 years. This is similar to the variations shown at Oostende and in the shorter records at Zeebrugge but less than the short term trend at Nieuwpoort.

Reviewing trends in mean sea level data around the British Isles Woodworth et. al. (Ref 10) conclude that trends in mean sea level in the Southern North Sea basin were consistent with those in obtained from NW Europe as a whole. Rates of Mean Sea Level at Sheerness are suggested as being of the order 0.16m per 100 years, similar to the estimates for the Belgian and Dutch sites with long records.

From these analysis it is evident that in the southern part of the North Sea the mean sea level is rising slowly at a rate of between 0.1 and 0.2m per 100 years.

B Temporal Trends in the Tidal Regime of the Schelde Estuary.

Reports provided by the Ministerie Van De Vlaamse Gemeensschap, Antwerpse Zeehavendienst, (Ref 4), which provide summaries of tidal data for the period 1981-1990 and includes data from 1888 , and also data from Ref 6, have been used as a data source to examine the temporal changes in tidal propagation and water levels in the Schelde Estuary. In Ref 6 the data is available in 10 year averages and three periods have been selected to illustrate the trends. The data used from Ref 4 is on pages 69-76 and 100.

The characterisation of the tidal regime in the Schelde is undertaken in terms of:Heights of High Water

1. Tidal Range
3 Mean Water Level
4 Speed of Propagation
5 Amplification

B1 Heights Of High Water.

The heights of high water and not low water are used for this analysis because the low water levels are more subject to random variations due to river flow and water abstraction although they are used in the examination of tidal range.
In Fig B.1 are shown 3 curves describing the longitudinal profile of the height of mean high water at 15 locations along the Schelde Estuary for three periods

during the period 1888 to 1990. From this graph it is evident that the heights of high water have risen all along the estuary during the period under consideration. It is also evident that the position of the maximum in water level has moved approximately 33 Km into the estuary from near Antwerp to near St Amands, an average of the order of 300m per year. The increasing asymmetry of the mean high water profile is also evident in Fig B.1.

B2 Tidal Range.

In Fig B2.1 are presented longitudinal profiles of mean tidal range for the periods 1888 to 1895, 1941 to 1950 and 1981 to 1990. Similar shaped curves to those shown in Fig 1B reveal that the tidal range has increased throughout the estuary and that the locus of maximum range has moved up-estuary from the vicinity of Prosperpolder/Lillo-Liefenshoek in 1888-1895 to the vicinity of Temse/St Amanda by 1981/1990, a distance of the order of 44Km, a mean rate of around 444m per year.
Fig B2.2 shows the longitudinal profile of increase in tidal range for the periods 1888 to 1990, 1888 to 1950 and 1950 to 1990. Seaward of Antwerp the overall profile shows a steady increase but then rises steeply. The intermediate profiles suggest that the changes are more variable in the short term. Further investigations of the changes in the section from Hansweert to Antwerp for the period 1888 to 1950 need to be related to morphological changes in this section of the estuary.

B3 Mean Water Level

Determination of Mean Water Level presents particular analytical problems not least because of the nodal and other cycles, random fluctuations due to climate and long term trends due to eustatic and isostatic adjustments. A detailed study of temporal changes in tidal characteristics at Antwerp is reported by Taverniers (Ref 6). This study shows that not only has tidal range increased between 1888 and 1998 but that mean water level has risen from 250 cm TAW to 270cm TAW, a rise of 0.2m per 100 years. This compares with 0.1m per 100 years at Oostende and 0.24m per 100 years at Vlissingen (Table 1).

B4 Speed of Propagation

The rate of propagation of the tide has been examined by comparing the High Water Interval , the time interval between the time of High Water at Vlissingen and the time of High Water at each station, along the estuary. The profiles for 1888 to 1895, 1941 to 1950 and 1981 to 1990 are shown on Fig B4. These data show that the high water interval has systematically decreased with time throughout the estuary indicating that the tide propagates more rapidly previously, a fact well known to mariners. In the period 1888 to 1990 the average speed of propagation of high water has increased from 6.55 metres per second to 8 metres per second, an increase of 18%. The speed since 1950 has increased from 7 to 8 metres per second, an increase of 12%.

B5 Amplification

The enhancement of tidal levels or tidal range is a particular phenomenon of coastal waters and estuaries and is principally a geometrically dominated phenomenon. Many estuaries which have the correct length and width/depth relationships, relative to the propagating wave achieve the amplification of tidal amplitude and tidal range. In Figure B5.1 the ratio of the high water height at various points along the Schelde estuary, are normalised to height at Vlissingen. It appears that height amplification has decreased and the locus of the peak has moved seaward by 31Km from St Amands to Antwerp. However part of this effect is probably due to the increase in height at Vlissingen. In Fig B5.2 the profiles for range amplification suggest that this too has decreased and that the locus for the peak amplification has moved seaward by about 34 km from Hemiksem to Prosperpolder.

C Comparisons With A Similar Estuary: the Humber Estuary, U.K.

Studies of the tidal regime of the Humber Estuary have been undertaken by the U. K. Environment Agency as part of the overall management plans for the estuary. Some parts of these studies are reported in references 1 and 2.
The Humber Estuary lies on the East Coast of England. It has a mean tidal range of the order of 5.8m. The tidal length of the estuary is approximately 120 Km. Like the Schelde the estuary is formed in post glacial deposits with an absence of rock exposures. A number of rivers discharge into the head of the estuary from a wide range of hinterlands.
At Spurn, the entrance to the estuary, the mean annual high water level has risen at a rate of 2.32mm per year during the period 1970 to 1990, a rate equivalent to 0.232m per 100 years. This is rather similar to Vlissingen but is higher than Oostende. The authors remark that perhaps this site at Spurn Head is not , in fact, outside the estuary influences. Furthermore the short term records can show anomalous long term trends due to the nodal cycle of 18.6 years as previously noted. Results from within the estuary at Immingham, 30Km up estuary and at Blacktoft , approximately 90Km up estuary, show rises of +0.35m per 100 years at Immingham and +0.211m per 100 years at Blacktoft, which has the longest data record. Comparative figures for the Schelde would be Vlissingen +0.19m per 100 years, Hansweert +0.25m per 100 years and Hemiksem, + 0.16m per 100 years.
Data presented in references 1 and 2 does not allow examination of changes in tidal range or propagation speed.

D Discussion.

The increase in High Water at Vlissingen from 4.1m in the period 1888/ 1895 to 4.35 in the period 1981/1990, an increase of 0.25m, contrasts with the change in high water at Oostende of +.18m in the period 1820 to 1999 (Table A1). Changes in mean sea level at Oostende are similar to changes at British Ports in the Southern North Sea. This suggests that tides at Vlissingen are influenced by the factors affecting the tidal propagation in the estuary and as such Vlissingen should not to considered as either outside the estuary or as a long term tidal reference station.

From the data in Ref 4 it is evident that tidal characteristics and propagation in the Schelde have changed markedly in the 102 years up to 1990. The tide propagates more rapidly than it did in 1888, the high water are higher and the range is greater. The observed position of the range maximum has moved up-estuary and so a change in the circulation dynamics is to be expected. If the volume of the estuary was the same then more water would be entering the estuary more quickly than in 1888. The inevitable consequences of this would be more energy in the system and greater morphological activity.

However, the processes of poldering have resulted in changes in the intertidal volume of the estuary (Table D1) so it is , at present , unclear what the changes in tidal characteristics represent in terms of the actual volumes and rates of water being transported and the relative energies involved. In Reference 5 it is noted that areas of the estuary may be designated as follows:

Table D 1: Intertidal Areas in 1997 and Poldered Areas 1800 to 1980

1999 Areas		Poldering	
Supra tidal	2958 Ha	1800 to 1860	7112 Ha
Intertidal	11029 Ha	1861 to 1905	2843 Ha
Subtidal	19634 Ha	1906 to 1931	1642 Ha
Harbours	760 Ha	1932 to 1960	2400 Ha
		1961 to 1980	1241 Ha
		Total	15284 Ha

From these data it appears that in 1800 the intertidal area of the Schelde occupied of the order of 26277 Ha. By 1980 of the order of 15248 Ha had been poldered, a loss of 58%. In that it is the intertidal area into which the tide propagates, the loss of 58% of the intertidal area will inevitably affect the tidal regime. From data examined in section A , it is evident that the tidal ranges and mean water levels outside the Schelde estuary have increased only slightly over this period, whereas within the estuary the tidal range and other tidal characteristics have changed greatly. In particular the location of height and range maxima have moved up estuary although peaks in the amplification profiles have moved seaward. We conclude that on the basis of the analysis so far the observed changes in the tidal regime of the Schelde Estuary are related to changes in the morphology of the estuary. At present the only documented changes are those which show a substantial reduction in the intertidal area of the estuary. The observed changes in tidal regime are wholly consistent with the noted reduction in intertidal area.

Recommendations.

It is felt that the link between the documented changes in tidal regime and documented changes in morphology provide an opportunity to identify the degree to which "natural" changes have influenced the tidal regime. This would require the analysis of changes to the tidal regime to be linked to morphological analysis and the effects of specific events, such as the 1953 dyke breaching, to be examined. This would have very important implications for a range of estuarial management options and strategies.

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Fig B. 1

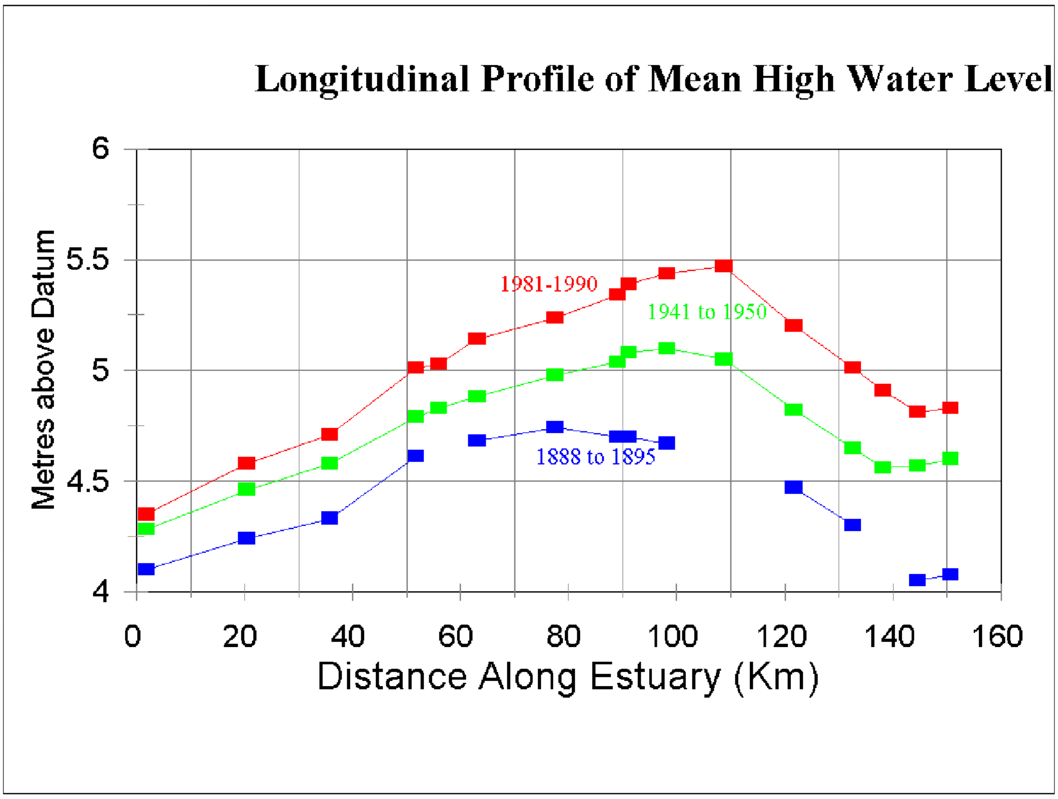


Fig B 2.1

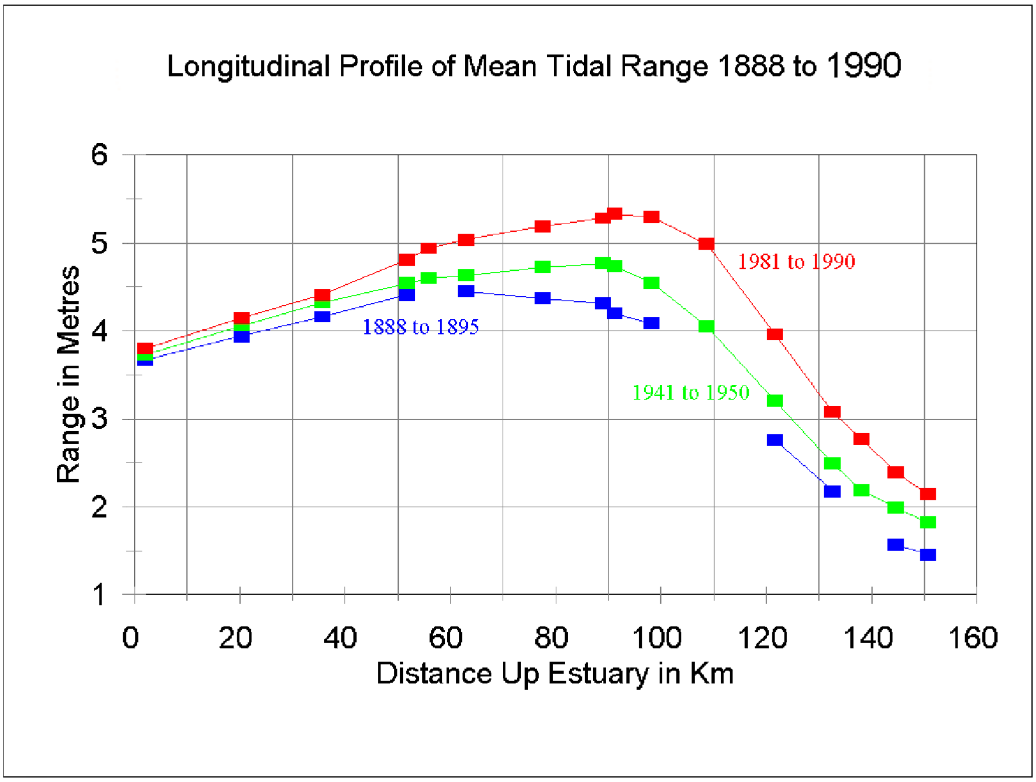


Fig B 2.2

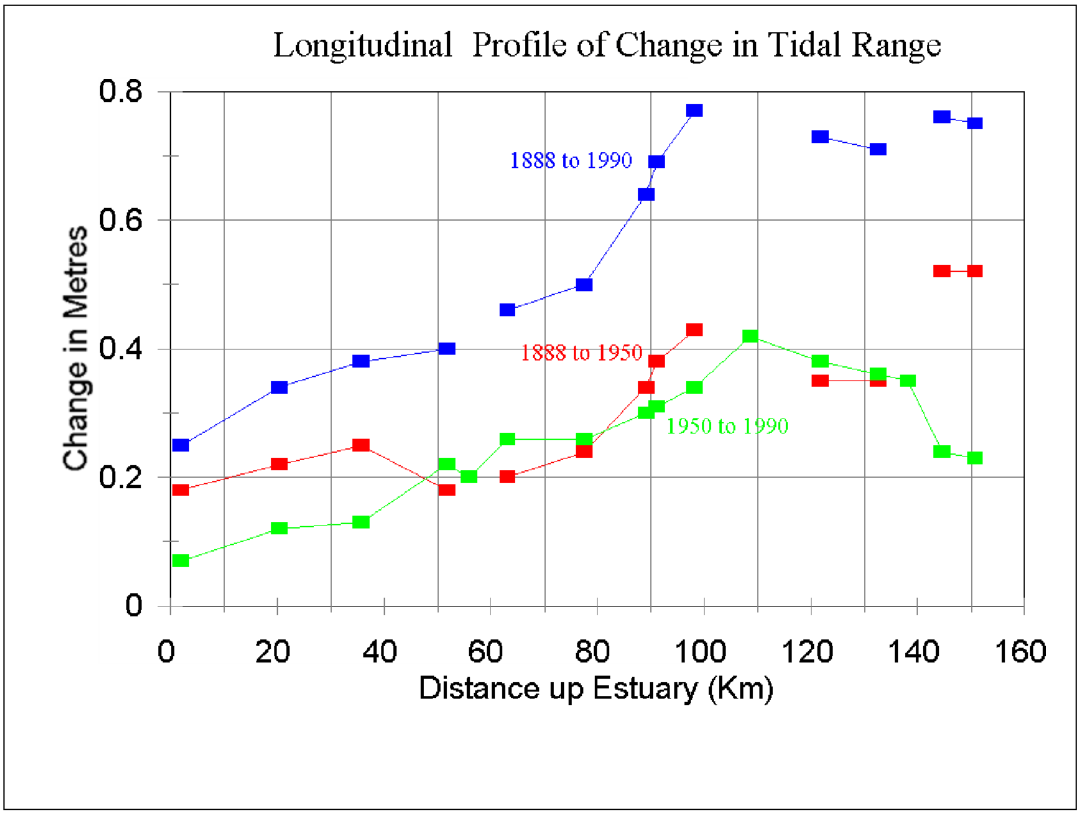


Fig B 4

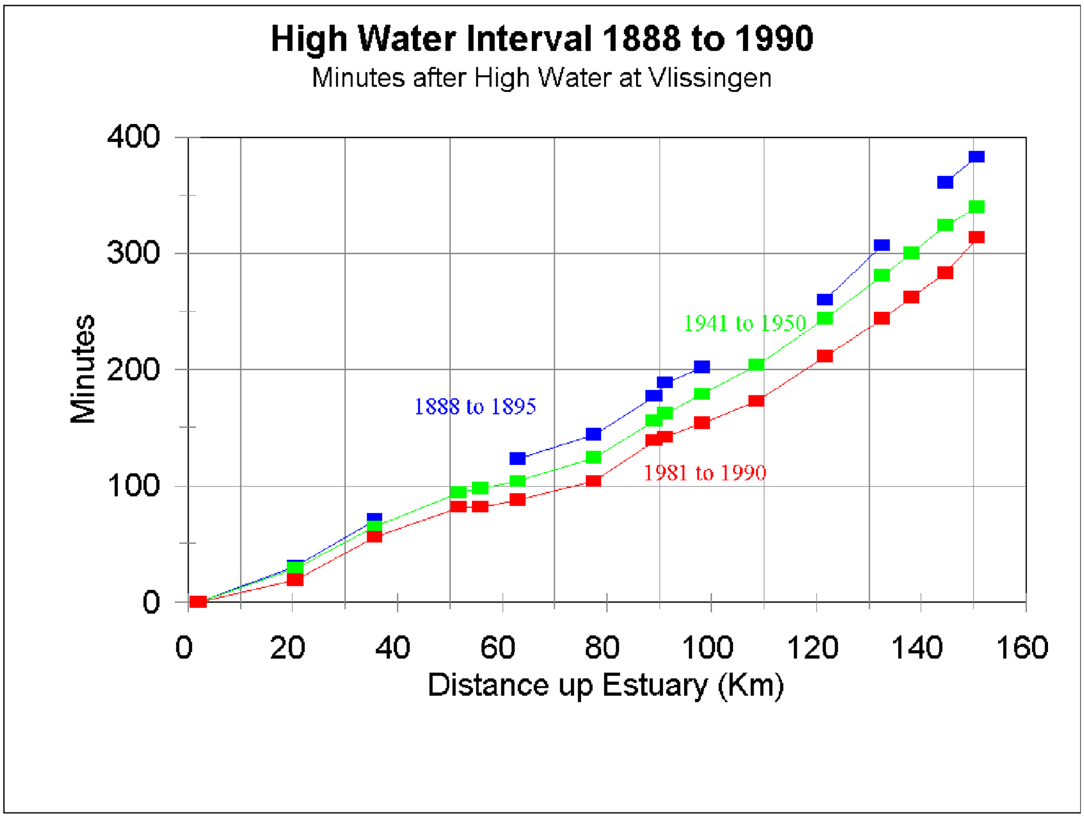


Fig B 5.1

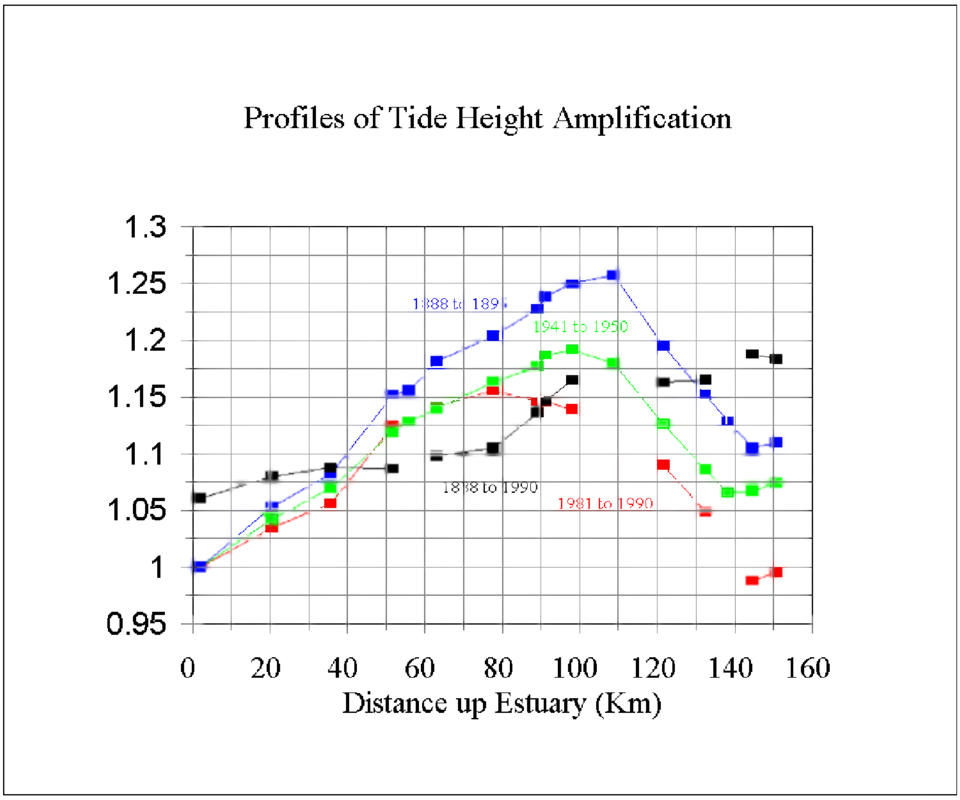
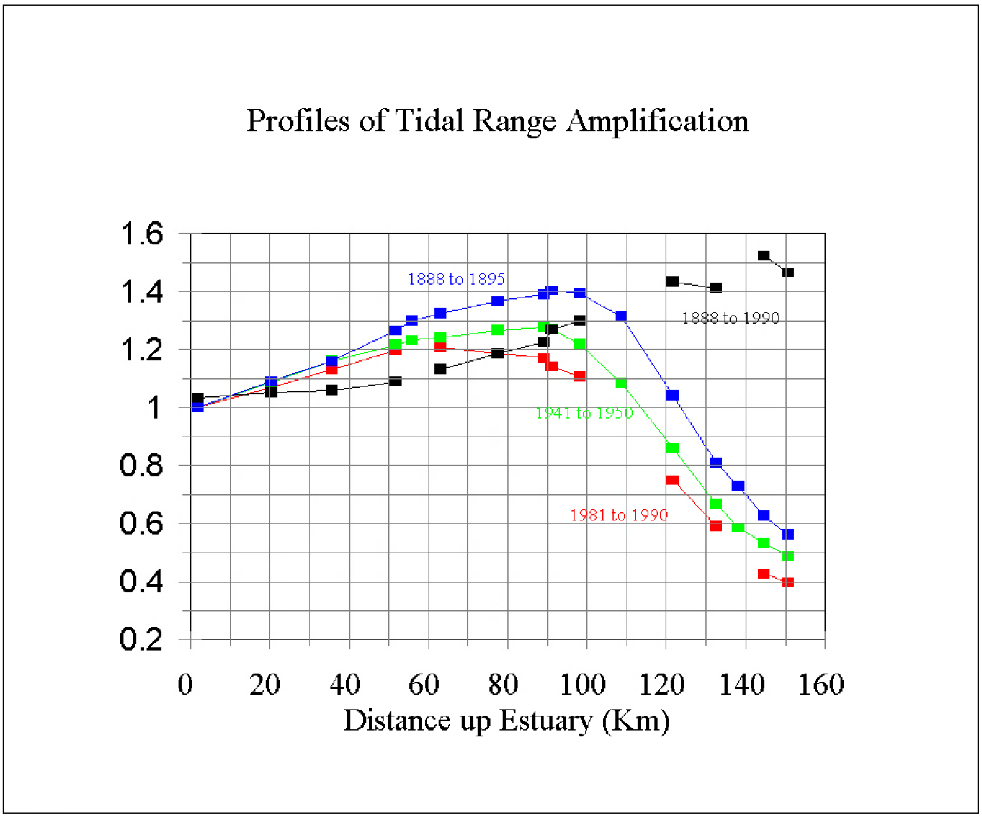


Fig. B 5.2



Appendix 3

Appendix 3

MATHEMATICAL SIMULATION

by

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5 June 2000

INTRODUCTION

The mathematical simulation is one of a number of tools used to assimilate, derive, and disseminate knowledge of the Schelde estuary. Placed in context of the tidal and morphological history of the estuary and the human influences that have contributed to changes in the behavior, the mathematical model can be a valuable tool. The results of mathematical modeling are an indication of only a part of the physical processes going on in the estuary. The results must be interpreted, translated from the mathematical world to the physical one. The best results are achieved when the assemblage of subject knowledge is diverse (all inclusive) and substantial. One could refer to such an assemblage as the Complete Package of Knowledge (CPK).

The LTV deals with three basic estuary issues: Accessibility (ease of access), Safety (from flooding), and Naturalness. The assembly of knowledge - mathematical simulation included - must be directed towards these three issues. The confidence level is highest when the predictions obtained from all tools converge to a common conclusion.

Mathematical simulation of tidal motion in estuaries is considered a necessary but not sufficient activity to the understanding many of the ongoing physical processes. The laws of motion are known. Newton's second law (most often referred to as the conservation of momentum equation) and the conservation of mass are valid for the Schelde and all other estuaries; that assertion is unchallenged. The problem arises in the formulations and solution algorithms for these laws. The movement of the water, its accompanying salinity, sediment, and other substances can be approximated to various degrees of validity and accuracy. When proven reliable to reconstitute events that have occurred in the past, there is a level of confidence that the simulation models can be employed to assess the intervention options – such as dredging - and their impacts on many of the estuarial processes.

The Antwerp Port Authority and LTV have a need to know the consequences for various dredging options to increase the navigational depth in the Schelde estuary from the North Sea to Antwerp. Likely, the history of dredging in the navigation channel, when put in the morphological setting, is the foundation knowledge for prediction of new interventions to achieve a deeper channel at the shallow crossings. The question is how to assess strategies that have not been undertaken before. This can be achieved by mathematical modeling provided the model simulates certain features of dredging. These ought to include:

1. The correct split of flood and ebb waters between channels at confluences and bifurcations and onto and from flats in this multi-channel estuary.

2. The correct split and amount of bed-sediment transport moved by flood and ebb waters through confluences and bifurcations and to and from flats.

3. The realistic movement of bed sediment from pool to crossing and from crossing to pool during the tidal cycle.

The movement of all substances – water, salinity, sediment, and contaminants – in the Schelde estuary is physically and hence mathematically 3-dimensional; that is, having movement in three directions. These are vertically and two directions in the horizontal. A 3-dimensional model of the Schelde would be prohibitively expensive, and it is generally not needed, at least over the entire estuary. The 3-dimensional model meets the three requirements listed above. In the 1-dimensional model, the direction of the flow is just "flood" or "ebb" in the channels. All the accelerations are changes in speed only, and not in direction. It ignores the influence of momentum is distributing flow at distributaries and confluences and onto flats. It generalizes the motion of sediment, grouping sediment to faithfully follow the 1-dimensional water motion. The 2-dimensional model (motion in two directions in the horizontal) helps to simulate the bending of the water paths at confluences and bifurcations, and onto the flats, but is not as helpful in determining the correct motion of sediment.

The prudent procedure is to start with a 1-dimensional model, calibrated and verified with field data, to quickly obtain a broad base of knowledge, Two-dimensional representation can be added where the 1-dimensional simulations in sections of the estuary are woefully weak. Unless the simulation model can reproduce the actions of water and sediment measured in the field, its use for any purpose must be considered suspect. Therefore field measurements of tidal data are essential to the building of a valid functioning mathematical simulation model.

The Schelde estuary is rich in tidal and morphological history, both in space and in time. It is a matter of putting these data in the framework of a predictive tool to accomplish the LTV goal and that of the Antwerp Port Authority.

DREDGING OPTIONS

Dredging for navigation takes place on the channel crossings where the bed is highest and the water depth the least. The simulation model is needed to predict how high the crossings can become, how much must be dredged, and how often. The model can be used to evaluate the effectiveness of different degrees of overdredging.

Looking after the products of the excavation is equally important. There are three places to put the dredge spoils – in the North Sea, in the Schelde estuary, or on the land outside the estuary. Within the estuary, the dredged materials can be placed in the flood channels, in the ebb channels, on sand flats, or in other places such as channel margins. Sediment taken outside to the polders and other places on land can be marketed or wasted. It is likely that the optimum dredged material disposal plan will be a combination of more than one of the options.

FIELD DATA

Comparison of field data and simulated results often lead to the accusation that "the data are wrong"! A more platonic view is that some aspects of the mathematical model are confirmed by field data and others are not. Thus, the field data serve to identify the strengths and weaknesses (limitations) of the model. In the final assessment of a proposed intervention, account can be made for the deviation between model results and field measurements.

The historical data on tides and morphology have been assembled and the analyses of these are essentially complete. In the last two decades, instruments have been developed that can measure the entire velocity vector field (x, y, and z) and the accompanying water discharge at any section in the Schelde estuary in a matter of minutes. The Acoustic Doppler Current Profiler (ADCP) has leaped field measurements equal to or ahead of mathematical simulation in the quest for hydrodynamic knowledge. Now, mathematical modelers of estuaries must judge their concepts against a much more profound view of reality.

In the Schelde estuary, one can measure the flow in each of the multi-channels and at a bifurcation for both flood and ebb tides. These data are used to check the formulation of the models and tune the empirical coefficients in the equations hopefully to get a more correct simulation. In fact, instead for viewing the field data as calibrating and verifying information for the mathematical model, it is most probably a better strategy to do some measurements - as with the ACDP – from which the conceptual mathematical model is then chosen or structured. It is unlikely that much change to the structure of the mathematical model can be made after the resources have been used to develop it.

In addition to the measurements of water, bed, and flat levels, flows, velocities, and so forth, there is another great body of knowledge. That is the experiences of all the people who have lived and worked on the Schelde estuary. This reservoir of knowledge should be tapped. The proven techniques of interviewing should be applied to gain the most benefit. Open-ended questions can result in uncovering nuggets of information which the interviewer had not conceived before. A good starting point is interviews with the pilots who bring the ships in from and out to the North Sea.

The dredging records for the navigation channel in the Schelde estuary are extremely valuable for judging future options for excavation and dumping sand to achieve a deeper channel. It is probably more efficient to study these records before developing the mathematical model than afterwards. The same is to be expected for interviews with the dredgers. The experiences of the hydrographers rank in value with those of the dredgers.

Aerial photographs taken at the 18.6-year lowest spring tide give the best image of how water (and sediment) move from the main channels onto and out of the flats. If there is vast system of micro-channels, they are exposed. At higher water, streaklines on aerial photographs indicate the direction of the surface water flow and sometimes the existence of converging currents. Shades of color or grayness portray different concentrations of sediment or depths of flow.

In general, the existence of field data often overtaxes our ability to utilize it. Suitable samples must be selected. For example, a mean vertical tidal cycle is selected to represent the continuing and changing cycle of neaps and springs.

CONCEPTS

There are two equally important concerns for the mathematical modeler. The first is to get the conceptual view of the physical phenomena basically correct. The second is to get the computational hydraulics functioning correctly. Only the conceptual issue is addressed in this report. It is assumed that the computational hydraulics is being done correctly.

In general, the substances transported are (in estimated order of importance by mass):

- Water
- Salinity
- Sediment

- Nutrients
- Aquatic biota
- Contaminants
- Other

The water motion is driven by the astronomical tides in the North Sea. At times there is a significant vertical salinity gradient in the flow, but in general the Schelde estuarial waters are well mixed in any subreach. For the dredging assessment then, the prime focus must be on water and sediment.

The sediment transport component of the model should include (in order of importance)

- Bed load
- Bed-material load in suspension
- Clay particles in suspension and mud

The flocculation of clay particles, and the formation of mud on the channel bed is special issue for the Belgium section of the estuary now. If this process is considered important, a special model emphasizing this feature should be built after other modeling is well advanced. Therefore, initially without mud, the important sediment transport variables or parameters for assessing dredging options (in order of importance) are:

- Water velocity (speed and direction) and associated turbulence
- Size and density of bed sediment
- Depth of water
- Water temperature

Because of the flat nature of bed forms in this estuary, the effect of temperature may not present itself in the dramatic form that is does in some navigation channels in rivers.

Conceptually then, the water velocity vector is the prime variable to simulate, followed by the correct representation of the bed material in the channel.

The Schelde estuary flows are driven by tides in the North Sea. Sand from the sea accompanies the flood tide into the estuary. The vertical tide in the sea and the sand transport in flood channels seaward of Vlissingen make up the seaward boundary conditions for the simulation model. At the other end, it is the river flow of fresh water and its sediment entering upstream from Antwerp.

The plan for the LTV is to judge intervention options on the basis of:

- Accessibility
- Safety
- Naturalness

Therefore. The model results have to be viewed and judged in the same manner. In considering hydrodynamics and safety, North Sea storms are the major factor. If the storm tide (spring tide plus storm surge) at the mouth of the estuary is not a adequate input to the mathematical simulation, the wind stress on the water surface can be added.

ONE-DIMENSIONAL TRANSPORT

Two-Channel Concept. The plan view of a two-channel (no flats or overbank storage) one-dimensional simulation model for water motion is shown in Figure 1. During the flood tide, the water entering the bifurcation from the left, some taking the side channel, the rest remaining in the straight-through main channel. Most 1-dimensional models makes this choice on the basis of channel morphology. In reality, the water makes the choice based on its top and bottom momentum which is related to both the upstream, and downstream morphology. Not all the water that enters the two channels leaves at the confluence where they join together again into one. Some water is stored in the channels reaches.

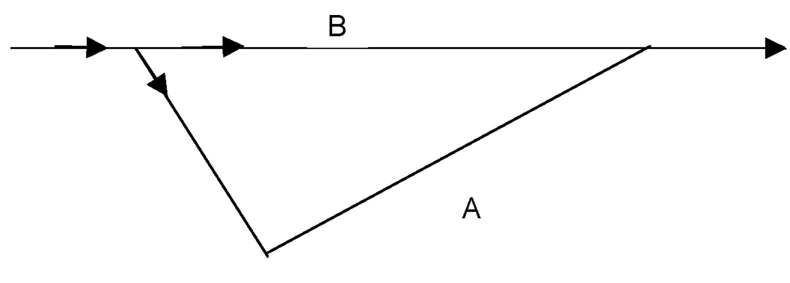


Figure 1. Plan view of a one-dimensional, two-channel model. The arrows indicate the direction of the flood tide. Flood flows are bifurcated at the left side and join together again on the right. The flow leaving the two channels is less than that entering due to storage in the channels.

On the ebb tide (Figure 2), the bifurcation is at the other (right) side and the flow must split itself again. For asymmetrical vertical tides and curved channels, the flood and ebb flows in each channel are different.

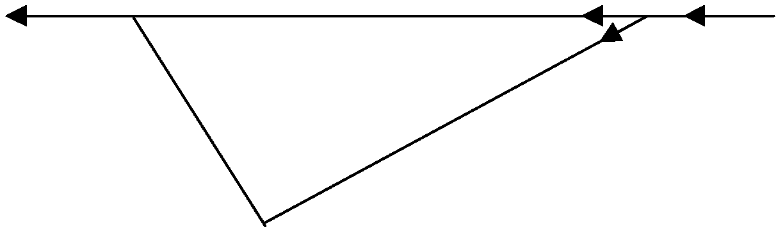


Figure 2. Plan view of a one-dimensional, two-channel model at ebb tide. Flows are bifurcated at the right side and join together again on the left. The flow leaving the two channels is more than that entering due to the reduction of storage in the channels.

In the 1-dimensional model, it is assumed that the sediment load moves with the water. The water does not accumulate in the estuary but the sediment can and in most estuaries it does. The very fine sediment (called wash load) concentration is considered uniformly distributed in the water column and is independent of the characteristics of the flow. It moves at the same speed and direction as the water.

The bed-material load, made up of the sizes of particles found on the bed, moves differently. Its speed depends on whether the particles make contacts with the bed or not. Moreover, the concentration of bed-material load is greater near the bed than above. The sand waves on the bed are a manifestation of the bed-load transport.

The morphology of the multi-channel estuary changes due to imbalances in what the water in each channel can carry and the amount of sediment brought to the channel by the flood and ebb flows. One reasons that if the morphology is not changing, then some degree of equilibrium has been realized.

The program of dredging in the ebb channel and spoiling in the flood channel is affecting the transport rate of bed material in both. Suppose sediment is dredged from the channel marked A in Figure 1 and dumped in the channel marked B. What will happen to the morphology and tidal propagation in this multi-channel estuary? The simple two-channel model is structured to answer this.

Channels and Flats. The Schelde estuary is much more complex than two simplex channels joined by short stretches of single channel. The next 1-dimesional level of complexity is to add tidal flats in the area between the channels and outside and adjacent to each. The model moves the water onto and away from the tidal flats based only on the assumption that the water level in the channel and on the flat must be the same when the flat is wet. The modeling of micro-channels and their overflows is forgone for expediency and the belief that any further modeling effort is not warranted.

The Delft Hydraulics' ESTMORF model is of this type. It contains the 1-dimensional equations for the force-acceleration balance for water motion and the dispersion (advection-turbulent diffusion) for sediment transport in the channels. Water is moved onto low flats and high flats bookkeeping to maintain the water levels the same. Aggradation and degradation can occur in the channels. On the flats, only settlement (sedimentation) is modeled.

A number of calibration coefficients are required to solve the 1-dimensional equations of water and sediment motion, especially sediment. The coefficients must reflect two type of information. Take for example, the roughness coefficient. Normally, this coefficient is described by the sand-grain and bed-form sizes. But, in the estuary 1-dimensional model, it must also account for the loss of hydrodynamic information we get by using only a one-dimension in the model instead of three-dimensions.

CELL MODEL

The cell model use by Delft Hydraulics to simulate water and sediment motion in the Schelde estuary is the 1-dimensional type offered as *A new morpholodynamic schematization of the Scheldt-estuary.* The authors are Winterwerp, Jeuken, van Helvert, Kuijper, Stive, Thoolen, and Wang. The information available is a PowerPoint file in Enlish for presentation to audiences.

This documentation was not given at the meeting in Delft on 1 June 2000 where clarification could have been had. Errors in the interpretation may due to lack of understanding of the abbreviated presentation, and not actual modeling limitations. There has been no opportunity to study the modeling calibration and output in detail. Only the summary is given.

One very appealing feature of the cell model is the effect of cell coupling. The most vulnerable system (to degeneration) is the series of single cells. The cell system becomes more resilient as more cells are added inside the primary one. The parallel and the mixed coupling are more robust morphological features than the series configuration. The mixed coupling is somewhat equivalent of the small deltas at the ends of the flood channels, described farther on in this report. The small delta is a source or sink for sediment at times the channels so desire.

The cell schematization extends from Vlissingen to Gent, a distance of 160 km. This includes 70 km of upstream riverine channel. Other features modeled were:

- River flows from 60 to 180 m3/s.
- Tidal range 4 m at the sea and 5 m at Antwerp.
- Planform from mapping in 1992.
- Bathymetry was that measured in 1999.
- Channel bed sediment is very fine to medium sand.
- Sand transport in from the sea was taken as 1 million m^3/year.
- Motive was the further deepening of the Schelde from the sea to Antwerp to a navigation depth of 14 m.
- Stated aim was to develop a healthy, multi-functional estuarine water system that can be used in a sustainable way for human needs.

The seaward end of the model should be to sea a distance so that the vertical tide is not influenced by the morphology of the estuary. This issue is discussed in Peters' morphology and tides report.

Three possible evolutions were considered by Delft Hydraulics:

- Drowning of the estuary so that no tidal flats are exposed at any time.
- Degeneration of the multi-channel system.
- Maintenance of the present system, considered in dynamic equilibrium now.

The planform morphological history suggests that the present morphology has been deformed unnaturally by human intervention and then held in place by structural protection works. There is a simpler and more likely more stable configuration that is more in accordance with the stated LTV aims. There is evidence is that the present-day multi-channel system is not self-preserving, nor of the most desired form. The evidence is in the ongoing changes in the estuary over the last 200 years.

The purpose of the morphodynamic studies is to determine the morphological response to human and other influences. The historical developments listed are:

- Changes on tidal volume, more than 50 percent in the past.
- Sea level rise of 20 to 60 cm/century.
- Ebb tide delta development.
- Large-scale deepening in 1970 and 1996.
- Internal sediment movements of 10 million m^3/year.
- Sand mining of 2.5 million m^3/year.
- Extension of Zeebrugge port.

- Development of tidal asymmetry.

The specific issues listed are:

- Sea level rise.
- Dredging and dumping.
- Sand mining.

The primary morphometric unit is called a cell, a tidal-channel complex at the meso and macro scales. It consists of adjacent ebb- and flood-dominant channels as in Figure 1. . Sediment moves back and forth in the cell, seemingly without connection to the cells either seaward or landward. The Western Schelde is schematized as a chain of such cells, each in equilibrium within itself and not communicating with its neighbors. It is claimed that this concept is qualitatively validated against observations by and experience of the Belgium and Dutch users of the cell system. No evidence of this validation is offered. Moreover, mathematical simulation models require quantitative calibration and validation, most often a very difficult undertaking.

The planform history of the Schelde estuary suggests that there can be a strong communication between cells and this is reflected in bars moving and building, channels deepening or filling and other more subtle changes. The details of what was used for qualitative validation are needed.

The formulation for the 1-dimensional cell model is complete. It includes:

- One-dimensional quasi-steady analysis.
- Continuity equations for water and sediment.
- Momentum equation for water.
- Transport equation for sediment, uncoupled.
- Channel–flat exchange of water and sediment.
- Distribution of water and sediment at junctions.
- Graphic solution of the set of equations.

Without specific information on each of the items in this list, no judgment can be made. For example: What are the values of all the empirical coefficients needed for the set of equations? How was the distribution of water and sediment at the junctions obtained? Is this a black-box approach at junctions? How steady is quasi-steady? Why is a graphic solution used?

The degree that a model is validated depends on the information used in the validation. For example, if the model produces a surface velocity field matching a streakline on aerial photographs over a long reach of curving multi-channels at the correct time in the tidal cycle, that validation is of different value than the statement that sediment accumulated in a cell. For dredging, the confirmation that a model crossing fills at the same rate as measured in the field is of great value.

The general results of the cell model are:

- If more than 10 percent of the gross transport is dumped into a cell from without, that cell degenerates.
- If sediment in excess of 5 percent of the gross transport is dumped into a parallel channel within a cell, that cell degenerates.
- Flat levels and sand bars need to rise only centimeters per century to keep up to sea level rise.

The first two are profound model results. One can visualize other responses, one being sediment dumped in one cell is spread to its neighbors, or even smeared along a part of the estuary. Dumping options range from dumping all in flood channels to dumping all in the sea. There is a best option somewhere in the range.

The view that is that an initial capital dredging of 35 to 50 million m^3 followed by maintenance dredging of 15 to 20 percent per year is needed to have a 14-m channel. Was this determined with the model?

It was identified that prediction for the highly dynamic areas of the estuary were more uncertain suggests that some channel planform change for such areas is warranted. The configuration of 1938 is a good starting point for discussion. A gentler channel shape may result in lower crossing and less dredging.

The schematization of the estuary into cells is not appealing from a strictly physical point to view. During every tidal cycle, water moves from the sea far inland and back again. The same water crosses many cells. Most of the suspended sediment does the same. Information is lost because of the conceptualization of this physical motion into cells.

In the 1970s, when computers were slow-moving, pea-brained dinosaurs, the Schelde estuary water motion was simulated with a 2-dimensional model. A much better effort could be made today. It is not clear why instead the cell model was employed in this study.

The cell model has brought a wide variety of information to bear on the selection of future interventions in the Schelde estuary. Equally it has stimulated thinking on management options to eliminate barriers to achieving the desired goal. When the results of the cell model have been compared to the vast amount of other information available, solid conclusions can be reached on the value of the cell model as well as on other issues.

Another Schematization. The plan form of the Schelde estuary in 1938 is of special interest. Its morphology is simpler, elegantly so, than in other mapped years. One 1-dimensional schematization (Figure 3a) is that of discontinuous flood channels terminating on small deltas. Starting on the seaward end (left side), there is one channel entering from the North Sea. It bifurcates, and soon after one branch disappears, then reappears. The other channel is continuous for quite some distance but then it terminates in a small delta (configuration represented by three short lines). In all, there are three bifurcations and two inland deltas. There is one continuous channel passing from one end to the other. The side channels are not continuous.

If the small deltas served as both a sink and source for sediment at times of morphological stress, then one can conceive of a morphology in a short of dynamic equilibrium. The continuous channel and other features remain essentially unchanged.

This interpretation suggests that one more small delta (Figure 3b), at the end of the first flood channel nearest the sea, would complete the dynamic but relatively stable configuration for the estuary.

The 1-dimensional mathematical model of water and sediment for the models in Figure 3 is much different that those described previously in this report. Ideally, one wants a model that would morph the plan form of 1938 to that of 1992 through the simulation of the important physical processes. Until the time that such a model is available, we must accept modeling with its limitations. Therefore, the knowledge of model limitations is as important as the model results.

DECISION MAKING

In the end decisions on the dredging options for navigation (excavation and dumping) will be made. The mathematical model is just one of many pieces of knowledge which will have been assembled to assist in the decision making. To help in the assembly of prediction tools, it is advantageous to look at the consequences of making mistakes. Consider the simple decision matrix (Table 1). There are only two outcomes from the dredging options. One is that all the desired impacts are obtained - a deeper navigation channel, more safety, and the naturalness. This outcome is labeled “Should Dredge” – “Dredge” meaning both a dredging and dumping operation. The other outcome is that a major undesired impact results; for example, loss of naturalness. This outcome is labeled “Should Not Dredge” – meaning should not dredge and dump this way.

Table 1. Decision Matrix

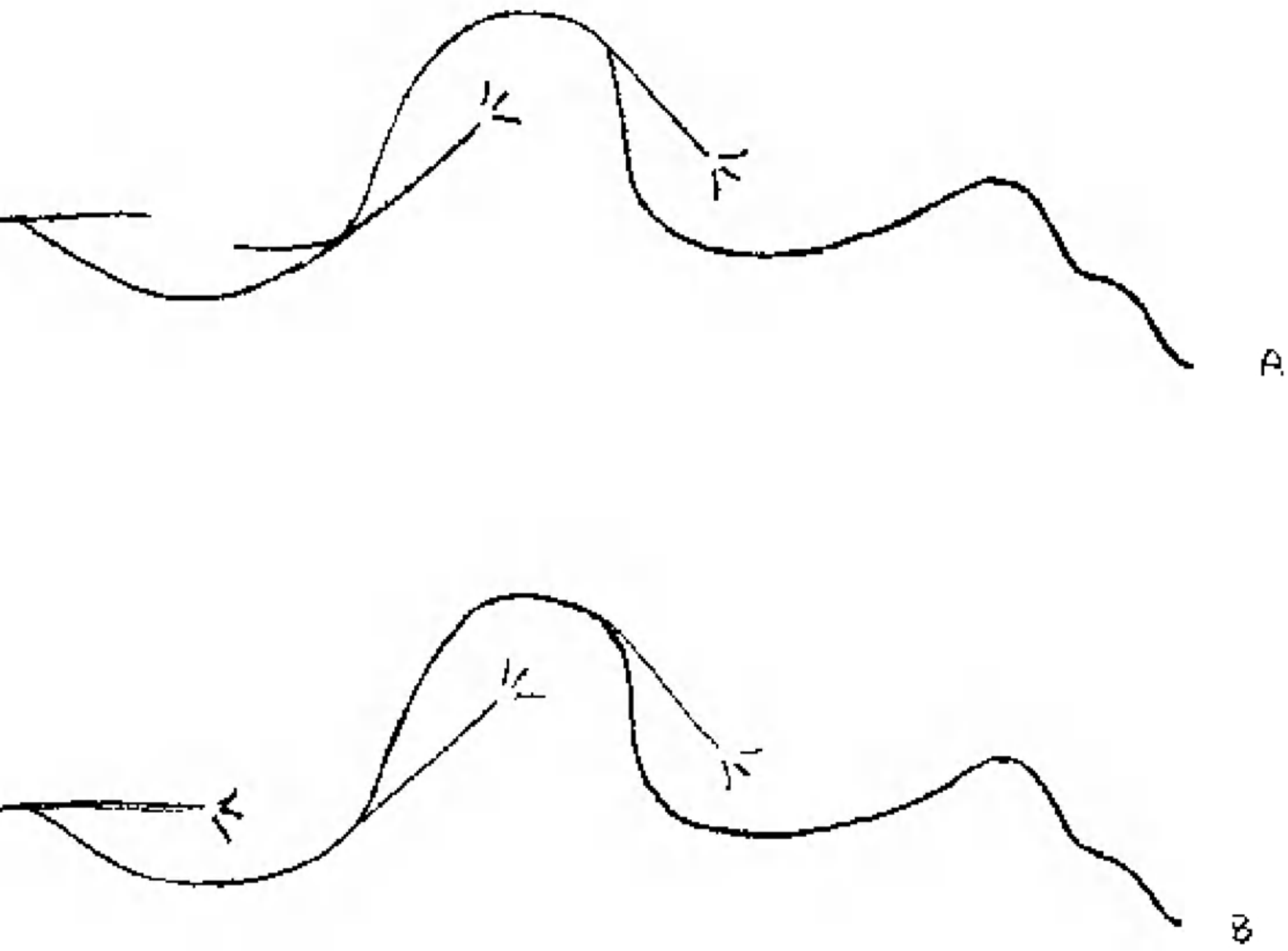
Decision	Should Dredge	SHOULD NOT DREDGE
Dredge	No Mistake	X Mistake
Don 't Dredge	X Mistake	No Mistake

There are but two decisions – to dredge or not to dredge. No mistake is made if we dredge and there is only desirable responses (good impacts) and if we don't dredge and thus avoid undesirable impacts. These decisions are labeled "No Mistake."

If we don 't dredge and we should have because the impacts would have all been desirable, that is a "Mistake," and a very serious one because all the benefits of a deeper navigation channel will have been lost, and only because the decision-making tools were not good enough.

If we dredge and we shouldn't have dredged because the outcome was many undesired impacts, that is also a "Mistake," again because of faulty tools. The question is then, "Is this mistake reversible"? "Can the mistake be corrected by some intervention that will restore the desired safety or naturalness or both"? For example, if the answer is no! - the naturalness cannot be restored. That is a very serious loss. However, if the answer is yes, naturalness can be restored, there is only the cost of the restoration to deal with.

When building tools to make forecasts and decisions, it is prudent to include reversing intervention options as an objective. Also, as much knowledge as can be assembled from all fields of science and engineering should be brought to bear on the decisions.



of the 1938 Schelde estuary plan form (A) and an extension of the simple elegant morphology to complete symmetry
e left. North is upward.

ADDITIONAL COMMENTS TO THE "MATHEMATICAL SIMULATIONS" (APPENDIX 3 TO BASELINE REPORT)

by

Jean Jacques Peters

INTRODUCTION

Future strategies for achieving a deeper navigation channel to the Port of Antwerp shall be discussed in the final report. However, LTV must formulate soon an opinion about the tools needed for deciding about the dredging strategy, including mathematical models.

Based on the information he could collect and analyse during his stay, Michael Stevens worked out the report presented in Appendix 3. Besides this, an assessment of the morphological evolutions is presented in Appendix 1, proposing another vision on how sediment-transport processes intervene in the morphological evolutions, apart of the role played by morphological and hydraulic controls. This view was already briefly suggested during a meeting in Delft Hydraulics, on 31 June 2000, but it needs further elaboration and eventually discussion in the LTV cluster morphology.

The expert team believes that the cell model concept can be used to assess, at a preliminary stage, what could be the overall impact induced by dumping given volumes of dredge material on the further development of secondary channels in the Westerschelde. The researchers at Delft Hydraulics show the need to combine the cell model with other mathematical tools, like ESTMORPH.

The aim of this note is to indicate where and how quick progress could be made, so that strategies might be developed for the management of dredge-products. It also intends to make more explicit for the LTV which direction will take the final reporting of the expert team appointed by the Port of Antwerp Authority.

Confronting the cell concept with the morphological analysis

As mentioned by Michael Stevens, it is not so clear to the expert team how precisely the available information was used to develop the cell concept. When looking on the maps from 1800 to 1992, it can be seen that reworking of the morphology in the Westerschelde has been quite strong in a period without significant dredging, between 1800 and the mid-nineties. The morphology of the Westerschelde in 1800 was not showing the typical pattern of dominant flood and ebb channels. Drawing cells in the Westerschelde of 1865 would not be easy.

With the present layout of channels and bars, it can be concluded that interactions exist between channels from different cells, cells as presented by Delft Hydraulics for the situation of 1992. The partition between the Middelgat and the Gat van Ossenisse channels of the flood flow coming from the Everingen controls the sediment distribution between these two channels. The sand leaving the Everingen continues travelling in next cell instead of being carried further in the same cell.

Obviously, one can argue that the cell concept is looking at the processes in a different way, as a kind of recirculation around bars. The question remains about the transfer from one cell to another, especially when considering the change in shape of the sandbars which volume may vary quite a lot. This was the case for the cells closest to the mouth area when the main channel between Vlissingen and Terneuzen shifted progressively to the West. The analysis made in the baseline report indicates that this was likely triggered by the poldering of the Braeckman and Sloe. The reduced storage area changed the flow patterns, but also of the construction of embankments controlled or guided the flow. Other typical evolutions happened with the Eastward shift of the Gat van Ossenisse and the Westward shift of the Zuidergat. Some areas are still undergoing such changes.

About the sediment transport capacity

One aspect of the modelling with the cells that merits more attention relates to the sediment transport capacity. This capacity is not only governed by section-averaged flow data. Valuable Information about flow intensities is provided in Figures 22 and 23 of the document "De Schelde Atlas, een beeld van een estuarium"16, showing the distribution of the maximum velocity during the flood and during the ebb. It is unclear how much the model results are corroborated by field data, but the distribution looks realistic. Because the highest velocities do not occur everywhere at the same moment, similar pictures with instantaneous velocity distribution at various stages of the tide could yield quite interesting information to test the validate the modelling of the flow distribution at confluences and bifurcations. It may also help selecting suitable places for dumping sediment.

However, "iso-vel" lines - iso-velocities, or distribution of flow intensity in plan form - on maps have to be interpreted with much caution because they may create a false impression of the flow direction. Moreover, they yield give a picture related to time-averaged flow, without information on the flow turbulence. The influence of turbulence needs to be integrated in the analysis of

[16] The Scheldt Atlas, a vision of the estuary

dumping sites, because hydraulic structures built in the estuary produce locally higher turbulence that affects the sediment transport capacity of the flow. Dumping sediment in the scour holes that are created by groynes will have a different impact than dumping in an evenly deep channel maintained by a quieter flow. The analysis of dumping strategies must take this aspect into account.

The morphological evolutions after 1800 indicate a continuous adaptation of the plan form geometry to the man-made changes like poldering, closure of creeks and building of embankments. All these actions have produced a redistribution of the sediment in the Westerschelde. It required transfer of sediment from one area - or cell - to another. This transfer was influenced by the flow structure, especially the degree of flow concentration and of turbulence. In recent times, groynes or dykes were used to stabilise the channels and they have most likely created additional turbulence, affecting sediment transport capacity.

It would be really useful to test the cell concept on these past evolutions and such tests could give more confidence about its use.

Conclusion

The cell concept is based on an interpretation of the present Westerschelde morphology. Apparently, past morphologies did not fit so well with this concept. It is however not a reason to say it would not work for the actual situation, but this needs to be checked.

A preliminary morphological assessment made for the advice requested by the Port of Antwerp indicates that the channels continue to evolve because of various human interventions. This would happen by transfer of sediment between areas considered by Delft Hydraulics as cells. The sediment transport capacities of the flow controlling these transfers are furthermore influenced by the plan-form distribution of the flow, and by its turbulence.

The final report will contain a more detailed analysis of the area between Hansweert and Bath to evaluate the relative impact of dumping dredge material on the morphological evolution. This could be interesting to assess the usefulness of the cell model.

13 June 2000